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A RESONANCE-TYPE ULTRASONIC THICKNESS GAGE FOR MEASURING THE WALL THICKNESS AND CORROSION OF CHEMICAL PLANT EQUIPMENT

by

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ABSTRACT: The author discusses the principles of thickness measurement by the ultrasonic resonance method and ~~describes~~ equipment designed for applying this technique to the measurement of the depth of corrosion in chemical equipment is described. Emphasis is placed on the proper use of transducers and coupling media for optimum results. In actual practice, certain key points should be selected for testing signal identification is best achieved with an oscilloscope, and if the resonant signal appears very often during measurements of thickness, the accuracy can be improved by taking the mean of several measurements. Some of the parameters of the Chinese model HS-1 meter, which has a maximum error of 4-4%, and an average error of 1-3% when measuring steel having a thickness of 3-30 mm, are given. At the present time, this technique cannot be used for measuring the wall thickness of small-diameter pipes. ( ) "Comrades Ku Wang (7357/2598) and Engineer Tso Ching-i (1563/2529/0122) also took part in the work." Orig. art. has: 1 table, 2 figures and 4 formulas. English Translation: 12 pages.

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M. C. Tang

1. Introduction

Due to the fact that chemical plant equipment is often subject to chemical corrosion, regular inspections and maintenance are necessary. In the past, the testing of the wall thickness of equipment such as high-pressure containers, pipelines, reservoirs, etc., employed the hole-drilling method to make mechanical measurements. This method of testing is not only uneconomical with respect to time and cost, but also has the disadvantage of not being applicable to the equipment in operation. If an ultrasonic resonant thickness gage is employed, it does not interfere with the plant operation; it is easy to use and makes it possible to perform measurements on operating equipment. Furthermore, it is also possible to detect internal cracks, pits, and unevenness in thickness of equipment such as pipes. Corrosion as well as weak spots between pipes and furnace walls can also be detected. Therefore, this type of gage has not become a very important instrument for corrosion tests [1-8].

II. Principle of Measuring Thickness by Resonance

An ultrasonic wave is produced by the stimulation of a piezoelectric crystal plate by means of high frequencies. The vibration caused by a crystal plate is similar to the vibration of a piston, and the vibrational frequency is the same as a high-frequency electrical oscillation. This kind of vibration produces ultrasonic waves. When the crystal plate is placed against the equipment to be measured with the aid of a coupling device, ultrasonic waves may be transmitted to the material.

The principle of the resonance-type ultrasonic thickness measurement technique is based on two fundamental characteristics of ultrasonic waves. First, ultrasonic waves produce reflections at the boundary of two materials with two different sound resistances. For example, at an air/steel or chemical medium/steel boundary, most of the ultrasonic waves reflect back to steel. Second, the velocity of propagation of an ultrasonic wave in a material depends on the density of the material and the elastic constant. For each material, the ultrasonic wave has a certain value of propagation velocity. For example, its velocity in steel is 5,600 meters/second. In the process of propagation, the wavelength is inversely proportional to frequency and directly proportional to velocity. Frequency does not affect velocity. Therefore, if the wavelength of the ultrasonic wave propagated between the correct and incorrect sides of the material is ascertained, the thickness reading of the material can be obtained. In actual practice, the frequency of the ultrasonic waves produced by the crystal plate usually undergoes a conversion through a variable capacitor of the regulating instrument, and the value may be directly indicated by the regulator in terms of megacycles (Mc). Therefore, the wavelength of the ultrasonic wave in the material can be controlled by adjusting the frequency. As soon as the wavelength of the ultrasonic wave is adjusted to a value at which the half-wavelength or the multiple of the half-wavelength is equal to the thickness of the material to be measured, a standing wave is established, thus producing resonance. This principle is similar to the resonance phenomenon which occurs in organ pipes. The equation is:

$$\lambda = 2t \qquad f_1 = V/2t \tag{1}$$

where λ = the wavelength of the ultrasonic wave

t = the thickness of the material to be measured

f_1 = the fundamental resonance frequency

V = the velocity of propagation of the ultrasonic wave in the workpiece.

The phenomenon of resonance can appear not only at the fundamental resonance frequency, but also at the multiples of the fundamental resonance frequency; namely, $2f_1$, $3f_1$, $4f_1$ ..... $2f_1$ is called the second harmonic frequency, $3f_1$, the third harmonic frequency, etc. If only the fundamental frequency is used to measure the thickness, it needs a very wide frequency range in order to be able to measure a certain thickness range. For steel with a thickness range of 0.025-0.5 inches, the frequency range should be 0.23 - 4.6 Mc. It is very difficult to arrange such a wide frequency range into one wave section. Therefore, in actual practice, harmonic frequencies are employed. In the process of measurement, one must know two adjacent resonance frequencies. Their difference is the fundamental resonance frequency. Now equation (1) can be written as

$$t = \frac{V}{2(f_n - f_{n-1})} \tag{2}$$

where f_n = the n-th harmonic frequency

f_{n-1} = the (n-1)-th harmonic frequency

$(f_n - f_{n-1}) = f_1$ = the fundamental resonance frequency

The frequency should be adjusted so that the material to be measured produces resonance. During resonance, the plate current in the oscillating tube is increased; after amplification, the resonance signal can be detected by means of earphones or by an electric meter. The signal can also be carried to the Y-axis of the oscillograph, and the height of the wave pip may be seen from the fluorescent screen as shown in Figure 1. Find any two adjacent harmonic frequency values and

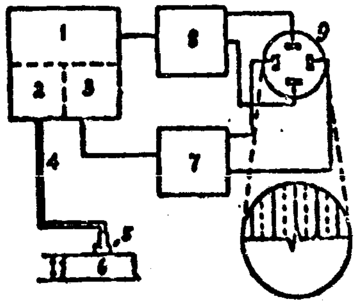

Figure 1. Schematic diagram of resonance thickness gage. 1. variable-frequency oscillator; 2. range-selector switch; 3 motor-driven capacitor; 4. cable; 5. energy converter; 6. workpiece; 7. sweep amplifier; 8. signal amplifier; 9. oscillograph.

substitute them into equation (2), and the thickness of the material to be measured can be calculated. In this equation, C/2 is a constant for a certain material. For steel, if t is given in mm, and frequency in Mc, C/2 equals 2.95. It is very convenient to calculate the thickness by constructing a frequency-thickness conversion table or by using a sliderule as calculating tools.

III. Crystal Energy Converter and Coupling Agents

There are many kinds of piezoelectric materials, such as lithium sulfate, quartz, barium titanate, etc. Quartz and barium titanate, however, are used the most for inspection purposes. Barium titanate piezoelectric crystals are made by heating titanium dioxide with barium carbonate at a high temperature, followed by polarizing treatment. It can produce comparatively strong ultrasonic waves. In the meantime, it is highly moisture resistant and can be easily made into crystal plates of a variety of shapes. Therefore, it has a more extensive application.

A crystal plate has its own natural frequency. The natural frequency is inversely proportional to thickness. Quartz has a frequency constant (the product of natural frequency and thickness) of 2.87 Mc·mm, while the frequency constant of a barium tatanate crystal is 2.5 Mc·mm. Hence, a crystal with a fixed thickness also has a fixed natural frequency. In measuring thickness, it is possible to detect the resonant signal of the crystal's natural frequency. Its appearance can be detected by looking for the existence of a resonant signal without contacting the material to be measured. Thus, we can distinguish a false signal from a real one. It is best to select the crystal plate used for the resonance-type thickness gage with such a thickness that the natural frequency of the crystal plate is higher than the highest operating frequency of the instrument. However, they should not be too far apart; otherwise, the sensitivity of the measurement will be greatly reduced. It has been proved in practice that it would be satisfactory if the frequency ratio does not exceed 2:1.

The size of the crystal pla[illegible]termined by the lowest operating frequency. Its diameter must correspond to several wavelengths of the ultrasonic wave in the material to be measured in order to assure the directive properties of the ultrasonic wave, which are necessary in thickness measurement. For quartz crystal plates, when the diameter is 5 or 6 times the value of the wavelengths, a resonance indication with better sensitivity and sharp pips may be obtained.

How to transmit ultrasonic waves to the workpiece is also an important problem in inspection. First of all, the surface of the equipment must be smooth. If the surface is rough, a large amount of ultrasonic waves will be weakened and lost; consequently, they are unable to be transmitted to the workpiece. In order to improve the sound coupling between the energy converter and the material, a layer of liquid (coupling agent) with comparatively high sound resistance such as transformer oil, glycerine, etc., may be applied to the surface of the material or some soft substances may be placed on the same. If ultrasonic waves are transmitted to the workpiece without the addition of coupling agent, the equipment should have a degree of glossiness of $\nabla\nabla\nabla\nabla_{12}$. If the latter is lower than $\nabla\nabla\nabla\nabla_{12}$, the coupling agent should be added during measurement. If it is lower than $\nabla\nabla_4$, the effect of the coupling agent is gradually decreased. If the surface is not smooth enough, an increase of the consistency of the coupling agent may improve coupling, but the sound transmissibility of ultrasonic waves is decreased. The use of a mantle made of a material such as polystyrene film may lower the degree of glossiness to below ∇_2. Sometimes rubber films are used to improve coupling. A liquid spray type energy converter cannot only improve sound contact, but also can be used in the inspection of high-temperature equipment [17 and 19]. This type of energy converter is shown in Figure 2. In order to prevent the silver-plated layer of the crystal plate from peeling, an anti-friction board may be employed for protection without causing much loss of the sensitivity o[f th]e crystal plate.

IV. Thickness-Measuring Operation

1. Determination of location for examination. The selection of the location for examination is best accomplished by the combined judgement of the examiner and

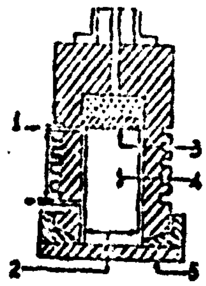

Figure 2. Construction of a liquid spray type energy converter. 1. circulating cooling water; 2. internal diameter of ultrasonic wave absorbing compartment; 3. piezoelectric crystal; 4. water chamber; 5. thermal-insulated sound-transmission housing.

the person who is familiar with the corrosion condition of the equipment in the plant. A selected location should be representative and significant. It should not be arbitrarily determined. For instance, the rate of corrosion at different depths of a reservoir is possibly not the same: e.g., the corrosion is different at the top from that at the bottom and is especially bad at the water level. Therefore, it is more important to examine the top and the water-level parts of a reservoir. The examining location must be accessible and easy to work with. In order to examine a high washing tower and the top of a reservoir, the examiner must use a suspension basket or similar means to elevate himself to that height to treat the surface and make the measurements.

2. Treatment of the examining locations. Insulating materials, thick layers of paint, and decayed products must be removed. Polishing equipment, such as hand sandwheels, files, sand paper, etc. may be employed in order to assure a good sound-coupling plane. The plane should be a little larger than the energy converter in order to allow enough space for the latter to move around. Because sometimes the internal surface of the equipment is too rough or pitted, it will lower the strength of the signal, or even no signals can be received. When the depth of a certain pit reaches 20% of the total thickness, it is impossible to make thickness measurements. If the energy converter can be moved a little freely, the thickness reading may be obtained.

In order to determine the corrosion rate of a certain location in a piece of equipment, such as a container or a reservoir, the polished parts must be well protected after the thickness measurement, otherwise the loss of equipment will be the result in both cases. The dirt and sediment on the internal surface and the materials inside the equipment do not affect the measurement, but the inclination at the back, corrosion marks, uneven areas and spots can affect signals, thus causing difficulty in measurement.

3. Interpretation of signal. It is more accurate to use an oscillograph to detect the appearance of the resonance point than to use an electric meter or earphones. Sharp wave pips will appear on the screen of the oscillograph as soon as the resonance point is reached, and they will disappear immediately if the resonance point is slightly off. During resonance, the amplitude is especially high. From the shape of the wave, the condition of corrosion on the inner surface of the equipment can be distinguished. If the inner surface is smooth, the shape of the resonance wave is high and regular. In actual practice, there must be some corrosion on the inner surface of the equipment, so the wave is usually not regular in shape. To perform a more detailed analysis of these conditions, it is necessary to make judgements based on a variety of wave shapes. It is difficult to take average thickness measurements of equipment with large inclinations. When the inner surface has spots and zigzag areas, the energy converter may take measurements by going around the spots or zigzag areas once. The wave shape is regular. The energy converter should be moved to the center of the spots or zigzag areas. The wave shape then becomes very irregular. Thus, the location and size of the spots and zigzag areas can be determined.

In general, the more uneven the inner surface is, the lower is the height of the wave and the more irregular is the wave shape; consequently, the more difficult is the measurement.

4. Measurement of wall thickness. In measuring the thickness of thick-walled equipment, the resonance signals are quite close together. To increase accuracy,

average values are adopted. It is best to make several measurements so that the resonance point will not be overlooked. In the same frequency range, fewer resonance points will appear in thin-walled equipment, because it is not possible to take a sufficiently large number of readings to get an average; therefore, it should be accurately measured each time. We used an HS-1 resonance-type thickness gage manufactured in this country to make experimental thickness measurements of chemical plant equipment in laboratories and factories. The result was satisfactory. The error was less than 3% of the measured thickness (measuring range: 3-30 mm). For high-pressure tubing with a diameter of several centimeters, however, since it is impossible to work out a more smooth surface on the tubing to assure a good sound coupling, measurements cannot be made. This is due to the fact that working on such a surface for inspection will affect the mechanical properties of the high-pressure tubing. However, the thickness measurement can be made for equipment with large diameters, such as reservoirs, towers, etc. On such large equipment, it is very easy to work on a surface with a diameter of about 25 mm without much effect on the mechanical properties of the equipment. We are now in the process of improving the circuits of the instruments and the shape of the energy converters, to broaden the field of application.

Two examples of the measurements are shown below:

EXAMPLE 1

Earphone indication	harmonic frequency (Mc)	2.390		2.960		3.535
	frequency (Mc)		0.570		0.575	
	average frequency (Mc)	0.5725				
	measured thickness (mm)	5.155				
	relative error (%)	3.1				

EXAMPLE 1 (continued)

Electric meter indication	harmonic frequency (Mc)	2.390 2.960 3.535
	frequency (Mc)	0.570 0.575
	average frequency (Mc)	0.5725
	measured thickness (mm)	5.155
	relative error (%)	3.1
Oscillograph indication	harmonic frequency (Mc)	2.665 3.260 3.865
	frequency (Mc)	0.595 0.605
	average frequency (Mc)	0.600
	measured thickness (mm)	4.915
	relative error (%)	1.7

EXAMPLE 2

Earphone indication	harmonic frequency (Mc)	2.645 2.940 3.235 3.530
	frequency (Mc)	0.295 0.295 0.295
	average frequency (Mc)	0.295
	measured thickness (mm)	9.995
	relative error (%)	0.5
Electric meter indication	harmonic frequency (Mc)	2.640 2.935 3.235 3.525
	frequency (Mc)	0.295 0.300 0.290
	average frequency (Mc)	0.295
	measured thickness (mm)	9.995
	relative error (%)	0.5

EXAMPLE 2 (continued)

Oscillograph indication	harmonic frequency (Mc)	2.645 2.945 3.240 3.535
	frequency (Mc)	0.300 0.295 0.295
	average frequency (Mc)	0.297
	measured thickness (mm)	9.92
	relative error (%)	0.8

One was a steel pipe with a wall thickness of 5 mm and a diameter of 350 mm; its inner wall had corrosion and accumulated dirt; the other one was a washing tower with a wall thickness of 10 mm and a diameter of 890 mm. Earphones, an electric meter, and an oscillograph were used to determine the resonance point. The surface was finished with a hand sandwheel, which had the shape of a bowl; the polishing time was 2-3 min. In order to make sure that the energy converter had good sound contact, transformer oil was used as the coupling agent.

The resonance-type thickness gage can measure not only the remaining thickness of a piece of equipment after corrosion, but also its corrosion rate. If the measured n-th harmonic frequency of a piece of equipment changes from the original $f^n_{m_o}$ to f^n_m after m months, the corrosion rate (i) is

$$i = (t_o - t_m) = \frac{12}{m}\left(\frac{2.95}{f^n_{m_o}/n} - \frac{2.95}{f^n_m/n}\right)$$

where i = corrosion rate (mm/year)

t_o = original thickness

t_m = thickness after m months

$f^n_{m_o}$ = original resonance frequency

f^n_m = resonance frequency after m months

n = number of harmonics

$k = 2.95$, a constant.

For example: $m = 16$ months; $n = 8$; $f^n_{m_0} = 1.75$ Mc; $f^n_m = 1.78$ Mc.

$$i = \frac{12}{16}\left(\frac{2.95}{1.75/8} - \frac{2.95}{1.78/8}\right) = 0.171 \text{ mm/year.}$$

V. Conclusion

The resonance-type thickness gage has been in mass production abroad. It has a wide application and has become an important inspection instrument for equipment corrosion in chemical engineering departments and refining departments. In this country, this technique is also urgently needed by different chemical firms in order to know the corrosion rate as well as the remaining wall thickness of the operating equipment. We have not spent much time in doing research in this respect. Thickness measurements have been made on steel materials with a range of 3-30 mm; the largest error is 4.4%, while most errors are 1-3%. As for thin-walled pipes with small diameters, we have not yet been able to use ultrasonic resonance-type thickness gages to make the thickness measurements; only the photometric method has been used. We are now improving the instrument circuits and the energy converter of the gage, so that it may have a wider application to meet the needs of the production departments.

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