Non-destructive testing method of micro-debonding defects in composite insulation based on high power ultrasonic

Hanqing Wang\(^1\), Li Cheng\(^1\) \& Ruijin Liao\(^1\), Sida Zhang\(^1\), Lijun Yang\(^1\)

\(^1\)State Key Laboratory of Power Transmission Equipment & System Security and New Technology, Chongqing University, Chongqing 400030, People’s Republic of China

E-mail: cheng16@cqu.edu.cn

Abstract: It is crucial to ensure the adhesive quality of the interface in composite insulation equipment for power grid security. Due to viscoelasticity of silicone rubber and roughness of interface, the thickness of the local air layer in the defective interface is <100 µm. This kind of defect is called micro-debonding defect in this paper, and it is significantly smaller than the millimetre-scale air gaps which could be detected by the x-ray, THz, and traditional ultrasonic method. It remains challenging to detect the micro-debonding in composite insulation by non-destructive testing methods. In this paper, the acoustic model and bi-linear stiffness model for micro-debonding in different stages are established. Accordingly, a conjecture is proposed that the bonding property of composite insulation is related to the acoustic impedance of interface and non-linear distortion of its constitutive relation. The result obtained from numerical simulation with and without defect is compared with the high-power ultrasonic experimental data to validate the correctness of the theoretical model. In addition, it can be concluded that the non-linear distortion of high-power ultrasonic wave can be effectively used to diagnose micro-debonding defect at the interface of composite insulation in its early stage (1–20 µm).

1 Introduction

With the construction of extra high voltage and ultra high voltage power grid and the change of the atmospheric environment, the requirement of anti-pollution flashover performance is constantly improving for external insulation equipment [1–3]. Due to the advantages of light quality and high pollution flashover performance, the high-temperature silicone rubber (SIR) and glass fiber reinforced plastic (GFRP) as the representative of composite material gradually replaced the original ceramic material on insulation equipment widely used in high-voltage transmission lines.

Interface defect is the main failure type of composite insulation. Taking insulators, e.g. the insulation breakdown caused by interface adhesion defects is the predominant failure type, accounting for 67% of the total breakdown of electrical damage [4]. In addition, the problem of interfacial adhesion is also considered as an important reason for another abnormal fracture which has usually happened on the composite insulators [5, 6].

Compared to insulation equipment in service, new equipment from the factory with interface defects is more difficult to distinguish. Through observing cross-section of composite insulation samples in this paper, it is found that the thickness of air gap caused by adhesive defects is <100 µm. This kind of defect is called micro-debonding defect in this paper. The formation of micro-debonding defects is a random process affected by many factors, such as bonding agent, vulcanising temperature, gas pressure, etc. Therefore, there are many stages of micro-debonding defects, which cause great difficulties in its non-destructive detection. This paper focuses on the early stage of micro-debonding with 1–20 µm gaps, and the late stage with 50–100 µm gaps.

Considerable research efforts have been devoted to the detection of composite insulation internal defects, such as electromagnetic wave detection [7], electric field distribution method [8], traditional ultrasonic technique [9, 10], and infrared imaging [11]. The same essence of these methods is to detect the macroscopic air gaps (millimetre scale) inside the defective interface. Although the detection accuracy of the existing methods has been reached 500 µm, these methods are incompetent to diagnose the micro-debonding defect, especially for its early stage. On the other hand, high-power ultrasonic methods increased the detectability by using induced contact acoustic non-linearity effects [12–14]. Typically, these techniques have involved the transmission of ultrasound through the bond and measurement of the harmonics generated, which reflected by the changes of the ultrasonic non-linearity parameter. However, relatively few studies and models have been focused on micro-debonding in the composite interface. Meanwhile, the constitutive mechanism of the high-power ultrasonic method for micro-debonding in the composite insulation is still unclear.

In this paper, the acoustic and mechanical constitutive models for micro-debonding in different stages are established. Accordingly, a conjecture is proposed that the bonding property of composite insulation is related to the acoustic impedance of interface and non-linear distortion of its constitutive relation. For the early stage of micro-debonding, the result obtained from numerical calculation indicates that non-linear mechanical effect at the interface is affected by micron air gap thickness. Besides, this paper established a high-power ultrasonic detection platform, and the 1–10 µm defects in the bonding interface of composite insulation were detected.

2 Interface modelling and numerical calculation

This section analyses the microstructure of the late stage and the early stage of micro-debonding in composite insulation. For this problem, two limiting cases can be solved exactly, namely the case of a micro air gap layer without contact, where the acoustic impedance theory [15] is valid, and that of an elastically contact with a completely failed coupling agent, where the bi-linear stiffness theory [16] is valid.

2.1 Micro air gaps: late stage of micro-debonding

The late stage of micro-debonding defect in the composite insulation can be equivalent to a three-layer structure made up of SIR, micro air gap, and GFRP, as shown in Fig. 1. The micro air
gaps present a continuous distribution, and the materials on the upper and lower sides of the air gap are completely separated (see Fig. 2). Thus, the sound pressure of ultrasonic echo from defective interface $P_{rd}$ can be estimated by the acoustic impedance of each layer of material:

$$P_{rd} = \frac{Z_a - Z_{SIR}}{Z_a + Z_{SIR}}P_{in} = 0.0004 - 1.66 \times 0.0004 + 1.66 P_{in} \approx - P_{in} \tag{1}$$

where $Z_a$ is the acoustic impedance of air gap, $Z_{SIR}$ is the acoustic impedance of SIR, and $P_{in}$ is the sound pressure of input ultrasonic wave. Meanwhile, for intact bonding interface, the sound pressure of ultrasonic echo $P_{ib}$ is

$$P_{ib} = \frac{Z_{GFRP} - Z_{SIR}}{Z_{GFRP} + Z_{SIR}} + \frac{-4Z_{GFRP}Z_{SIR}}{(Z_{GFRP} + Z_{SIR})^2} P_{in} = \frac{15.6 - 1.66 + \frac{-4 \times 15.6 \times 1.66}{(15.6 + 1.66)^2}} P_{in} \approx 0.46P_{in} \tag{2}$$

where $Z_{GFRP}$ is the acoustic impedance of GFRP. By combining (1) and (2) we can obtain (3) as below

$$P_{ib} \approx -0.46P_{rd} \tag{3}$$

According to the acoustic impedance theory, the micro air gaps can be detected by linear analysis of the ultrasonic signal, which is achievable through both traditional and high-power ultrasonic methods. However, the detection of this late stage of micro-debonding is of less significance, because at the same time the insulation equipment may be in a dangerous condition such as abnormal temperature rise and internal breakdown [17].

### 2.2 Kissing defect: early stage of micro-debonding

Due to the viscoelastic properties of SIR and the roughness of GFRP, the early stage of micro-debonding without continuously distributed air gap can be observed by optical microscopy (see Section 3) as a partially close interface. This special and essential type of defect is known as kissing defect, which occurs when the adhesive and the adherent are in direct physical contact but lack strong chemical bond [18–20]. Regrettably, kissing defects remain challenging to detect due to the variety of material and structure of adhesive joints.

Considering that the kissing defect in composite insulation is elastically contact, the bi-linear stiffness model [16, 21] can be valid for this case (Fig. 3). This model is constructed based on the lateral motion of crack, leading to the change of global stiffness [22]. The bi-linear characteristic was also employed for stress–strain relation [14] as

$$\sigma = C^{II} \left[ 1 - H(\varepsilon - \varepsilon_0) \frac{\Delta C}{C_{II}} \right] \varepsilon \tag{4}$$

where $\sigma$ is the stress, $\varepsilon$ is the strain, $H(\varepsilon)$ is the Heaviside unit step function, $C^{II}$ is the intact material of second-order elasticity, $\varepsilon_0$ is initial static contact strain, and $\Delta C$ is obtained by

$$\Delta C = C_{II} - \frac{d\sigma}{d\varepsilon} |_{\varepsilon > 0} \tag{5}$$

Excited by the input ultrasonic signal, the strain of interface can be assumed as

$$\varepsilon = \varepsilon_m \cos \omega t \tag{6}$$

where $\varepsilon_m$ is the amplitude of $\varepsilon$. Owing to the asymmetry of stiffness, the amplitude-dependent modulation pulse length $\tau$ is

$$\tau = \frac{T}{\pi} \arccos \left(\frac{\varepsilon_0}{\varepsilon_m}\right) \tag{7}$$

where $T$ is the period of $\varepsilon$. Furthermore, higher harmonic amplitudes $\sigma_m(\omega)$ can be expressed by

$$\sigma_m(\omega) = \frac{\varepsilon_m(\Delta C/C^{II})}{T} \sum_{n = -\infty}^{\infty} \sin(n\pi/\tau) \cdot \delta(n \pm 1 - i) \tag{8}$$

where $\delta(n)$ is the unit impulse function.

The numerical calculation of $\sigma_m(\omega)$ indicates that the kissing defects lead to the non-linear distortion of constitutive relation, as shown in Fig. 4. Consistent with the existing result [14], the harmonic amplitudes increase monotonically right within the threshold. At the threshold, the equivalence of $\varepsilon_0$ and $\varepsilon_m$ means that
The experimental samples were prepared using standard production processing techniques used in the preparation of the samples were the same as the composite insulators used in the ±1100 kV HVDC transmission line from Changji to Guquan. Plate and cylindrical samples made by insulator manufacturer are used to detect and analyse, as shown in Fig. 2. Cylindrical samples in two different sizes were manufactured, which were named C1 and C2. Among them, C2 can be further classified as C2A and C2B, due to the production from different insulator manufacturers. Samples C2A and C2B have the same rated parameters, dimensions, and vulcanisation process, but their SIR materials were formulated differently. Besides, the thickness of the SIR layer of plate samples is 4 mm. Considering interface characteristic, these samples were divided into two categories: intact bonding samples and micro-debonding defective samples. The former was evenly coated with appropriate amount of adhesive. Conversely, the micro-debonding defective samples were not coated with any adhesive to ensure that these samples fail to bond chemically.

As shown in Fig. 2b, microscope photographs of these specimens demonstrate that compared with the intact sample (in black-dotted frame), micro-scale air gaps exist at the interface of micro-debonding defective samples. Inside the defective interface in late stage, 50–100 μm air gaps (in red-dotted frame) present a continuous distribution, and the materials on the upper and lower sides of the air gap are completely separated.

Moreover, the roughness of the bonding interface is clearly essential for the formation of micro-debonding defects. In order to improve the roughness of the interface, the roughened GFRP were sand frosted and cleaned with ethanol. As shown in the blue-dotted frame of Fig. 2b, kissing defect, which appears as the early stage of micro-debonding, is a partially closed interface with contacting regions and 1–20 μm gaps. The rough interface can further reduce the defect size to <10 μm (Fig. 5).

3.2 Experimental setup

The test system is composed of RITEC RAM-5000 SNAP, matching resistor, attenuator, low pass filter, ultrasonic transducer, transducer fixed, and counterweight device. The centre frequency of the ultrasonic transducer used in the experiment is 2.25 MHz. The transducer has a high gain for the fundamental frequency of 1.5 MHz and the second harmonic frequency of 3 MHz. The probe produces an ultrasonic longitudinal wave under the action of the current and the ultrasonic echo signal is converted into the current signal return to the system. In addition, the input signal waveform is modulated by the Hanning window and the number of cycles is ten. To measure the ultrasonic non-linearity parameter, a finite amplitude monochromatic ultrasonic signal is excited on one side of the specimen and the reflected signal is detected on the same side. The non-linear ultrasonic measurement was conducted five times at each test point. These signals were averaged to improve the signal-to-noise ratio and the frequency spectrum of the averaged signal was calculated through a FFT after applying a Hanning window.

4 Results and discussion

4.1 Composite insulation with plate structure

Fig. 6 shows that there are obvious differences in amplitude and phase of ultrasonic reflection signals between the intact samples and the defective samples with 50–100 μm. By observing the order in which the positive and negative peaks appear in the pulse sequence, it can be seen that the two signals are inverse to each other. As shown in Fig. 6a, the three peaks closed to the center of the pulse sequence obtained from intact bonding sample are positive, negative and positive in turn, meanwhile those from micro air gaps defective sample are the exact opposite. The maximum peak-to-peak value of the signal for the intact sample at different test points is about 0.5 times that of the defective sample, as shown in Fig. 6b. These results are consistent with the theoretical calculation (3) quantitatively and can be repeated.

The comparison of non-linear ultrasonic testing results shows that there is no significant difference between the time domain waveforms of intact bonding and kissing defective samples, which proves that traditional linear ultrasound method is difficult to realise the detection for the micro-debonding defect in the early stage. By comparing Figs. 7a and 6 with Fig. 4, it is found that the numerical calculation results are in good agreement with the
experimental results, indicating that the kissing defects lead to the increase of the second harmonic amplitude of ultrasonic reflected signal. Consequently, the theoretical model established in this paper is valuable to reveal the mechanical properties and the constitutive relationship of the SIR/GFRP composite interface.

One unanticipated finding was that although the second harmonic amplitude $A_2$ of the kissing defective sample is significantly increased, which is similar to the simulation result, the fundamental amplitude $A_1$ of the intact bonding sample is slightly higher than that of the defective sample. This minor difference may arise from the thickness error of the SIR sheath, which affects acoustic wave attenuation. Therefore, under the circumstance that it is difficult to completely eliminate the accuracy error of sample processing, directly comparing $A_1$ or $A_2$ cannot be a robust detection method.

In order to find a more stable, more reliable and more effective detection indicator, the relative non-linearity parameter $\beta'$ of all experimental data were calculated according to (10). Since the absolute value of $\beta'$ is so tiny that it is difficult to visually reflect the detection effect, we normalise the relative non-linearity parameter $\beta'$ to the normalised non-linear coefficient $\beta'_n$ by (11).

$$\beta'_n = \frac{\beta' - \min(\beta'_i, \beta'_j, \ldots, \beta'_N)}{\max(\beta'_i, \beta'_j, \ldots, \beta'_N) - \min(\beta'_i, \beta'_j, \ldots, \beta'_N)}$$

where $N$ is the number of test points. The normalised non-linear coefficient $\beta'_n$ has certain physical meaning. Linear normalisation of $\beta'$ is not only for the purpose of intuitively comparing the $\beta'$ in the same set of data, but also reflecting the degree of non-linear distortion of the ultrasonic transmission caused by micro-debonding defects.

Fig. 8 indicates that the normalised non-linear coefficient $\beta'_n$ has strong discrimination in the interface of different bonding quality. This could be explained by the numerical calculation of the bi-linear stiffness model for micro-debonding in early stage (see Fig. 4). When the initial strain increases within a narrow range, the second harmonic amplitude $A_2$ shows an increase to a maximum, while the fundamental wave amplitude $A_1$ remains unchanged. Thus, the increase of initial contact strain $\varepsilon_0$ can lead to the enhancement of the normalised non-linear coefficient $\beta'_n$. Meanwhile, the initial contact strain of the interface is positively correlated with the defect size. Therefore, the non-linear distortion of high-power ultrasonic wave can be effectively used to diagnose micro-debonding defect at the interface of composite insulation in its early stage.

### 4.2 Composite insulation with cylindrical structure

The normalised non-linear coefficient $\beta'_n$ of the cylindrical samples C1, C2A, and C2B obtained from experimental data as shown in Fig. 9.
Complex. In this paper, the two-dimensional distribution of the air plate gap is not introduced into the micro-debonding model. Therefore, the mechanism of micro-debonding defects and experimental interface curvature increases in cylindrical sample, the distribution

![Graph](image)

Fig. 9 Normalised non-linear coefficient of the cylindrical samples with micro-debonding detected in early stage

(a) $\beta_n$ of sample C1, (b) $\beta_n$ of sample C2, (c) The effect of input ultrasonic excitation energy on the generation of non-linearity

Fig. 9a shows that the robustness of C1 is weaker than that of plate samples, which might be due to the limitation of one-dimensional bi-linear stiffness model. Considering that the interface curvature increases in cylindrical sample, the distribution of defects in the acoustic field of the transducer becomes more complex. In this paper, the two-dimensional distribution of the air gap is not introduced into the micro-debonding model. Therefore, the mechanism of micro-debonding defects and experimental design of composite insulation with cylindrical structures require further study.

It should be pointed out that, the proposed method could maintain high robustness in larger cylindrical samples C2A and C2B, as can be seen from the comparison between Figs. 9b and a. A possible explanation is that increasing the radius of a cylindrical sample can reduce the curvature of the interface. Thus, the interface characteristic of the cylindrical sample C2A and C2B are more similar to the plate structure in the theoretical model. Moreover, the normalised non-linear coefficient $\beta_n$ of C2A and C2B have good consistency, which indicates that the high-power ultrasonic method is not affected by the slight change of the composition of the SIR filler.

The influence of the ultrasonic excitation signal amplitude on the detection results was studied by taking the 1–10 μm kissing defective samples among C2A as an example. Fig. 9c indicates that the square of the second harmonic is proportional to the amplitude of the fundamental wave at the same test point. According to (10), the non-linear coefficient remains unchanged under different excitation energy, which further proves the reliability and flexibility of the proposed method. Therefore, in the potential practical application, the appropriate input energy and ultrasonic transducer can be selected in accordance with the actual needs. The input energy can be reduced to improve the economy of the detection method, when the thickness of the measured sample is relatively small.

Although the validity of the high-power ultrasonic method has been experimentally verified using composite insulating specimens, the proposed method remains to be validated for actual equipment under different circumstance. Since the realisation of the proposed method requires contact measurement, it is not necessary to consider some actual working conditions of composite insulation equipment, such as surface contamination and icing. However, it is worth mentioning that the aging of composite insulation has a considerable impact on the ultrasonic measurement. The aging of SIR and GFRP could lead to an increase in ultrasonic non-linearity. Therefore, further studies are needed to quantitatively study the ultrasonic non-linearity caused by the aging of composite insulation.

5 Conclusions

i. This paper reports the micro-debonding defect in SIR/GFRP composite insulation first. The thickness of the local air layer in the defective interface is <100 μm. It is worth mentioning that the early stage of micro-debonding known as kissing defect is a partially closed interface with contacting regions and 1–20 μm gaps. The rough interface can further reduce the defect size to <10 μm.

ii. For the late stage of micro-debonding defective interface, where the acoustic impedance theory is valid, and that of the early stage, where the bi-linear stiffness model is valid. Numerical calculation results of bi-linear stiffness model are in good agreement with the experimental results of composite insulation samples, indicating that the kissing defects lead to the increase of the second harmonic amplitude of the ultrasonic reflected signal. It is inapplicable for the existing methods in the field of non-destructive testing of power equipment to detect the non-linear distortion of constitutive relation.

iii. The ultrasonic non-linearity parameter measured by high-power ultrasonic method can be effectively used to diagnose micro-debonding defect at the interface of composite insulation in its early stage. The proposed testing method in this paper has strong discrimination in the interface of different bonding quality, and 1–10 μm defect in the bonding interface of composite insulation was detected. In addition, the increase of the roughness of GFRP can lead to the enhancement of the normalised non-linear coefficient. It is also potential to quantitatively evaluate the internal defects of the composite structure of other polymer materials.

6 Acknowledgment

This work was supported by the National Natural Science Foundation of China [Grant No. 51707020].
7 References

[1] Li, C., Shanfeng, S., Sida, Z., et al.: ‘Research on the long-time operation performance of composite insulator shed hydrophobicity under hydrothermal conditions’, High Volt., 2018, 3, (1), pp. 67–72

[2] Yong, L., Boxue, D., Massoud, F.: ‘Self-normalizing multivariate analysis of polymer insulator leakage current under severe fog conditions’, IEEE Trans. Power Deliv., 2017, 32, (3), pp. 1279–1286

[3] Can, C., Zhidong, J., Wei, Y., et al.: ‘Condition assessment strategies of composite insulator based on statistic methods’, IEEE Trans. Dielect. Electr. Insul., 2016, 23, (6), pp. 3231–3241

[4] Hanqing, W., Li, C., Ruijin, L.: ‘Nonlinear mechanical model of composite insulator interface and nondestructive testing method for weak bonding defects’, Proc. CSEE, 2019, 39, (3), pp. 269–279 (in Chinese)

[5] Bernhard, L., Li, C., Zhicheng, G., et al.: ‘Analysis of a fractured 500 kV composite insulator – identification of aging mechanisms and their causes’, IEEE Trans. Dielect. Electr. Insul., 2012, 19, (5), pp. 1723–1731

[6] Xidong, L., Weininger, B., Yanfeng, G.: ‘Decay-like fracture mechanism of silicone rubber composite insulator’, IEEE Trans. Dielect. Electr. Insul., 2018, 25, (1), pp. 110–119

[7] Li, C., Liming, W., Hongwei, M., et al.: ‘Research of nondestructive methods to test defects hidden within composite insulators based on THz time-domain spectroscopy technology’, IEEE Trans. Dielect. Electr. Insul., 2016, 23, (4), pp. 2126–2133

[8] Kone, G., Volet, C., Ezzaidi, H., et al.: ‘Experimental investigation of internal defect detection of a 69-kV composite insulator’, IEEE Elect. Insul. Conf., Montréal, Canada, June 2016, pp. 260–263

[9] Chao, Y., Congrben, X., Licheng, L., et al.: ‘Ultrasonic phased array detection of internal defects in composite insulators’, IEEE Trans. Dielect. Electr. Insul., 2016, 23, (4), pp. 525–531

[10] Honglei, D., Zhanfeng, H., Li, C.: ‘Ultrasonic guided wave-based detection of composite insulator debonding’, IEEE Trans. Dielect. Electr. Insul., 2017, 24, (6), pp. 3586–3593

[11] Zhenting, Z., Guohui, X., Yinching, Q.: ‘Representation of binary feature pooling for detection of insulator strings in infrared images’, IEEE Trans. Dielect. Electr. Insul., 2016, 23, (5), pp. 2858–2866

[12] Dawei, Y., Bruce, W.D., Simon, A.N.: ‘Measurement of the ultrasonic nonlinearity of kissing bonds in adhesive joints’, NDT E Int., 2009, 42, (5), pp. 459–466

[13] Gennady, S., Christ, G.: ‘Nonlinear clapping modulation of lamb modes by normally closed delamination’, IEEE Trans. Ultrason. Ferroelectrics Freq. Contr., 2010, 57, (6), pp. 1426–1433

[14] Solodov, I.Y., Krohn, N., Busse, G.: ‘CAN: an example of nonclassical acoustic nonlinearity in solids’, Ultrasonics, 2002, 40, pp. 621–625

[15] Auld, B.A., Green, R.E.: ‘Acoustic fields and waves in solids: two volumes’, Phys. Today, 1974, 27, (10), pp. 63–64

[16] Broda, D., Staszewski, W.J., Martowicz, A., et al.: ‘Modelling of nonlinear crack–wave interactions for damage detection based on ultrasound – a review’, J. Sound Vib., 2014, 333, (4), pp. 1097–1118

[17] Zhikang, Y., Youping, T., Yongfei, Z., et al.: ‘Analysis on heat source of abnormal temperature rise of composite insulator housings’, IEEE Trans. Dielect. Electr. Insul., 2017, 24, (6), pp. 3578–3585

[18] Dale, J., Rose, J.L.: ‘An ultrasonic interface layer model for bond evaluation’, J. Adhes. Sci. Technol., 1991, 5, (8), pp. 631–646

[19] Teles, S.V., Chimienti, D.E.: ‘Closed dihond detection in marine glass-epoxy/balsa composites’, NDT E Int., 2008, 41, (2), pp. 129–136

[20] Peiyu, W., Zhencheng, L., Licheng, Z., et al.: ‘Microwave nondestructive detection and quantitative evaluation of kissing defects in GFRP laminates’, Compos. Sci. Technol., 2018, 162, (4), pp. 117–122

[21] Ostrovsky, L.A.: ‘Wave processes in media with strong acoustic nonlinearity’, J. Acoust. Soc. Am., 1991, 90, (6), pp. 3332–3337

[22] Fristwell, M.I., Penny, J.E.T.: ‘Crack modelling for structural health monitoring’, Struct. Health Monit., 2002, 1, pp. 139–148

[23] Gang, R., Jongboem, K., Kyungyoung, J.: ‘Relationship between second- and third-order acoustic nonlinear parameters in relative measurement’, Ultrasonics, 2015, 56, (2), pp. 539–544

[24] Gebrekidan, S.B., To, K., Hakjoon, K.: ‘Nonlinear ultrasonic characterization of early degradation of fatigued Al6061-t66 with harmonic generation technique’, Ultrasonics, 2018, 85, (4), pp. 23–30