Application of Dry-coupling Ultrasonic Technology in Oil-level Detection of Oil-filled Equipment in Power Grid

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Abstract. Dry-coupling ultrasonic technology is applied to detecting oil-level of oil-filled equipment in power grid. Vinyl silicone rubber is used to substitute liquid coupling agent to fabricate dry-coupling ultrasonic probe, which makes the ultrasonic directly enter the oil-filled equipment through the special structure of dry-coupling probe and detect oil-level of oil-filled equipment accurately and rapidly. Omitting the step that smearing liquid coupling agent on the probe can avoid the contamination on the surface of equipment and significantly improve the detection efficiency.

1. Introduction
At present, the inspection of the oil level of the oil-filled equipment in power grid (e.g. transformer, conservator, shunt reactors) is carried out by manual visual observation or telescope observation. The accuracy of checking the oil-level basically depends on the experience of inspectors. For the pointer-type oil-level gauge, the distortion of oil-level indication is often caused by failure of mechanical transmission, damage of capsule in conservator, leakage of oil level gauge, clogging of respirator, etc. [1] The glass-tube-like oil-level gauge cannot accurately determine oil-level of oil-filled equipment due to contamination of glass windows after operation. What’s more, oil-filled equipment is so close to the high-voltage electrical line that it is impossible to manually check the oil-level accurately without power outage, which is adverse for reducing outage time. Therefore, it is necessary to study technology of oil-level detection without approaching the electrical equipment to meet the daily maintenance requirements of power grid and to find out abnormal oil-level of oil-filled equipment in time, which is necessary to ensure the reliable operation of power grid. At present, infrared imaging technology basing on comparing, analysing and calculating surface temperature field of equipment is a common means of detecting oil-level without power outage[2]. However, the accuracy of this technology is not high because it is so vulnerable and restricted to influence of environmental temperature that it just can be used in overcast days and at night.

As a typical non-contact measuring instrument, ultrasonic liquid level gauge has been widely used in many industrial fields[3][4]. The principle is that ultrasonic wave has great penetration ability in liquid and it will form a significant echo signal after contacting a gas-liquid interface. Thus the distance between monitor point and gas-liquid interface is calculated. Due to the principle of acoustic impedance, ultrasonic energy will decay rapidly in air. In order to overcome attenuation of such sound wave and reduce interference of air, the coupling agent that makes more ultrasonic wave transmit into equipment must be employed between ultrasonic probe and the surface of equipment[5]. The sticky substances such as butter, silicone oil and Vaseline are common liquid coupling agents. However, liquid coupling agent would adhere to the surface of equipment after detection due to their excessive fluidity. And such agents cannot be removed manually because most oil-filled equipment in power
grid are far away from ground, which leads to a dirty appearance of oil-filled equipment. In this study, the ultrasonic dry coupling technology is applied to oil-level detection of oil-filled equipment in power grid. The dry coupling ultrasonic probe is prepared by utilizing vinyl silicone rubber instead of liquid coupling agent, thus ultrasonic wave directly enters the surface of equipment through dry coupling special structure at the front end of probe to achieve an accurate detection of oil-level[6]. At the same time, the liquid coupling agent is not required during detection process, thereby avoiding making the surface of oil-filled equipment dirty and significantly improving the detection efficiency.

2. Experiments

2.1. Devices and materials
Planar longitudinal wave probe with centre frequency of 100 kHz; Tektronix oscilloscope; Vinyl silicone rubber (MVQ); Polyformaldehyde resin (POM); Vaseline; Steel barrel with a diameter of 200mm and a height of 600mm.

2.2. Experiment method
A dry coupling ultrasonic probe with coupling agent made by slice MVQ or POM is tested to detect insulating oil level in the steel barrel and the ultrasonic echo signal is recorded by an oscilloscope.

3. Results and Discussion

3.1. The effect of different dry coupling agents
Dry coupling agents must possess good elasticity and commonly are classified into plastics and rubbers. MVQ and POM are both of good elasticity and cut into thin sheet of 2mm and each sheet is fixed on a same type of ultrasonic probe in this experiment, which are named as MVQ probe and POM probe respectively. Each probe is pressed hard at the bottom of a steel barrel and the echo signal is compared to probe with Vaseline as coupling agent.

As a dry coupling agent, two requirements must be met in acoustic performance [7]: (1) its acoustic characteristic impedance value should match the value of shell materials of equipment; (2) when acoustic wave passes through dry coupling agent, energy loss must be slight. The density of MVQ is 1.1kg/m$^3$ and the propagation velocity of sound waves in MVQ is 2311m/s; the density of POM is 1.4kg/m$^3$ and the propagation velocity of sound waves in POM is 2540m/s. According to the formula of acoustic characteristic impedance $Z=\rho c$, the acoustic characteristic impedances of above two agents are $2.5\times10^7$ and $3.6\times10^7$Pa•s/m respectively which are so consistent with that of steel which is the common material in oil-filled equipment in power grid ($4.53\times10^7$ Pa•s/m) that they both meet the requirements as a coupling agent. Although the acoustic characteristic impedance of POM is closer to steel, its acoustic attenuation coefficient (0.61dB/mm) is greater than that of MVQ (0.22 dB/mm). As shown in Figure 1, the amplitude of the echo signal received by the MVQ probe is slightly greater than that of POM with the same signal source and it is also closer to the result of Vaseline as the coupling agent. And considering that oil-filled equipment is close to high-voltage electrical line, the insulation performance of MVQ changes little in circumstances with high humidity and temperature, which satisfies our requirements more.

![Figure 1. The echo signal of different coupling agents.](image-url)
3.2. The effect of the thickness of dry coupled structure
The MVQ was cut into sheets of 0.5, 1, 2, 4, 6, 8, 12 mm, which were respectively fixed on the same ultrasonic probe, and detection results are compared as Figure 2.

When thickness of MVQ is 0.5mm, the amplitude of ultrasonic echo signal received is slightly higher than that of Vaseline. In the range of 1-4 mm, amplitude of signal gradually becomes less but not significantly. When the thickness is greater than 8 mm, not only signal intensity is greatly reduced, but also the frequency of signal in time domain changes. The signal intensity of the MVQ probe with a thickness of 0.5mm is even slightly greater than that of Vaseline, which is caused by characteristic of Vaseline that is a so semi-solid material with no fixed shape that the difference of acoustic impedance between it and steel is greater than that of MVQ. Therefore, when MVQ is used as a dry coupling agent, the thickness should be within 4 mm.

![Figure 2. The echo signal of MVQ probe with different thickness.](image)

3.3. The effect of pressure
Due to the processing technology, surface of oil-filled equipment in power grid cannot be flat enough. When the dry-coupling agent probe is clung to equipment, energy of ultrasonic wave will greatly attenuate if without pressure because air filling with the uneven interface blocks the propagation of ultrasonic wave. Therefore, external pressure must be employed in dry-coupling ultrasonic applications. The dry coupling agent with good deformation ability deforms on the interface of probe and equipment under pressure to make itself fill the air gap to achieve coupling effect like Vaseline. The relationship between the transmittance of ultrasonic wave $T$ at propagation interface and its first-order stiffness $m_1$ between interfaces as follows.

$$ T = \frac{2m_1}{\rho v \omega \sqrt{1+4m_1^2/\rho^2v^2\omega^2}} $$

where $\rho$, $v$, $\omega$ are constants, the relationship between $T$ and $m_1$ is as shown in Figure 3.

The transmittance of the ultrasonic wave rises rapidly at the initial stage with growth of $m_1$, but growth rate lessens as $m_1$ continues to rise and $T_1$ approaches the maximum, which means the coupling effect of the dry coupling material has reached the best. According to previous studies, the first-order stiffness of interface $m_1$ is approximately proportional to the applied pressure $p$, so the tendency of the relationship between the transmittance $T_1$ and the applied pressure $p$ is similar to $T_1$ and $m_1$. Although dry coupling agent turning thinner under pressure can make the echo signal intensify, such influence on the signal echo is much less than application of pressure which brings excellent coupling performance.
Figure 3. The relationship between the transmittance of ultrasonic wave $T_1$ at propagation interface and its first-order stiffness $m_1$ between interfaces.

In order to verify the validity of theoretical derivation, a force controller is connected to the dry-coupling probe to detect echo time and signal amplitude under different pressure conditions. As pressure rises, the signal amplitude intensifies to a fixed value after reaching 35 N. Therefore, the relationship between the amplitude of signal and applied pressure is valid. During the use of dry-coupling probe, the corresponding pressure must be adjusted according to signal amplitude to ensure a good coupling effect.

3.4. The influence of roughness

A smooth surface is more beneficial for dry coupling agent to adhere to oil-filled equipment as the same pressure is applied. However, different manufacturer has its own demand for roughness. In order to study the effect of surface roughness, four regions with different roughness are artificially fabricated at the bottom of the steel barrel. The 4mm-thickness MVQ is used as the dry coupling agent for oil-level detection in different areas. In this experiment, a force controller is connected to the probe to ensure that the pressure applied is same for each test kept at 40 N pressure and the oscilloscope is set at a same gain to receive signals. It is obvious that the smoother the surface is, the greater the signal intensity will be, the rougher the surface vice versa (in Figure 4). Although dry coupling agent is flexible enough, it still cannot fix on surface of equipment completely under the applied pressure when surface is significantly uneven. Air gap existing between probe and equipment causes severe attenuation of ultrasonic wave so that echo signal is greatly reduced. It is found that the echo signal observed at rough surface can only be amplified by increasing the gain of oscilloscope, which leads to a low signal-to-noise ratio simultaneously. For dry-coupling ultrasonic detection, surface of the oil-filled equipment should not be too rough.

Figure 4. The echo signal of different surface roughness detected by MVQ probe.

4. Applications

A portable dry-coupling ultrasonic oil-level detector (Figure 5. and Figure 6.) is designed. The instrument is a rod-type telescopic structure and staffs can operate it manually. In December 2018, an oil-level gauge of a 500kV transformer conservator in Guangxi Power Grid dropped sharply to alarm value. To reduce losses caused by outage, the oil-level of this conservator was detected by our detector
in the case of main equipment failure. As results, oil-level detected by the dry-coupling ultrasonic detector was 0.53-meter which was approximately 44% of total oil-filled equipment that was 1.20-meter as designed. Then the oil-filled equipment was observed by infrared temperature measurement at night and the contact interface between transformer oil and capsule was the highest temperature point of whole conservator which indicated the position of oil-level (see Figure 7.), which was similar to the test results given by dry-coupling ultrasonic detector. Both results indicated that the actual oil-level of this conservator was normal and the fault was caused by oil-level gauge.

5. Conclusion
(1) In the paper, the performance of dry coupling agents such as MVQ and POM for oil-level detection of oil-filled equipment is studied. The accuracy and sensitivity are consistent with the routine coupling agent like Vaseline and MVQ is better as a dry coupling agent considering the attenuation coefficient, acoustic characteristic impedance and electrical insulation than POM.

(2) The thickness of the dry coupling material MVQ should be selected according to the surface roughness of oil-filled equipment and it is notable that the sensitivity of probe drops rapidly after

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Figure 5. The portable dry-coupling ultrasonic oil-level detector.

Figure 6. Application of portable dry-coupling ultrasonic oil-level detector.

Figure 7. Oil-level detected by infrared temperature measurement.

Oil-level detection of oil-filled equipment in different voltage levels (10-500 kV) was carried out by utilizing our dry-coupling ultrasonic oil-level detector. The results show that the technology is rapid and accurate in oil-level detection of all kinds of oil-filled equipment in power grid, and surface roughness of various kinds of equipment under current processing technology does not affect detection.
thickness of MVQ exceeding 4mm. The probe should be pressed with enough pressure onto surface of oil-filled equipment to ensure good coupling effect and detection accuracy.

(3) A dry coupling ultrasonic detector basing on this experiment is designed with high accuracy and portability. It is found that the surface roughness of the oil-filled equipment in power grid processed by current technology does not affect the application of the detector.

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