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EDDY CURRENT TESTING DEVICE USING UNBALANCE BRIDGE

DISPOSITIF D'ESSAI NON DESTRUCTIF PAR LE COURANT DE FOUCAULT EN UTILISANT UN PONT INÉQUILIBRÉ

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SUMMARY: An easily readjustable unbalance bridge has been invented and in utilizing the same, an eddy current testing equipment excellent in suppression of the lift-off effect and high in the detection sensitivity has been developed.

RESUME : Un nouvel appareil d'essai non-destructif par le courant de Foucault ayant une haute sensibilite de detection de defaut et une excellente qualite de suppression du signal par la variation d'espace entre la bobine et le metal est ameliore a l'aide d'un pont inequilibre de nouveau type dont le reglage est facile.

I. INTRODUCTION

In the eddy current testing using a hand probe type test coil, an obstructive signal impedimental to the testing is generated by changes in air gap or lift-off between the test coil and the test object. Therefore, to detect a defect, etc. reliably, a signal analysis should be made to suppress such lift-off effect and take out only those signals arising from a defect, etc. to be detected. For signal analysis, there are a method of assuming an obstructive signal on a voltage plane and approximating it to a straight line and a method of approximating it to a circle. The synchronous detection method and the phase detection method are available for the former and the unbalance bridge method for the latter, as well known.

Though changes in test coil impedance due to lift-off are linear, the locus of voltage change detected approximates to a circular arc. For this reason, the signal analysis to approximate voltage locus to a circle is considered to be superior to the signal analysis to approximate it to a straight line. Though the unbalance bridge method of approximation to a circle has already been reported[1], readjustment of the bridge is extremely difficult under this method and it is impossible to deal with test coil change or difference in test piece material, etc.

The authors have invented an easily adjustable unbalance bridge. In respect of this unbalance bridge method and the synchronous detection method as a linear approximation method, theoretical studies were made on the suppression of lift-off effect and the detection sensitivity. Further, the equipment was made trially and experiments were conducted. As a result, it could be confirmed that this unbalance bridge method is excellent in suppression of the lift-off effect and higher in detection sensitivity in comparison with the synchronous detection method.

II. DETECTION VOLTAGE LOCUS AND DETECTION SENSITIVITY

According to the theorem of conformal representation, the linear transformation of a circle and a straight line results in a circle. In Fig.1, a normalized detection voltage e can be expressed as :

$$e = \dot{V}_o / \dot{V}_i = \dot{Z} / (\dot{Z}_S + \dot{Z}) \qquad (1)$$

and if $\dot{Z}_S$ is assumed to be constant and the locus of changes in $\dot{Z}$ a circle or a straight line, the locus of e will be a circle.

Fig.2 shows the detection circuits often employed for the eddy current

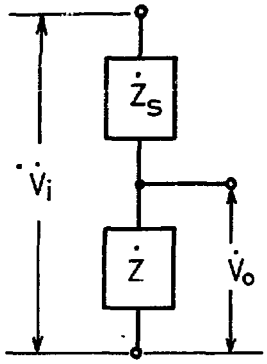

Fig.1 Detection circuit

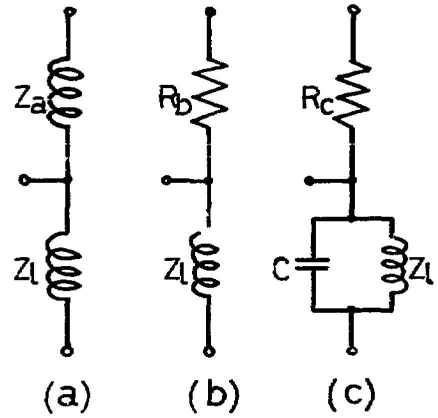

Fig.2 Practical detection circuit

testing. If it is assumed that test coil impedance $\dot{Z}_\ell$ changes linearly, in the detection circuits (a) and (b) of Fig.2, the locus of e becomes a circle because of $\dot{Z} = \dot{Z}_\ell$ in the formula (1). On the other hand, in the detection circuit shown in (c) of Fig.2:

$$\dot{Z} = \dot{Z}_\ell / (1 + j\omega C \dot{Z}_\ell) \qquad (2)$$

and the locus of changes in $\dot{Z}$ will be a circle and accordingly the locus of e, a circle. As above, the locus of output voltage e of each detection circuit shown in Fig.2 draws a circular arc.

Now, assuming that $\dot{Z}_\ell = r_0 + j\omega L_0$ applies when the test coil is brought into a close contact with a test piece and that $\dot{Z}_\ell$ changes linearly due to lift-off, it can be expressed, with x as a variable, as follows:

$$\dot{Z}_\ell = r_0 + j\omega L_0 + \Delta r + j\Delta(\omega L_0) = r_0\{(1 + jQ) + x(1 + jA)\} \qquad (3)$$

where $Q = \omega L_0\, r_0,\ x = \Delta r / r_0,\ Ax = \Delta(\omega L_0)\ r_0,\ j = \sqrt{-1}$ (4)

Here, if one puts $e = X + jY$, (5)

the equation expressing the relation between X and Y due to changes in x becomes an equation of a circle. If the values in Fig.2 are assumed to be generally selected values, that is

$$\left.\begin{array}{ll} \dot{Z}_a = r_0 + j\omega L_0, & R_b = \sqrt{r_0^2 + (\omega L_0)^2} \\ R_c = \{r_0^2 + (\omega L_0)^2\}, & \omega C = \omega L_0 / \{r_0^2 + (\omega L_0)^2\} \end{array}\right\} \qquad (6)$$

so the radius of curvature of the circular arc can be obtained as shown in Table 1.[2)]

Further, if, with variations of e due to variations of $\dot{Z}_\ell$ or $d\dot{Z}_\ell$ as de, the sensitivity of the detection circuit is defined as $|de/(d\dot{Z}_\ell/\dot{Z}_\ell)|$, the detection sensitivity of each detection circuit will be as shown in Table 1. Table 1 also shows numerical values obtained from the results of measurement of $\dot{Z}_\ell$ of the test coil $(A \simeq -7.06, Q = 5.34)$ to be described latter. It can be seen from Table 1 that in the

Tab.1 Radius of curvature and sensitivity in each practical detection circuit

Det. circuit	(a)	(b)	(c)
Radius of curvature	$\frac{\sqrt{1+1/A^2}}{4} \cdot \frac{\sqrt{1+Q^2}}{\lvert 1 - Q/A \rvert}$ 0.783	$\frac{1+1/A^2}{4} \cdot \frac{2\sqrt{1+Q^2}}{\lvert 1 + 1 + Q^2 - Q/A \rvert}$ 0.385	$\frac{\sqrt{1+1/A^2}}{4}$ 0.255
Sensitivity	$1/4$ 0.25	$1/2(1 + 1/\sqrt{1+Q^2})$ 0.42	$\sqrt{1+Q^2}$ 5.43

detection circuits shown in Fig.2 (b) and (c), the radius of curvature is small and should be approximated to a circle, whereas in the circuit shown in (a) of Fig.2, the radius of curvature is large and should be approximated to a straight line. On the other hand, in respect of sensitivity, it can be seen that sensitivity in the case (c) employing a LC parallel resonance circuit is by far excellent in comparison with others

III. PRINCIPLE OF UNBALANCE BRIDGE

III-1. Basic principle

Let it be assumed that as shown in Fig.3, the locus of obstructive signal voltage to be suppressed is a circular arc $\widehat{\dot{V}\dot{V}_l}$ and the locus of signal voltage to be detected is $\widehat{\dot{V}\dot{V}_s}$. If the reference voltage $\dot{E}_r$ is fixed at the center of the circular arc $\widehat{\dot{V}\dot{V}_l}$, the amplitude $V_l=|\dot{V}_l-\dot{E}_r|$ of voltage as a difference between obstructive signal and reference voltage does not change. On the other hand, the amplitude $V_s=|\dot{V}_s-\dot{E}_r|$ of voltage as a difference between signal voltage to be detected and reference voltage changes and becomes a value different from V_l . If these difference voltages are rectified into DC voltage, such DC voltage won't be changed by an obstructive signal and will vary only with a signal to be detected.

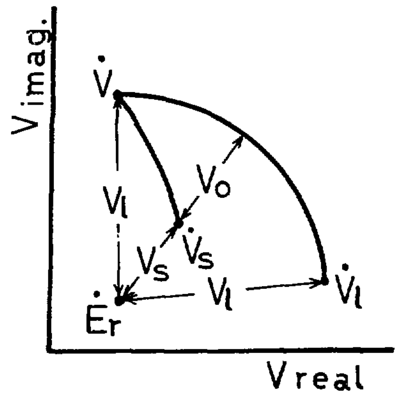

Fig.3 Principle of unbalance bridge method

III-2. CONSTRUCTION OF BRIDGE CIRCUIT

Though a balance adjustment of the normal bridge circuit may be made in such manner as to minimize output voltage, the unbalance bridge should be so provided that the amplitude of output voltage is not reduced to zero nor changed by an obstructive signal, and therefore, unless the method of bridge adjustment is defined clearly, there is an infinite possibility and bridge adjustment becomes impossible.

For that reason, the authors invented the following adjusting method. In Fig.4, the center of the arc $\widehat{\dot{V}\dot{V}_l}$ is on a perpendicular bisector of the segment connecting the points $\dot{V}$ and $\dot{V}_l$. Accordingly, if two points $\dot{E}_{r1}$ and $\dot{E}_{r2}$ at an equal distance from $\dot{V}$ and $\dot{V}_l$ are fixed, the straight line connecting $\dot{E}_{r1}$ and $\dot{E}_{r2}$ is perpendicular bisector of the segment $\overline{\dot{V}\dot{V}_l}$ and therefore, if reference voltage $\dot{E}_r$ to change along $\dot{E}_{r1}\dot{E}_{r2}$ is fixed in such manner that there is no change in output voltage amplitude with respect to changes on the arc $\widehat{\dot{V}\dot{V}_l}$, $\dot{E}_r$ will be at the center of $\widehat{\dot{V}\dot{V}_l}$.

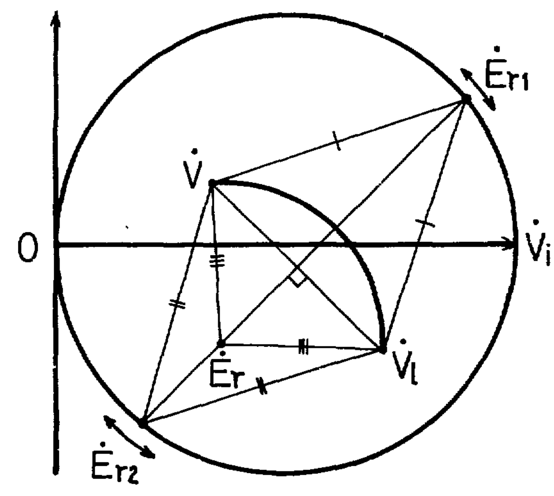

Fig.4 Adjusting method of unbalance bridge

Fig. 5(a) shows a bridge circuit in which such adjustment is possible. In this figure, if the capacitance C connected in parallel with the test coil $\dot{Z}_x$ is changed, detection voltage $\dot{V}$ changes. If C is selected properly, it is possible, as shown in Fig.5 (b), to cause the perpendicular bisector of the segment $\overline{\dot{V}\dot{V}_l}$ to pass the origin O . On the other hand, voltage $\dot{E}_{r1}$ at the middle

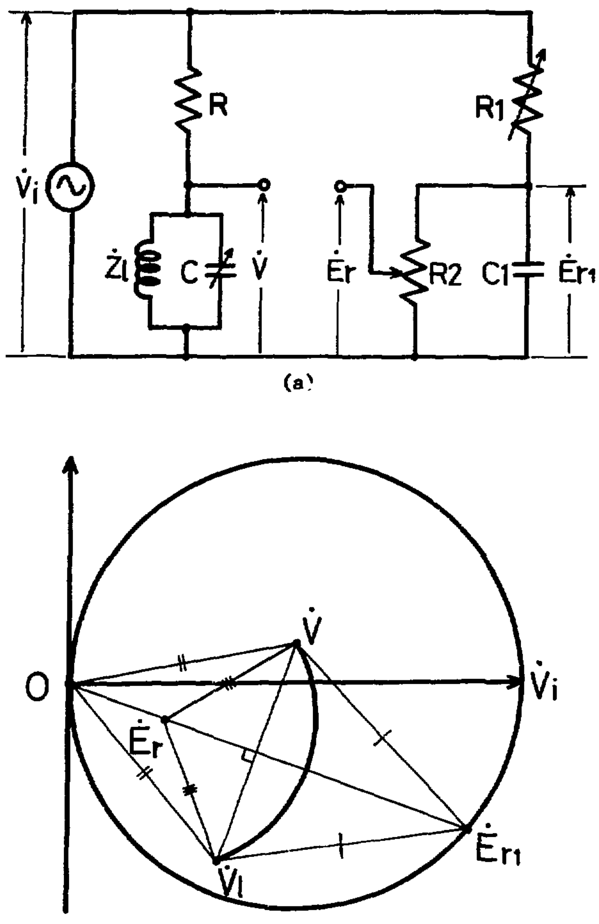

Fig.5 (a) Unbalance bridge circuit and (b) its adjusting method

point between variable resistance R_1 and capacitance C_1 shown in Fig.5 (a) changes, if R_1 is changed, along the semicircle with input voltage $\dot{V}_i$ as the diameter as shown in Fig.5 (b) and therefore, if R_1 is fixed properly, $\dot{E}_{r1}$ can be made the other end point of the perpendicular bisector. Since middle point voltage $\dot{E}_r$ of variable resistance R_2 is a voltage divided from voltage $\dot{E}_{r1}$, $\dot{E}_r$ is at the center of the arc $\widehat{\dot{V}\dot{V}_l}$ if $\dot{E}_r$ is determined in such manner that the amplitude $|\dot{V}_l - \dot{E}_r|$ won't change with respect to the arc $\widehat{\dot{V}\dot{V}_l}$.

The adjustment of the bridge shown in Fig.5 (a) is made as follows. C is determined such that $\dot{V}$ and $\dot{V}_l$ become equal in amplitude. Next, R_1 is so adjusted as to attain $|\dot{V} - \dot{E}_{r1}| = |\dot{V}_l - \dot{E}_{r1}|$. Lastly, R_2 is so adjusted that $|\dot{V} - \dot{E}_r|$ won't change with respect to changes in $\widehat{\dot{V}\dot{V}_l}$. If such adjusting procedures performed, testing can be conducted corresponding to test pieces.

IV. BASIC STUDY

In respect of suppression of the obstructive signal, the linear and circle approximations were examined comparatively by calculation in applying the results of measurement of test coil impedance. The approximation to a circle was analyzed as the unbalance bridge method described in the section III "Principle" and the approximation to a straight line as the synchronous detection method generally employed for signal analysis.

A hand probe type test coil was made, comprising a ferrite core, 10 mm in length and 3 mm in diameter, wound round with enamel wire. Further, as test pieces, 200×50×5 mm^3 copper and alminum plates provided in the middle part with artificial slitlike defects different in depth. As to the copper test pieces, the test coil impedance was measured with the Maxwell bridge at the frequency of 50 kHz in changing lift-off from 0 to 2.0 mm at intervals of 0.1 mm and on changes in the depth of artificial defects, and the results as normalized are shown in Fig.6. From this figure, it can be seen that the locus of impedance changes due to changes in lift-off are linear.

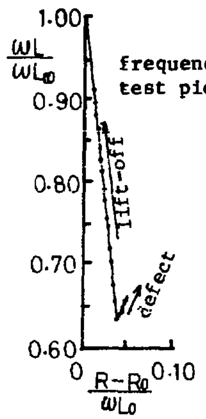

Fig.6 Normalized impedance of test coil

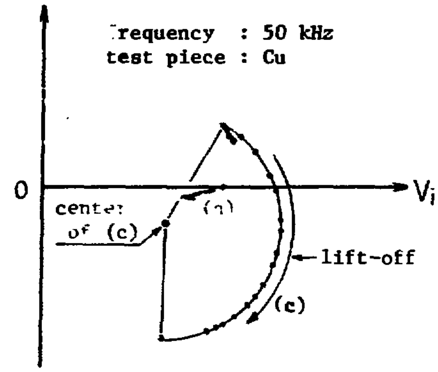

Fig.7 Difference of detected voltage in detecting circuit (a) and (c) in Fig.2

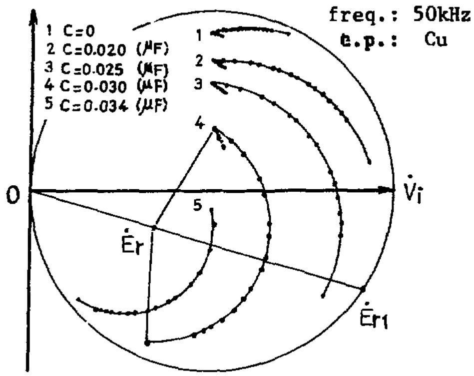

Fig.8 Detected voltage changes due to variation of capacitance C

Based on the results of measurement of test coil impedance and as to the detection circuits shown in Fig.2 (a) and (c), detection voltage V_0 was obtained by calculation and the result is shown in Fig.7. It can be seen from this figure that in the circuit shown in Fig. 2 (c), voltage change is quite great and accordingly, sensitivity is high. Further, it can be understood that since the locus due to lift-off forms a circular arc and its radius of curvature is small, the detection circuit is suitable for the unbalance bridge method for approximation to a circular arc. On the other hand, in the circuit shown in Fig.2 (a), the radius of curvature of the locus is large and a method of approximation to a straight line seems to be preferrable. Fig.8 shows the locus with capacitance C shown in Fig.2 (c) as the parameter, from which it can be seen that if the value C is determined properly, it is possible to cause the perpendicular bisector to pass through the origin O .

Here, changes in test coil impedance due to lift-off are linear, but not a straight line.[3] Therefore the locus of voltage detected does not form a true circle. Accordingly, when suppressing the lift-off effect, signal analysis is made in approximating voltage locus to a straight line or a circle. Since the test coil is used for the eddy current testing in close contact with a test piece or in condition similar thereto, the analysis was made in assuming that the condition is so set up as to limit the range of suppression of lift-off effect and minimize the approximation error within the range.

Under the unbalance bridge method of approximating voltage locus to a circle, the analysis was made in assuming that as described in the section III (Principle), center of the lift-off arc is on a perpendicular bisector of the segment connecting zero point and infinity point and the center is so set as to move along the perpendicular bisector and minimize the maximun value of error in the lift-off suppression range.

Under the synchronous detection method to approximate voltage locus to a straight line, the analysis was made in assuming that based on its principle, the lift-off changes the gradient of a straight line passing through the zero point and the

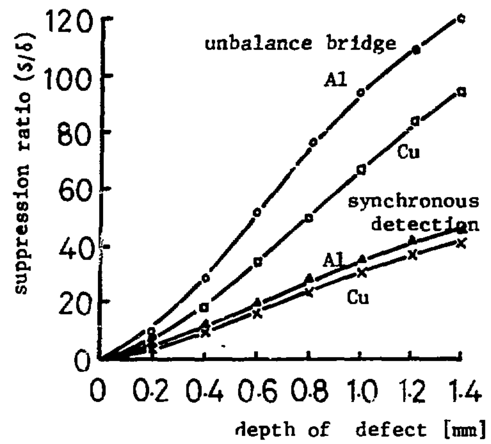

Fig.9 Calculated value of suppression ratio

condition is so set as to minimize the maximum value of error in the lift-off suppression range.

When comparing the performance in suppression of obstructive signal due to the lift-off effect, it is meaningless to compare the magnitude of errors. It is because equipment output voltage varies with the signal analysis process of the testing equipment and amplifier gain, etc. Therefore, in defining the ratio S/δ or the ratio of the magnitude of signal with respect to a defect (S) to the maximum value error (δ) as the suppression ratio, the signal analysis methods were examined comparatively in terms of the suppression ratio. It can be said that the greater the suppression ratio , the better the obstructive signal suppression characteristics.

Based on the results of measurement of test coil impedance, the synchronous detection method was applied to the detection circuit in Fig.2 (a) and the unbalance bridge to the detection circuit in Fig.2 (c) and the results of calculation of suppression ratio are shown in Fig.9. In this figure, the maximum value of lift-off error was determined in the range of 0~0.4 mm as a practical range. It can be seen from the figure that the unbalance bridge method of approximation to a circle is more than twice better in suppression ratio than the synchronous detection method of approximation to a straight line.

As above, it can be seen that the unbalance bridge method is higher in sensitivity than the synchronous detection method and yet superior in performance of lift-off effect suppression.

V. TRIALLY-MADE EQUIPMENT AND EXPERIMENTAL RESULTS

The block diagram of the trially-made eddy current testing equipment using the unbalance bridge is shown in Fig.10. Output voltage of the oscillator is applied to the unbalance bridge. Its output is passed through a differential amplifier and a zero-adjusting device and then converted through a rectifier into positive DC voltage and serves as input to a adder.

Further, output of the oscillator is passed through the amplifier, after which it is converted through the rectifier into negative DC voltage and serves as another input to the adder. Output of the adder is indicated on the meter. The zero-

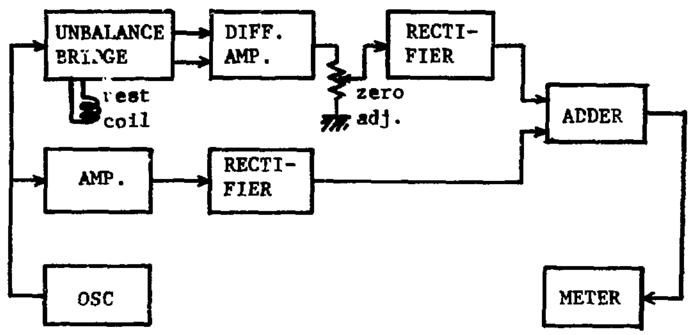

Fig.10 Block diagram of unbalance bridge method

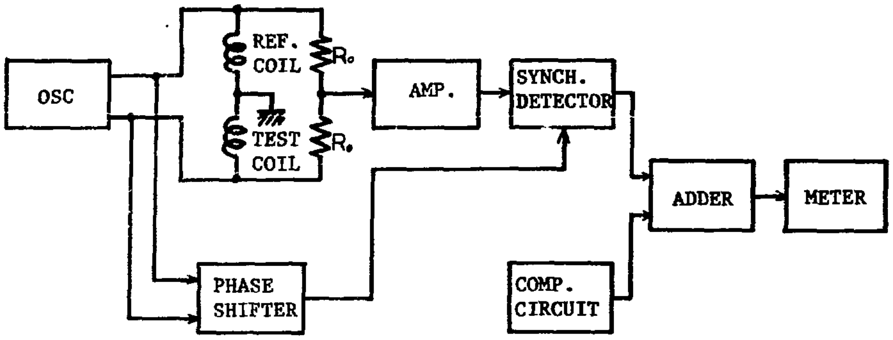

Fig.11 Block diagram of synchronous detection method

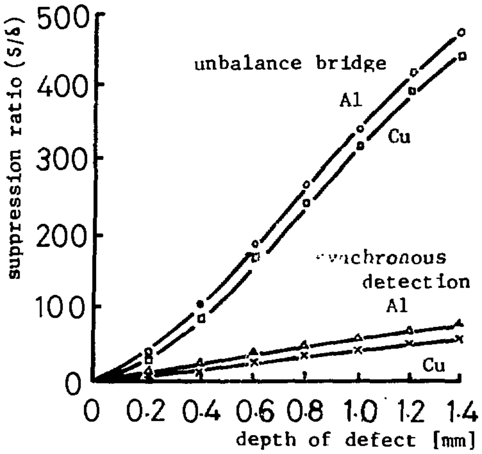

Fig.12 Experimental results

adjusting device is provided for zero-adjustment of the meter. If the bridge of this equipment is adjusted as described before and zero-adjustment of the meter is made with the zero-adjusting device, the lift-off effect is suppressed and the indication from a defect only is given on the meter.

The traílly-made equipment under the synchronous detection method was set up on the basis of its principle as in Fig.11. Since this set-up is employed generally, it is considered unnecessary to explain about it. The compensation circuit is provided for zero-adjustment of the meter. In this equipment, if the phase of reference signal is so set through the phase shifter that meter indication won't be changed by lift-off, defects only are indicated on the meter.

Fig.12 shows the suppression ratios obtained from the results of experiments with the trial equipments applying the unbalance bridge and the synchronous detection. The test conditions were entirely same as the conditions given in the section IV. As shown in the figure, the result that the suppression ratio under the unbalance bridge method is about 6∿9 times greater in comparison with the synchronous detection method. Though the suppression ratio in Fig.12 is greater than in Fig.9, it is considered to be attributable to the effect of error in the measurement of test coil impedance.

VI. CONCLUSION

It has been shown that since impedance of the hand probe type test coil used for the eddy current testing changes linearly due to lift-off, voltage locus of the detection circuit forms a circular arc.

Accordingly, the unbalance bridge method to approximate voltage locus to a circular arc was confirmed to be superior in suppression of the lift-off effect to the synchronous detection method to approximate it to a straight line. Under the unbalance bridge method, the sensitivity is high because the test coil can be provided in a resonance circuit, and accordingly the gain of the amplifying circuit may be small, thus making it possible to realize a testing equipment stable with respect to noise and drift, etc.

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