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Research on ultrasonic detection of complex surfaces

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Abstract: Parts of complex surface are widely used now in many fields, and their detection has caused much concern. In China many manufactories still carry on the traditional way of manual detection, which requires highly skilled personnel and efficiency is low. Some large manufactories have imported auto-detecting equipments, which require CAD data on the parts, or just divide the surface into several approximate planes for automatic detection. Phased-array system is seldom used, and the cost is high. Besides, most of the systems have not considered the automatic sensitivity compensation of parts with varying thickness. To improve the detection quality and efficiency of nondestructive test (NDT) of parts of complex surface, this paper puts forward an integrated ultrasonic NDT system characterized by: (1) Use of ultrasonic measurement and reverse of curved surface to solve the CAD data problem; (2) Use of an automatic sensitivity compensation algorithm (based on the part's modelling information obtained in surface reverse) to fit the variety of the thickness; (3) Use of template matching and pseudo-color imaging to improve the quality of detection results. The system features integration of low cost mature technologies, and is suitable for detection of various parts of different complex surfaces in medium-and-small enterprises. The test results showed that the system can automatically detect parts of complex surface successfully, and that the inspection result is good and reliable.

Key words: Ultrasonic NDT, Complex surface, Automatic sensitivity compensation, Ultrasonic measurement, Surface reverse, Template matching, Pseudo-color imaging

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INTRODUCTION

Parts of complex surfaces have found wide applications today in airplane, ship, automobile industry, medical science, etc. How to detect the internal defects of parts of complex surfaces efficiently and accurately is an important issue. Due to its special advantages of high sensitivity, good detection, strong penetration ability, and harmlessness to human body, ultrasonic detection has become a most important method of Nondestructive Test (NDT).

However, at present in China, to detect the parts of complex surfaces, the most widely adopted detection method is still the traditional ultrasonic NDT methods based on manual operation. This requires highly skilled testing personnel, can only judge internal defects by experience, and efficiency and reliability of the detection are much limited (Sun, 2004). Some big manufactories have imported auto-detecting systems to detect parts of complex surfaces, but these systems usually require the CAD data of the parts, which are not readily available in many cases. Some auto-detecting systems just divide the complex surface into some approximate planes and work in plane detecting mode. Auto-detecting systems with phased-array technique are few and expensive. Furthermore, most systems have not considered the problem of automatic sensitivity compensation, which is important for the accuracy of detection. Therefore, it is of great importance to design an ultrasonic detection system with flexibility, high precision, high efficiency and acceptable cost.

Table 1 shows some of the most widely used ultrasonic NDT methods both in China and abroad for the detection of parts of complex surfaces.

It can be seen from Table 1 that the method suggested in reference (Ma *et al*., 2002) is a good one for detecting the parts of complex surfaces, but this method has a strict requirement on the phased arrays, and adaptive algorithms are needed for various com-

Table 1 Ultrasonic methods for detection of parts of complex surfaces

Methods	Advantages	Disadvantages
1. Adaptive system with phased arrays, using automatic selection of active elements of the array to reduce disturbing surface echoes resulting from overlap passes (Ma *et al*., 2002)	Convenient to locate and easy to recognize the defects, with simplified mechanic structure and control system	Adaptive algorithms are needed to inspect specimens with smoothly-varying surfaces, and high-standard requirement for the phased arrays
2. Ultrasonic NDT system with 5-DOF, including data acquisition module, control module, 5-axis mechanical device, etc. (Mahaut *et al*., 1998)	Automatic detection of parts of complex surfaces, with improved precision and efficiency	CAD data on the parts of complex surfaces are required
3. Traditional ultrasonic NDT method by dividing the surface into some plane areas to fit the curved surface	Simple and easy to apply	Abundant experience of personnel is required, efficiency is low, and detection accuracy is limited

plex surfaces. The method in (Mahaut *et al*., 1998) is widely used with satisfactory detection results, but the required CAD data on complex surfaces are not available in many manufactories. Furthermore, the methods in (Ma *et al*., 2002) and (Mahaut *et al*., 1998) both require the modelling information, and no method in Table 1 has considered the problem of automatic sensitivity compensation.

To improve the situation in detecting parts of complex surfaces, this paper puts forward an integrated ultrasonic NDT system, including ultrasonic measurement, surface reverse, database, a 5-DOF manipulator and an ultrasonic data acquisition card. Main improvements of this system include: (1) By adopting ultrasonic measurement and reverse of curved surface, the problem of CAD data is solved; (2) To fit the thickness variety, an automatic sensitivity compensation algorithm is developed based on the part's modelling information obtained in surface reverse; (3) The techniques of template matching and pseudo-color imaging are used to improve the quality of detection results.

This system features integration of mature technologies with low cost, and is suitable for the detection of various parts of different complex surfaces in medium-and-small enterprises.

WORKING PRINCIPLE OF INTEGRATED ULTRASONIC NDT SYSTEM

Ultrasonic measurement and reverse of complex surfaces

There are some difficulties in detecting complex surfaces with ultrasonic wave. Due to the existence of surface curvature, dispersion, scattering and other complex modes of propagation will occur when an ultrasonic beam impinges on the surface. To get accurate acoustic image, the axis of the ultrasonic probe must always be perpendicular to the surface. Therefore, the CAD model of the part to be detected must be obtained to reconfigure the surface shape of the part.

But in practice the manufactories usually do not have the CAD data on each part of the complex surface. In order to improve the flexibility of the NDT system, this paper adopts the ultrasonic pulse echo method to conduct ultrasonic measurement to collect geometrical information on the complex surface. Then, geometric modelling is conducted, detecting path is planned, and finally real-time detection is carried out.

Geometric modelling with data obtained in ultrasonic measurement is a process of surface reverse, and boundary measurement is the most important step of surface reverse. Detection path planning can be carried out only after the boundary information is obtained. Surface reverse is a key step in the ultrasonic NDT process. Usually, the object to be reversed in ultrasonic NDT is the surface of the part to be detected. The model of the surface can provide 3D information on the part of complex surface, and is convenient for imaging with available methods of computer graphics with fast calculating speed and moderate computational efforts. Quadrilateral B-spline surface is adopted in geometric modelling, then the surface is discretized adopting an approximately-uniform-arc-length approach, and normal vector is calculated for each discrete point.

Database also plays an important role in the system, since almost all the modelling data, intermediate data and result data obtained in the detection process are stored in corresponding databases. If the part to be detected is of a new kind, modelling data on this part will be added to a part model database.

Kinematics equations of ultrasonic NDT system

Definition 1 (Kinematics points ***P***) Set of translating and rotating states of all the moving translating- and rotating-joints when ultrasonic probe moves to a spatial position.

Definition 2 (Position and attitude of probe ***A***) Set of spatial positions and attitudes of the ultrasonic probe.

Position data collected by ultrasonic probe in profile measurement, which covers the whole complex surface, is not composed of coordinate values of the complex surface but the ***P*** of the probe. Therefore, a kinematics equation is established with the parameters of the mechanic structure, and ***P*** of the probe is put into the equation to do kinematics forward analysis, and then coordinate values of surface points are calculated.

When CAD modelling is finished, discretization of the CAD model is needed before inspection, and then ***P*** with a preset detecting gap for the whole surface is calculated by kinematics backward analysis. Then, in the process of real-time detection, each joint of the manipulator will move in a trajectory defined by ***P***.

Workflow of integrated ultrasonic NDT system

The architecture of the integrated ultrasonic NDT system includes an industry PC, a servomotor control card, an ultrasonic data acquisition card, ultrasonic probes, a 5-axis precision mechanical device and five servomotors. Workflow of the system is shown in Fig.1.

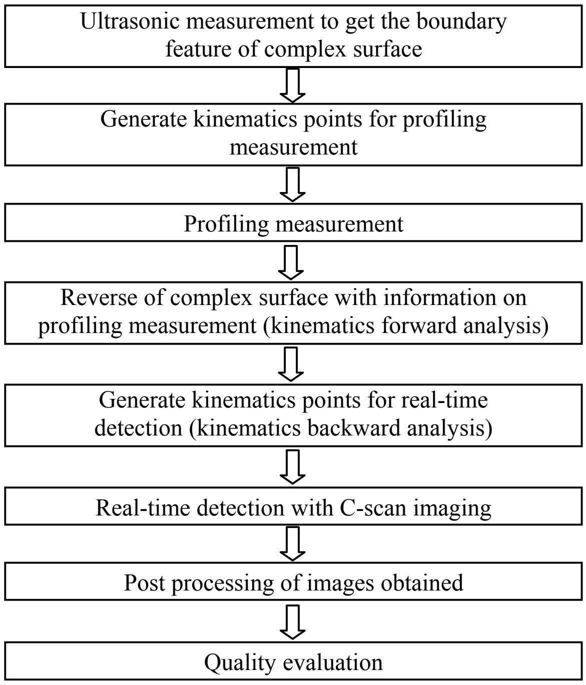

Fig.1 Workflow of integrated NDT system

TEMPLATE MATCHING

Thickness-grayscale imaging is made during the process of real-time detection, and template matching will be performed after the detection. The principle of thickness-grayscale imaging is similar to the method introduced in (Kang *et al*., 2002). But in the acoustic image, the value of gray-level is in direct proportion to the thickness of the part of complex surface. Since the depth of defect must be less than the thickness of the part, a change of gray-level will happen when there exists any defect.

$$R(i,j)=\frac{\sum_{m=1}^{M}\sum_{n=1}^{N}S^{i,j}(m,n)\times T(m,n)}{\sum_{m=1}^{M}\sum_{n=1}^{N}[S^{i,j}(m,n)]^2} \qquad (1)$$

Common template matching is a kind of translating template matching, and Eq.(1) calculates the matching degree of templates, in which T represents the template (part of the same type as the part to be detected but with no defect) translating on the source image S. The part under T is called sub graph, represented by $S^{i,j}$. $R(i, j)$ represents the match degree with the template. The bigger the $R(i, j)$ value, the more successful is the template matching (Farhan *et al*., 2004).

As shown in Fig.2, T may be different from S not only in translating position but also in angular position. Therefore, both translating template matching and rotating template matching are needed. There is only information on the detected part in the thickness-grayscale image and *T*. So, if gray-level of the background is 0, the center-of-gravity of *S* is also the center-of-gravity of the detected part, and the centers-of-gravity of *S* and *T* should coincide. This feature can be used to simplify the template matching. Before translating matching, the centers-of-gravity of *T* and *S* are calculated respectively, then *T* is translated on *S* so that the centers-of-gravity of *S* and *T* coincide. After that, *T* is rotated around the center-of-gravity within 360°. By calculating the correlation of *T* and *S*, best matching position can be obtained.

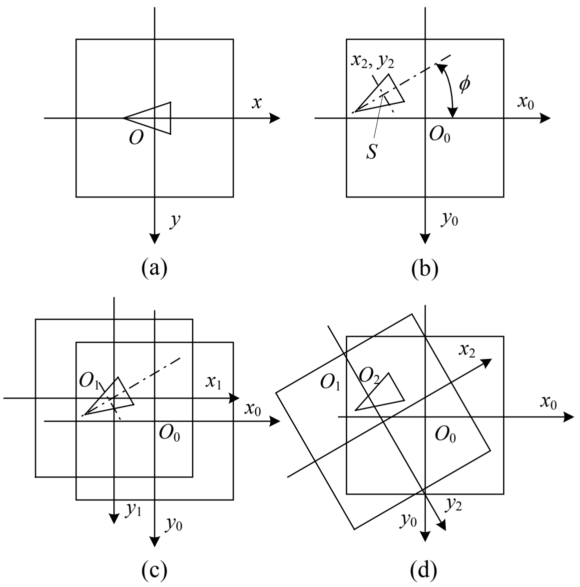

Fig.2 Templates matching process
(a) Template image; (b) C-scan image; (c) Translate so that the center-of-gravity coincide; (d) Rotate template image to get best match

AUTOMATIC SENSITIVITY COMPENSATION

Parts of complex surfaces always have variable thickness and sometimes the change in thickness is sharp. In such cases, fixed sensitivity of ultrasonic detection will lead to erroneous judgment of defects. Therefore, to ensure the accuracy of inspection, besides keeping ***A*** of the probes stable, sensitivity of detection should also be automatically adjusted, i.e., real-time thickness calculation and sensitivity compensation are needed (Jiang *et al*., 2004).

Suppose that the sound pressure (amplitude of vibration) at x=0 is P_0, the sound pressure at x is P_x, the attenuation coefficient equation is as follows:

$$P_x = P_0 e^{-\alpha_0 x} \tag{2}$$

where α_0 is the attenuation coefficient.

From Eq.(2) we have:

$$\alpha_0 = \frac{1}{x} \ln \frac{p_0}{p_x} \tag{3}$$

where the unit of α_0 is Np. When expressed in dB,

$$\alpha = 20\ln\alpha_0 = 8.686\alpha_0 \tag{4}$$

In daily detection practices, dB is also used to express the relation between sound intensities (I_1 and I_2) or sound pressures (P_1 and P_2) of two sonic waves, n is the value of dB.

$$n = 10\lg(I_1/I_2) = 20\lg(P_1/P_2) \tag{5}$$

The relation among sound intensity I, sound pressure P and echo depth h is:

$$I \propto P^2 \propto h^2 \tag{6}$$

Because the water path of the probes will not change during the process of detection, to ensure the accuracy of inspection and avoid erroneous judgment, amplitude of the basic wave should be kept stable when the thickness of the part is changed, and then defects in areas of different thickness can be recognized with correct size. Therefore, system should keep real-time tracing of the amplitude of basic wave and calculate the thickness of the part being detected. Eq.(6) shows that amplitude is in direct proportion to sound pressure, so:

$$\Delta = 20\lg(P_1 / P_2) = 20\lg(A_1 / A_2) \tag{7}$$

where A_1 is fixed amplitude of basic wave, and A_2 is the amplitude of current basic wave. Δ (dB) is the increment of gain that can be used to adjust the amplitude of basic wave back to A_1.

To keep the amplitude of the basic wave stable and avoid erroneous adjustment of gain, the thickness of the part should be calculated:

$$D=P_e-P_s \quad (8)$$

where P_s represents the peak position of the interfacial wave, P_e represents the peak position of the basic wave, and D is the thickness of the part of the complex surface.

Theoretically the change in thickness occurs almost all the time, then Δ (dB) should be calculated and the gain of the ultrasonic data acquisition must be adjusted frequently. To reduce the burden of the integrated NDT system, a range of thickness variety should be set, which means that gain adjustment will be made only when the change of thickness goes outside that range.

VISUALIZATION PROCESSING

To improve the readability of acoustic images, the technique of pseudo-color imaging is adopted: the gray-level image is kept unchanged in normal areas of the part, where the value of gray-level represents the thickness of the detected part. But in areas with defects, the amplitude of the defect wave is mapped into pseudo-color space to perform pseudo-color imaging, thus improving the quality of the acoustic images.

In performing pseudo-color imaging, the most widely used intensity hierarchical technique is adopted in the integrated NDT system.

Explanation of intensity hierarchical technique: By constructing planes parallel to the image coordinate plane, the image will be layered into several areas by the planes. Intensity hierarchical technique is derived from gray-level intensity technique. If the different intensity planes are assigned with different colors, then any pixels in the same gray-level plane can be coded with the same color (Milan,S, 2002). Mathematically, the intensity hierarchical technique can be described as follows:

Suppose that X_m planes are constructed at places where the gray-levels are L_1, L_2, …, L_m. Let L_1 represent color1: $\{f(x, y)=0\}$; L_2 represent color2: $\{f(x, y)=1\}$; …; L_m represent color m: $\{f(x, y)=L\}$. If $0<m<L$, then gray-levels will be divided into $m+1$ levels by these m planes. Pseudo-color is defined by the equation below:

$$f(x, y)=C_k, \text{ if } f(x, y)\in R_k \quad (9)$$

TEST RESULTS AND CONCLUSIONS

To test the effect of the integrated ultrasonic NDT system, an aluminum specimen (shown in Fig.3) is detected. Fig.4 shows the detection result after modeling, ***P*** generating, real-time detection (with sensitivity compensation), thickness-grayscale imaging and template mapping. Two hole-shaped defects (Φ 4 mm×9 mm, Φ 6 mm×12 mm respectively) on the left of the part are recognized, displayed in *C*+*A* mode. Fig.5 shows the defects with a better resolution.

Fig.3 Photo of specimen (made of aluminum)

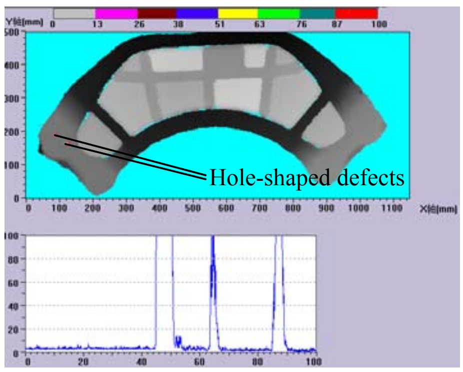

Fig.4 Acoustic images of the specimen

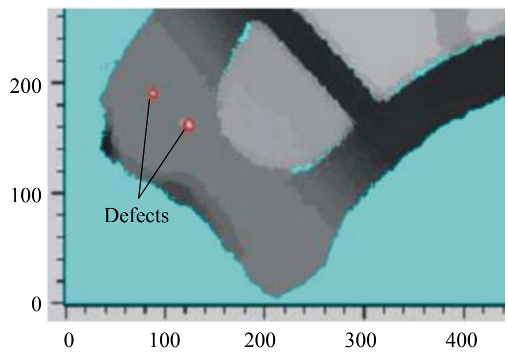

Fig.5 Enlarged figure of the defects

When clicked on the points on the thickness-grayscale image, the A-scan image of the point is shown, thus helping us to better analyze the defects. The wave shown in Fig.4 is the A-scan image of the defect with size of Φ 4 mm×9 mm.

Besides the example given above, more experiments were also been conducted. The test results showed that the integrated ultrasonic NDT system conducts automatically detect of parts of complex surface successfully, and that the inspection result was good and reliable.

From the discussions above, the following conclusions can be drawn:

1. CAD data is obtained by ultrasonic measurement and surface reverse. Though the data obtained is not as accurate as design CAD data of the part, these data can satisfy the requirements of ultrasonic NDT because the ultrasonic wave is a beam with determinate diameter. And the system is suitable for various parts of different complex shapes. Compared with the method introduced in (Mahaut *et al.*, 1998), the method suggested above eliminates the requirements of CAD data, thus making the system more practical and acceptable.

2. Automatic sensitivity compensation is achieved, and detection sensitivity can be adjusted according to the change of part thickness, thus improving the accuracy of detection. This avoids the distortion of defects mentioned in method 3 in Table 1.

3. The techniques of template matching and pseudo-color imaging are adopted to improve the detection results. This reduces false defects caused by the noise formed in dispersion and scattering of the ultrasonic beam.

But the system also has its disadvantages. Since twice imaging is needed, the process of imaging needs more time than methods introduced in (Ma *et al*., 2002; Mahaut *et al*., 1998). It is also to be noticed that it is not an easy task to get a template, i.e., part of complex surface with no defect. Additional work must be done to eliminate detected defects in a normal acoustic image and generate a virtual template with the help of modelling information.

Other ongoing works include new algorithms of nonlinear synthetic aperture focusing technology (SAFT) to improve the effect of imaging.

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