Reliability Simulation Research for Structure In-situ Ultrasonic Nondestructive Testing Based on COMSOL

XiaoFeng Xue[1*], YuanZhuoWang[1], ShaoZheng Zhan[2], PeiQiang Tian[1] and Cheng Lu[1]

[1] Northwestern Polytechnical University, China, Xi'an
[2] Aviation Industry Aircraft Strength Research Institute, China, Xi'an

[*]Corresponding author: xuexiaofeng@nwpu.edu.cn

1. Introduction

Non-destructive testing(NDT) reliability is the ability to test defects by non-destructive testing technology. It is defined as "the probability of detecting defects in a certain size range under certain testing conditions and processes" [1, 2]. The US Air Force had presented the probability of detection(POD) function form for different test data in the MIL-HDBK-1823A [3]. When performing structural in-situ NDT operations, due to limitations in detection conditions, environment, structural complexity, and operating time, there are lots of problems such as few detection times and small samples of detection data, resulting in limited credibility of NDT results. Therefore, combines historical data, expert experience and other information, and conducts research on various influencing factors through reliability simulation methods based on COMSOL, so as to provide guidance for the structural in-situ ultrasonic NDT plan formulation and improve the credibility of test results.

2. POD calculation method based on Log-logistic model

When performing ultrasonic testing, under certain detection conditions and a certain crack size, for "Signal Response" type data, a indicates the crack size, $\hat{a}$ indicates the detection signal amplitude. It is considered that there is a log-linear relationship between them and $\ln \hat{a}$ obeys the Lognormal distribution, which is called the Log-logistic model [4]. It is the theoretical basis for the reliability simulation of ultrasonic nondestructive testing. Then the detection reliability $\mathrm{POD}(a)$ at this time can be expressed as:

$$\mathrm{POD}(a) = \int_{\hat{a}_{th}}^{\infty} \mathrm{g}(\hat{a})\,\mathrm{d}\,\hat{a} \tag{1}$$

Where $\mathrm{g}(\hat{a})$ is the probability density function of the Lognormal distribution of the detected signal; $\hat{a}_{th}$ is the threshold of detects signal. That is, the POD(*a*)is probability of $\hat{a} > \hat{a}_{th}$. The POD curve of a specific detection scheme can be obtained by detecting and reliability analysis of a series of defects.

3. Ultrasonic non-destructive testing reliability simulation method

The reliability of ultrasonic nondestructive testing results is affected by many factors; this paper mainly studies the reliability simulation of nondestructive testing in terms of the crack size, the angle between the sound beam axis and the crack orientation, and the crack depth.

Under the conditions of the structure and material determination of the non-destructive testing, the parameter can be directly set into the COMSOL simulation model, means mainly refer to the relevant parameters of the detection equipment, including parameters such as probe frequency and size, and can also be directly set in the COMSOL simulation model.

4. Simulation case and result

The simulation verification model is a cylindrical structure with a diameter of 50 mm and a height of 30 mm. For the defect simulation, a flat bottom hole with a diameter of 0.5 mm and a depth of 10 mm is machined at the center of the bottom surface of the test block. The material is Ti-6Al-4V, and the wave speed is 6000 m/s. The model is shown in Fig. 1. Take one-fifth of the wavelength as the largest unit size of the mesh.

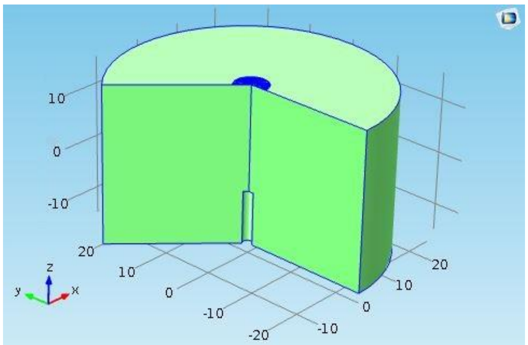


Fig.1 Ultrasonic testing simulation model of flat bottom hole defects

The simulation is performed to obtain the instantaneous sound field slice map and the ultrasonic test waveform map of the ultrasonic detection process, as shown in Fig. 2. Combined with the actual settings of ultrasonic echo amplitude, noise level and detection threshold, it can be seen that the ultrasonic NDT simulation model established is in good agreement with the results of ultrasonic testing under laboratory conditions[5].

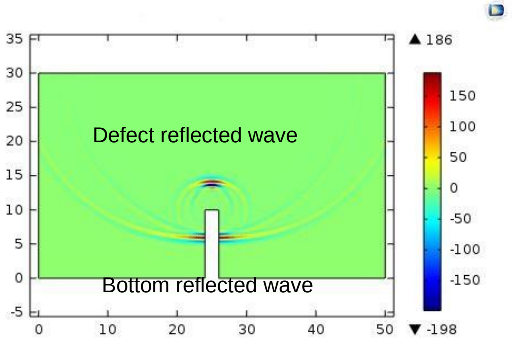
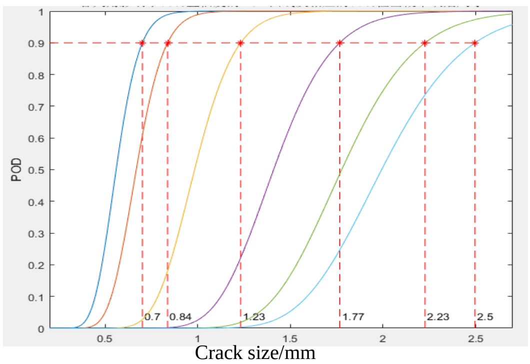


Fig.2 Slice diagram of instantaneous sound field detected by ultrasonic simulation of flat bottom hole

In order to study the influence of the crack sizes and angle on the POD, different crack sizes were taken based on the crack of 0.5 mm length, and detection reliability simulation were carried out at angles of 90°, 86°, 82°, 78°, 74° and 70°. Among them, the reliability simulation results with an angle of 90° are listed in Table 1. Furthermore, the simulation results of the detection reliability at angles above are shown in Fig.3, which show the curves at different angles and the minimum size under 90% detection probability.

Table 1 Detection reliability simulation of different size cracks at an angle of 90°

Item	Simulation results					
a/mm	0.36	0.50	0.55	0.64	0.81	1.27
A	19.04	28.93	31.69	38.38	54.17	87.69
$\hat{POD}$	0.05	0.34	0.50	0.89	0.97	1.00
P_L	0.00	0.21	0.33	0.71	0.81	0.90



(The curves from left to right are 90°, 86°, 82°, 78°, 74°, and 70°,respectively)

Fig.3 POD curves at different angles and their corresponding sizes of $a_{90/95}$

In order to study the influence of crack depth on the POD, different crack sizes were taken based on the crack of 0.5 mm length in the aluminum alloy structure, and different cracks detection simulation were carried out under the conditions of crack depth of 6 mm, 10 mm, 14 mm, 18 mm, 22 mm and 24 mm. Among them, the echo sound pressures at different depths are listed in Table 2.

Table 2 Echo sound pressure at different depths

Crack depth /mm	Echo sound pressure /Pa					Mean /Pa
6	4.601	4.584	4.569	4.747	4.755	4.503
10	3.292	3.127	3.193	3.151	3.224	3.155
14	1.846	1.648	1.956	2.001	2.012	2.007
18	1.576	1.697	1.695	1.580	1.663	1.640
22	1.321	1.211	1.211	1.252	1.261	1.363
24	1.042	1.054	1.108	1.125	1.076	1.102

5. Conclusion

(1) The crack size is closely related to the echo amplitude. As the crack size increases, the amplitude of the detected echo increases, and the probability of detection will also increase.

(2) The angle between the sound beam axis of the ultrasonic probe and the crack orientation leads to an increment in the dispersion of the detected echo amplitude; In the actual detection, in order to reduce the influence of the angle on the detection result as much as possible, the probe direction can be appropriately adjusted around the maximum echo amplitude to ensure that the positional relationship between the ultrasonic detection sound beam axis and the crack orientation is vertical, improve the detection probability.

(3) Under the same detection conditions, the smaller the crack depth is, the larger the detected echo amplitude is, and the higher the POD is. In the actual detection, the crack depth can be obtained by the propagation speed and echo time of the ultrasonic wave in the medium tested, and the POD curve and the minimum detectable crack size at certain depth are further determined.

Reference

[1] Charles R A Schneider, John R Rudlin. Review of statistical methods used in quantifying NDT reliability. *Insight-Non-Destructive Testing and Condition Monitoring*, 2004.2:1-7.

[2] Ward D. Rummel. Probability of Detection As aQuantitative Measure of Nonde-structive TestingEnd-To-End Process Capabilities. *Materials Evaluation*,1998. 2: 56

[3] Department of Defense. MIL-HDBK-1823. Nondestructive Evaluation System Reliability Assessment. Air Force. USA, 2004.

[4] Berens A P, Hovey P W. Statistical Methods for Estimating Crack Detection Probabilities. *Astm. Probabilistic Fracture Mechanics and Fatigue Methods: Applications for Structural Design and Maintenance* . Philadephia: Astm Special Technical Publication 798, 1983: 79-94.

[5] Nath S K. Effect of variation in signal amplitude and transit time on reliability analysis of ultrasonic time of flight diffraction characterization of vertical and inclined cracks. *Ultrasonics*,2014, 54(3): 938-952.