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AN EXPERIMENTAL TECHNIQUE FOR MONITORING DYNAMIC CRACKS

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FOREWORD

The research reported herein was conducted by the staff of the Monsanto/Washington University Association under the sponsorship of the Advanced Research Projects Agency, Department of Defense, through a contract with the Office of Naval Research, N00014-67-C-0218 (formerly N00014-66-C-0045), ARPA Order No. 876, ONR contract authority NR 356-484/4-13-66, entitled "Development of High Performance Composites."

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A technique is presented which, by means of plating and etching processes, permits the creation of a wide variety of crack propagation gages. High precision gages of arbitrary size and shape are easily prepared. Specific gage configurations are shown for center notch, edge notch and cleavage type specimens. Optimum gage design is discussed and typical readout circuits are shown.

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R. E. Lavengood, D. Peretz, F. L. Brissey and E. M. Wu

The study of propagating cracks has traditionally been hampered by the lack of a convenient technique for monitoring crack growth. High speed photography can cover a wide enough field to satisfy most needs, but the peripheral equipment is quite expensive, and the data reduction is slow and laborious. Ultrasonic transducers are occasionally used to impose a sinusoidal variation on the existing state of stress, thereby causing ripples on the fracture surface which may be used as timing marks. This technique is acceptable with some elastic materials, but may not be used with viscoelastic materials because the properties of such materials are strain rate dependent. An alternate approach, which is adequate for many specific applications, involves bonding on crack propagation gages, which are commercially available from strain gage suppliers. These devices are similar in appearance to bonded strain gages, however, the gage section is shaped like a ladder. The lead wires are connected to the sides of the ladder, and the change in resistance is monitored as the crack breaks the successive rungs. The major disadvantage of this approach is the very small size of the gages (typically, 1/8" wide). The path of a freely propagating crack can usually not be anticipated with sufficient accuracy to insure correct placement of these small gages. This paper describes a new technique which permits crack propagation gages of arbitrary size and shape to be applied to specimens with great precision.

The basic approach consists of plating the surface of the specimen with a thin, continuous film of copper, and then using a state-of-the-art printed circuit technique to selectively etch away copper to leave a grid of parallel conductors perpendicular to the direction of crack propagation. If the specimen is conductive, it must first be painted with a "stop-off" lacquer or other insulating film. Such lacquers, plating and etching supplies are readily available from Shipley, Kodak, DuPont or MacDermid.

The simplest way to detect an advancing crack with such a gage is to put the gage in a D. C. Wheatstone bridge and monitor the output voltage. If the bridge is initially balanced and each element of the gage has the same resistance, the breaking of one element would produce the following change in the output of the bridge:

$$\Delta V = \frac{N \quad V_s}{(2N + n)^2 - 2N-n} \qquad (1)$$

where ΔV = change in output voltage of the bridge

V_s = excitation voltage on the bridge

N = total number of elements in the gage

n = number of broken elements in the gage.

With polymeric materials, V_3 must be kept small to minimize the heat generated in the gage. Therefore, as N becomes large, the ΔV associated with the breaking of the first element becomes very small. This makes detection difficult. As each successive element is broken, a larger voltage change is induced; thus the detection problem is associated primarily with the first element. The magnitude of this initial change decreases as the number of elements is increased. This is illustrated in Figure 1 which shows this initial ΔV as a function of the number of elements in the gage. Resolution problems usually limit this type of gage to 8 or 10 elements. Even then, it is sometimes difficult to trigger an oscilloscope properly.

This problem can be somewhat alleviated by making gages in which the elements do not have uniform resistance. This can be accomplished either by varying the length of the elements, or the width. Experimentally, it is usually more convenient to change the length, therefore, wherever possible, we use a tapered gage, such as the one shown in Figure 2. This gage is used with the classical center-notched specimen. The gages are tapered so that the first elements to be broken are the shortest, and therefore lowest resistance. This increases the initial ΔV and reduces the nonlinearity in the bridge output.

The extra conductor marked "T" is used to trigger the sweep circuit on an oscilloscope. The left and right hand gages are connected as two active arms in a four-arm bridge and the output is displayed on either an oscilloscope or an oscillograph, depending on the time scale involved.

For edge notched specimens, the crack inevitably starts at one edge and travels completely across the specimen in one direction. This direction can be controlled by making one of the notches somewhat sharper than the other. The gage shown in Figure 3 is used with this type test. The trigger loop, marked "T", is used as before and the four gages are connected as a four arm bridge and readout on an oscilloscope. This set-up requires that each gage be shunted by an external resistor so that continuity is maintained after all elements of a gage are completely broken. Figure 4 is a schematic illustration of the detection circuit used with this type gage. The four normally closed switches are used to simulate the gages breaking. This facilitates calibration of the readout device. Figure 5 is a photograph of an oscilloscope screen showing a typical output for gages mounted on glass-reinforced epoxy.

The above techniques are particularly well suited for rapidly propagating cracks, but there is also a need to monitor the progress of slowly growing cracks. The gage shown in Figure 6 was designed for this purpose. Each of the four segments of this gage is connected as the input resistor on a high gain operational amplifier with resistive feedback. This circuit, shown schematically in Figure 7, is effectively a summing circuit. The output voltage of the operational amplifier is given by:

$$V_o = V_s \left[\frac{R_f}{R_g}\right] = -n\, V_s \left[\frac{R_f}{R_e}\right] \qquad (2)$$

where V_o = output voltage

V_s = excitation voltage

R_f = feedback resistance

R_g = gage resistance

R_e = the resistance of an individual gage element

n = the number of unbroken elements

Equation 2 shows that the output voltage is directly proportional to the number of unbroken elements. The change in voltage resulting from breaking one element is therefore constant, and is given by:

$$\Delta V_o = -\left[\frac{n\ R_f}{R_e}\right] V_s - \left[\frac{-R_f(1-n)}{R_e}\right] V_s = -\frac{R_f}{R_e}\ V_s \qquad (3)$$

This linearity is a consequence of putting the crack transducer in the input network of the operational amplifier. The output of this amplifier is monitored and recorded by a PDP-12 digital computer manufactured by Digital Equipment Corporation. When all the elements of one gage are broken, the computer automatically switches to the next gage. Present equipment permits up to 10 gages with as many as 30 elements each for a total of 299 monitored increments. As each element breaks, the computer calculates the crack velocity and generates an output signal which is used to control an MTS closed loop testing system. With this equipment the researcher can specify a desired crack propagation rate, or propagation rate profile, and the equipment will automatically adjust the loading conditions as necessary to produce the desired crack propagation.

The above discussion is intended to illustrate the versatility of this technique for monitoring dynamic cracks rather than to recommend a specific gage configuration. The photographic nature of the process gives the researcher the freedom to design gages which are optimized for each research problem.

Acknowledgments

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LIST OF FIGURES

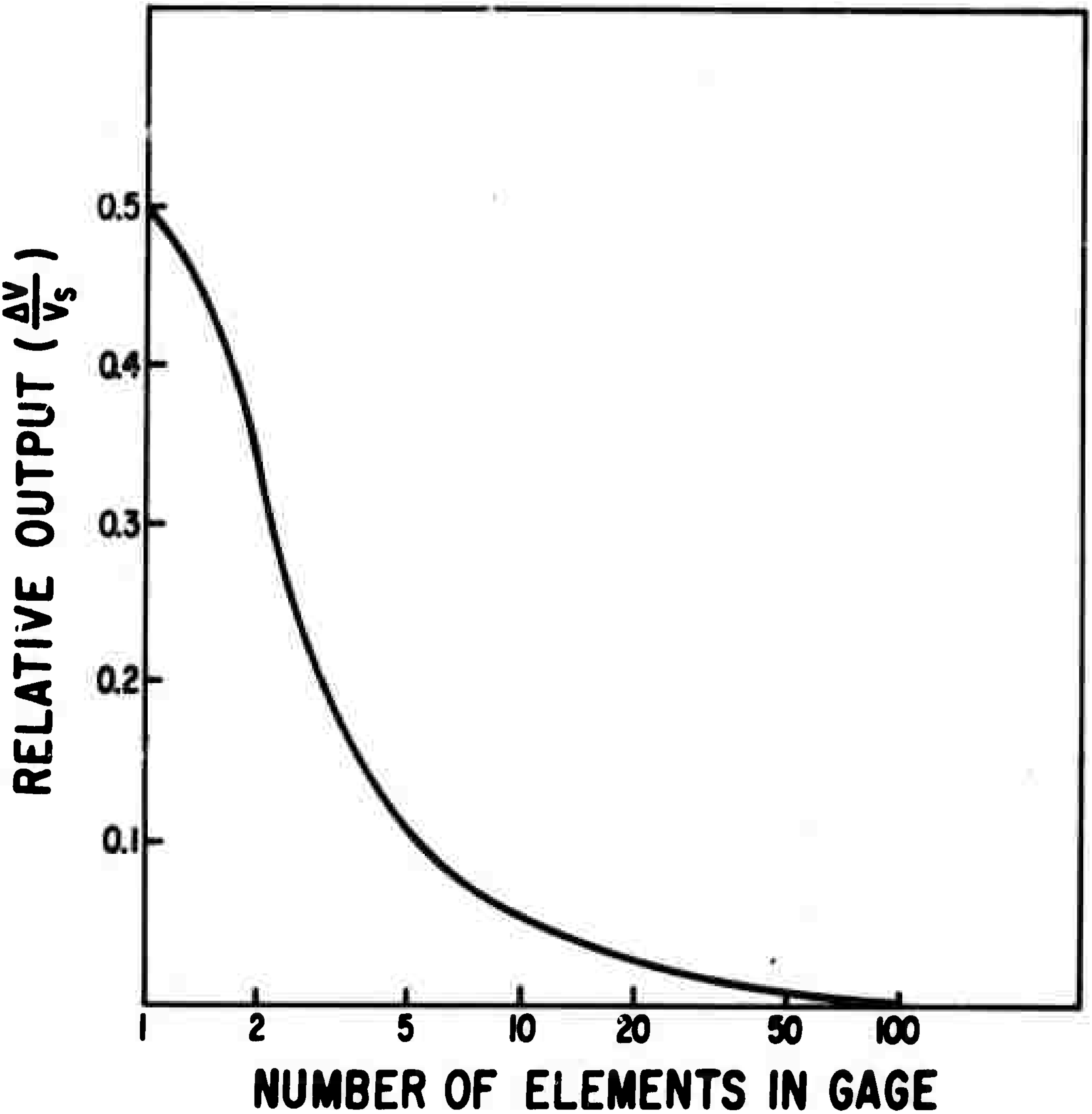

Figure 1. Change in bridge output corresponding to the breaking of the first element of the crack propagation gage.

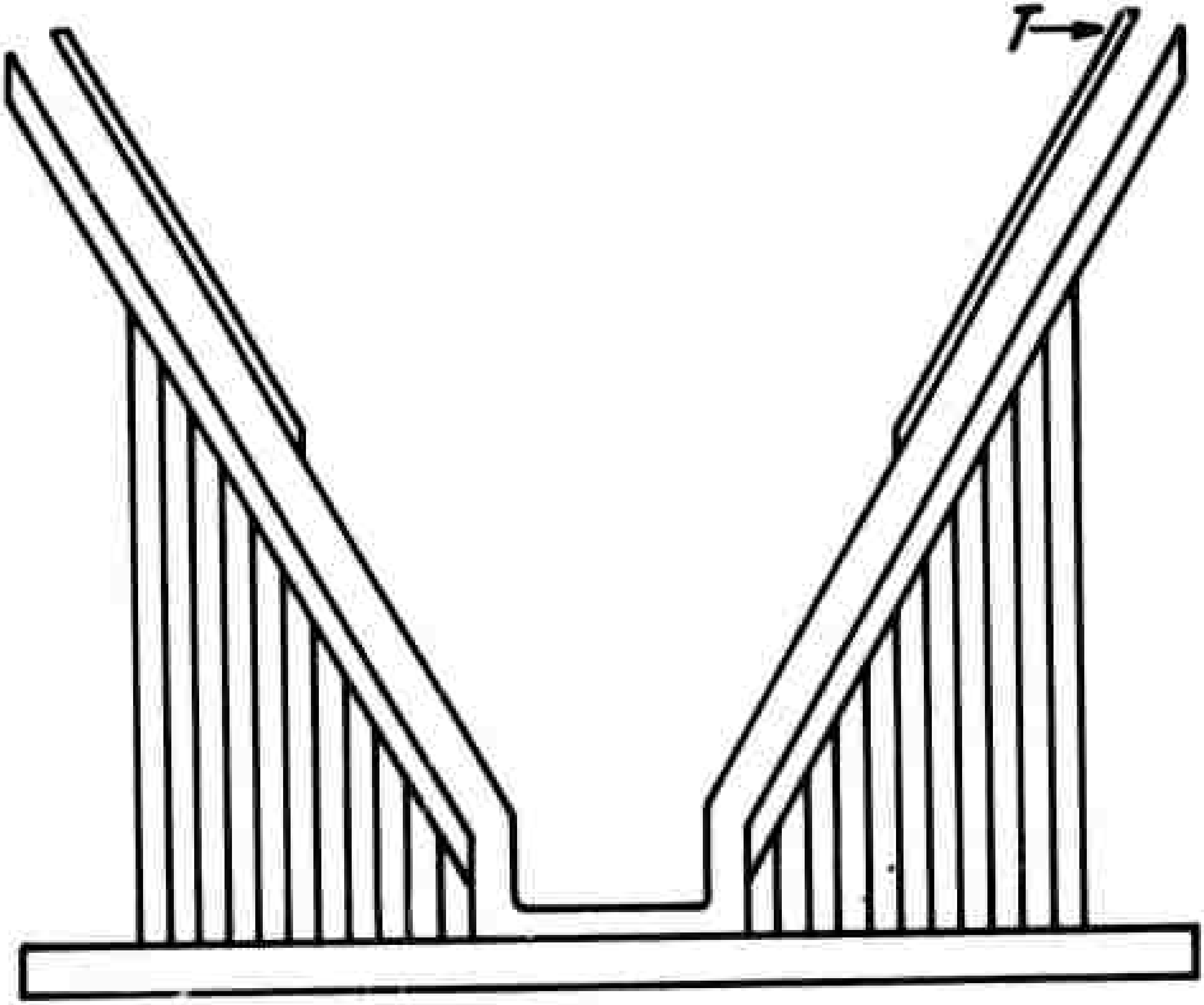

Figure 2. A tapered crack propagation gage for use with a center notched specimen.

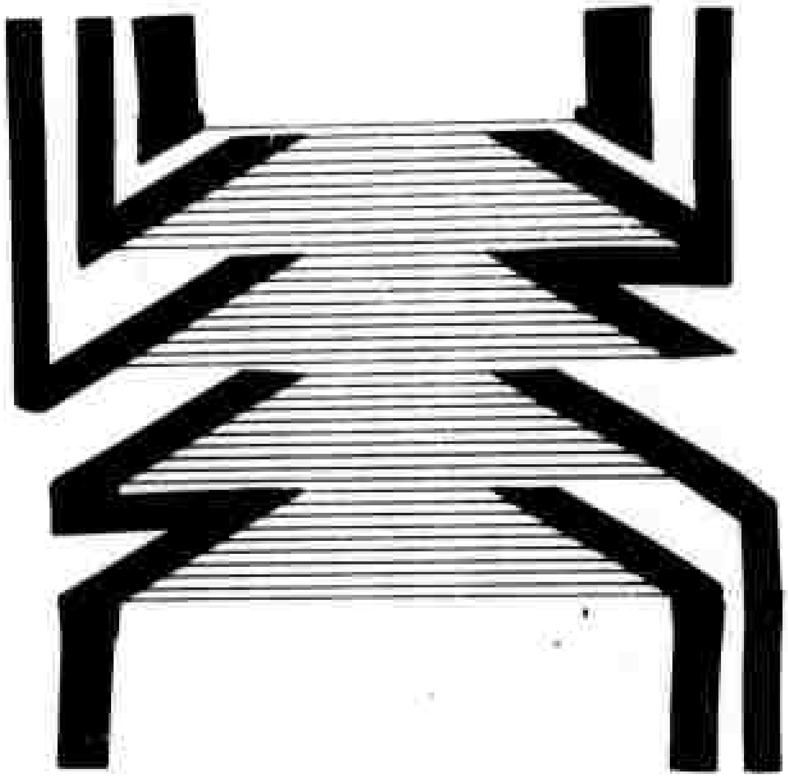

Figure 3. Typical configuration of a crack propagation a gage for edge notched specimens.

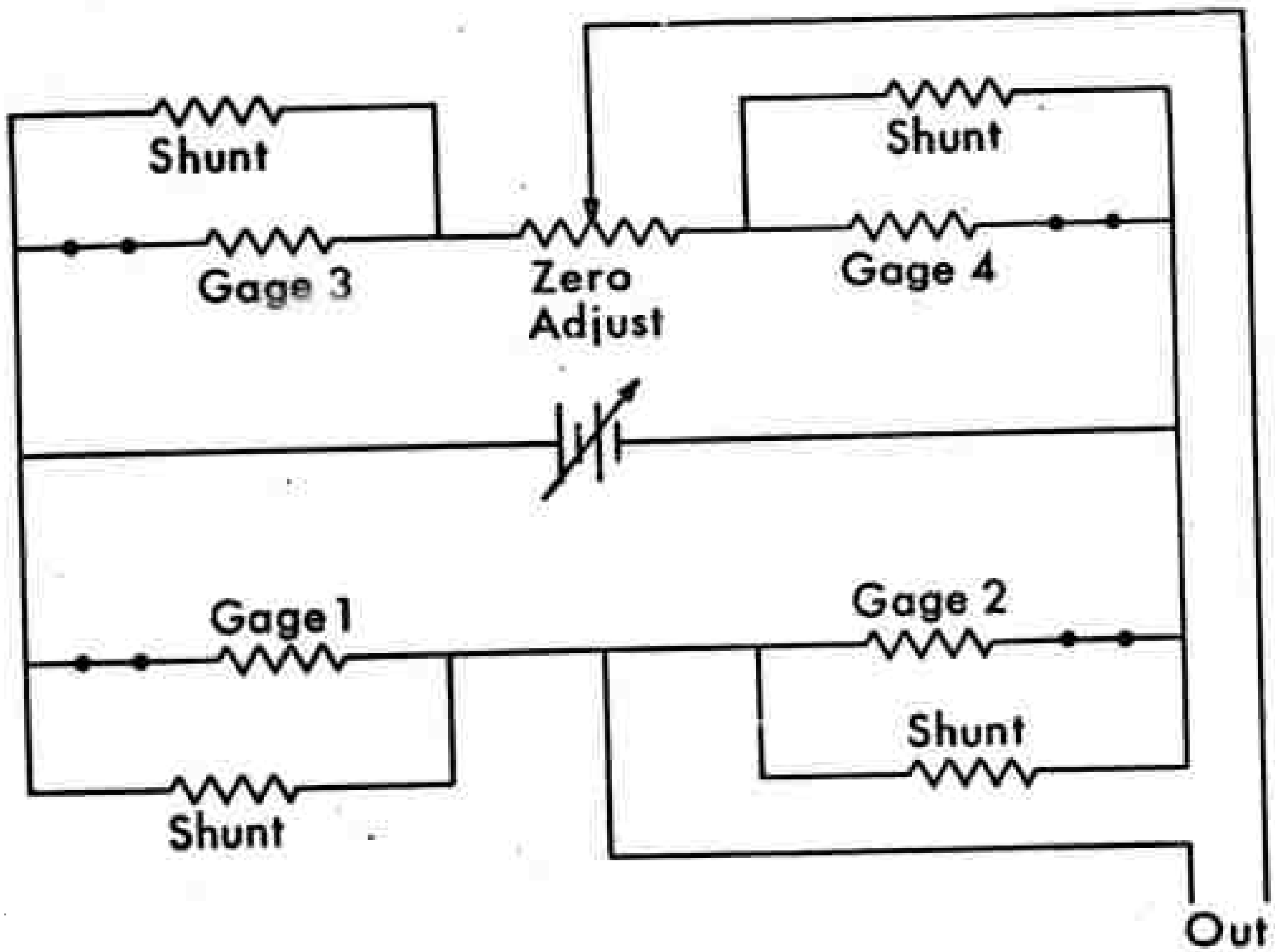

Figure 4. Schematic illustration of the detection circuit used with the gage shown in Figure 2.

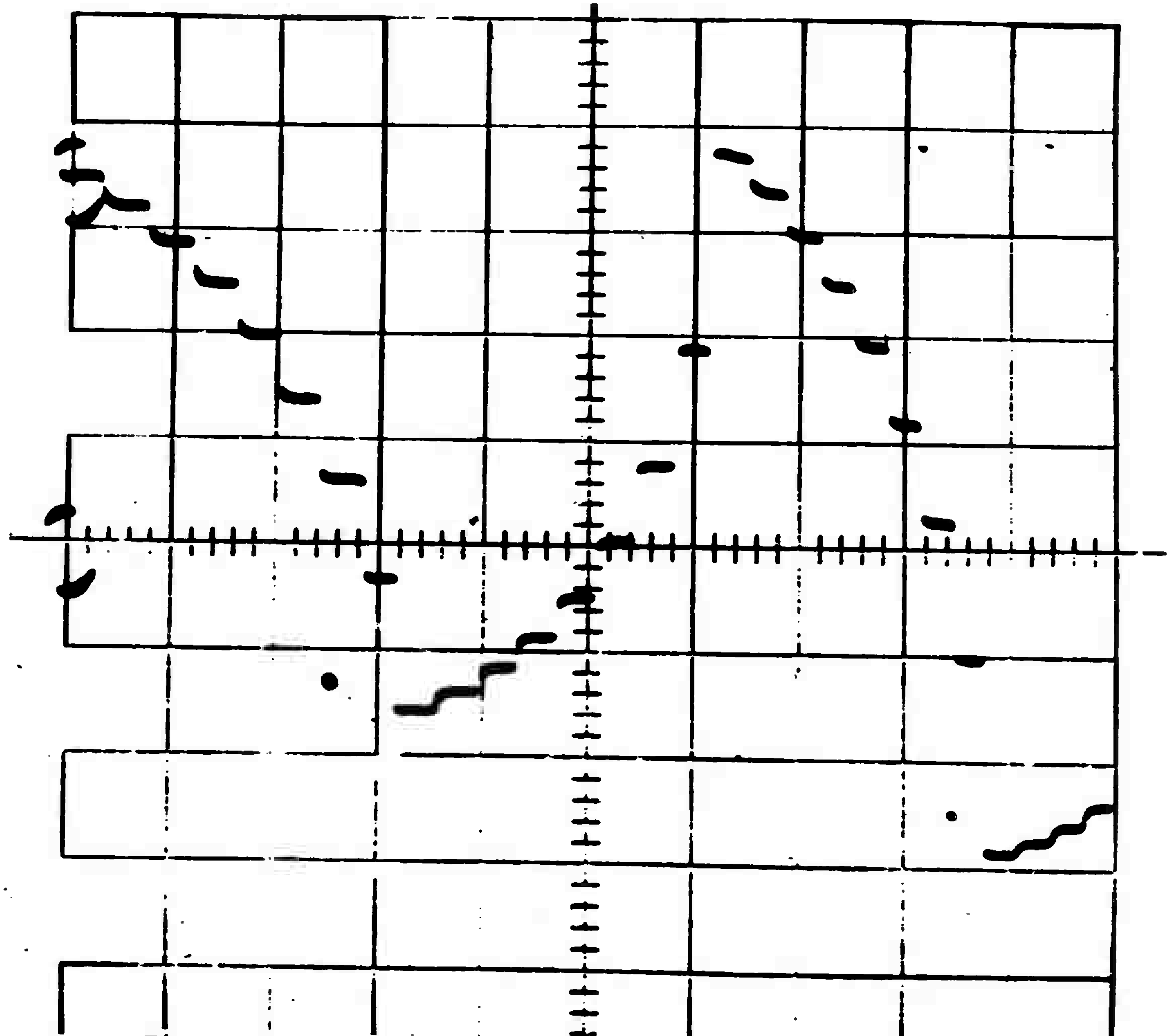

Figure 5. Typical oscilloscope display for propagating edge crack.

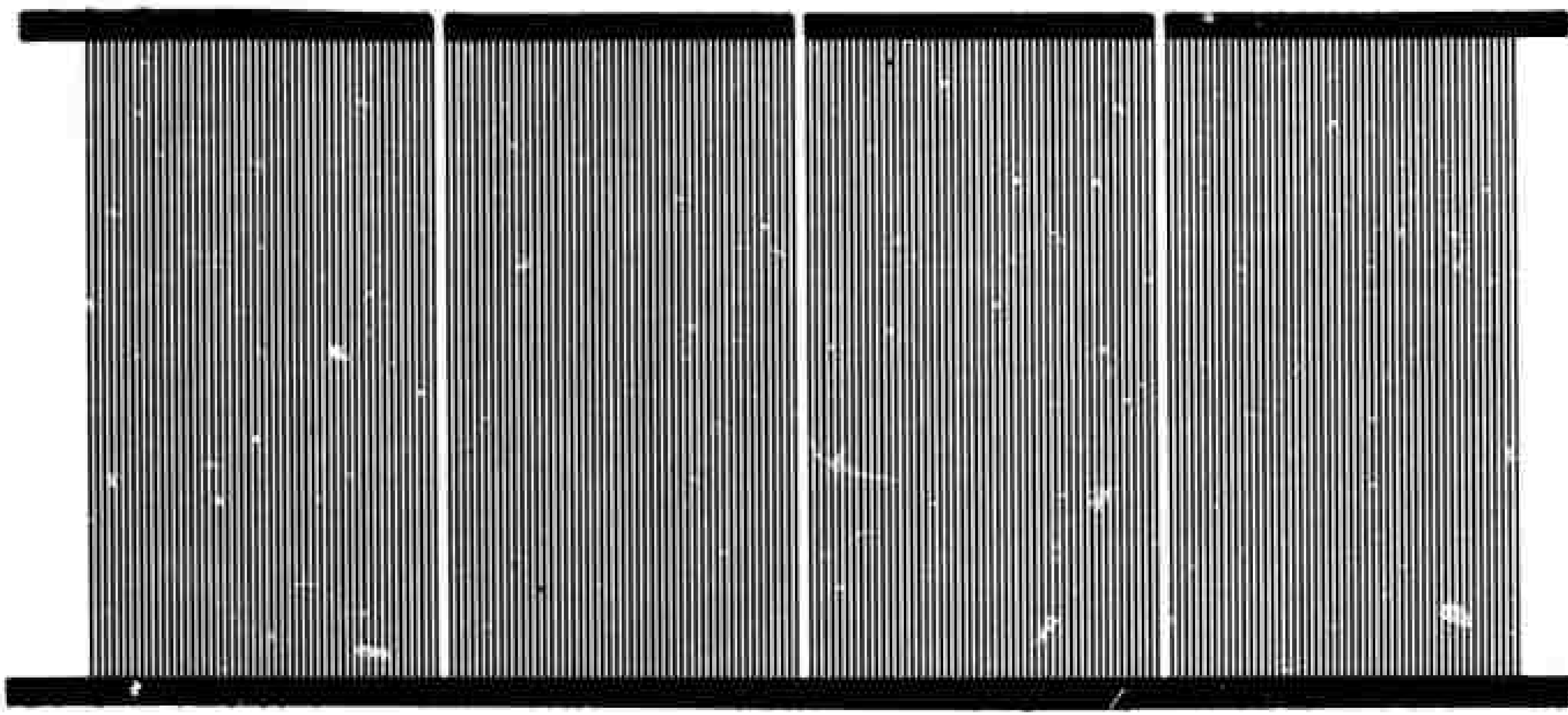

Figure 6. High resolution gage for monitoring progress of slowly moving crack.

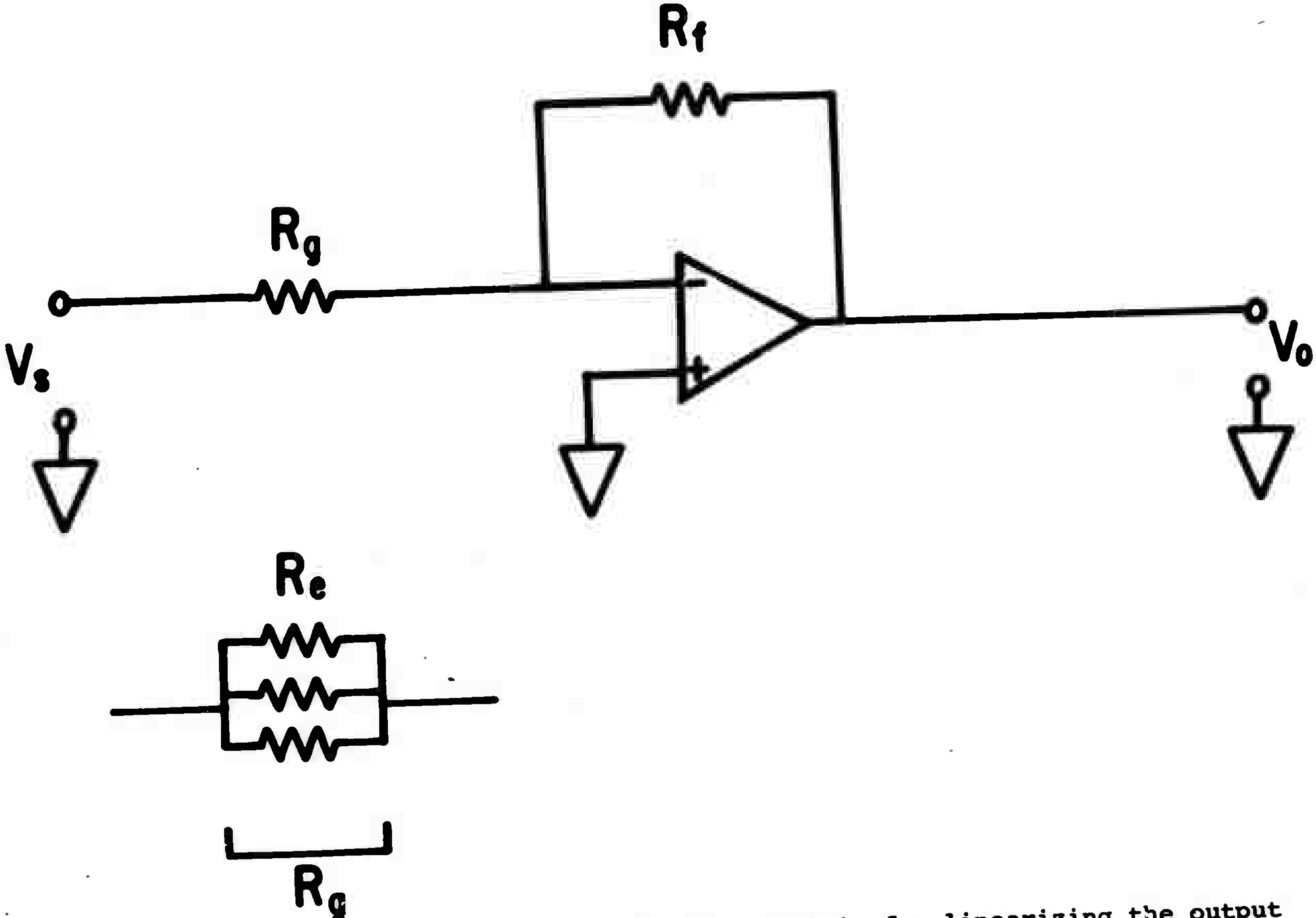

Figure 7. Amplifier circuit for linearizing the output of the slow crack gage.