A Study on Ultrasonic Detecting Technology for the Base Gap on the Inner Cone

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Abstract: - In order to detect whether there is a base gap between the explosive charge and the inner cone of a shell and ensure its fighting performance, this paper puts forward an ultrasonic inspection method of base gap based on the principle of conservation of sound flux in propagation and according to the special construction of the shell. Inspection of artificial base gap on the inner cone and actual measurement on shell bodies shows that the method can identify the base gap effectively. The inspection of debond on other cone may draw lessons from the method.

Key-Words: - Shell, Inner cone, Base gap, Conservation of sound flux, Ultrasonic inspection

1 Introduction

Some model of armor-piercing shell is assembled with inner tapered cone and explosive charge under high pressure and certain temperature. Such defects as non-uniform adhesion, offset and base gap are often formed between inner pyramidal face and explosive charge during the assembling process. These three defects severely affect the firing safety features of shells. Non-uniform adhesion and offset can be controlled and eliminated by readjusting assembling technology, but air gap is difficult to eliminate by process control, so it must be weeded out only by final detection. The shell structure and base gap distribution are shown as Fig. 1. Definition of base gap in charging security requirements of shells is as follows: Air gap which is thicker than 0.38mm and wider than 30mm is called base gap. How to detect the defect and ensure safety features of the shell is the core of our study.

Base gap belongs to the kind of debond defect. Nondestructive examination measures of debond include ultrasonic wave, microwave, X ray and infrared ray[1] [2] [3] [4]. But reports on base gap detection has not appeared yet because the structure of shell is special (complex in frame members) and base gap is on a conical face. This paper puts forward an ultrasonic inspecting method which can detect the base gap effectively based on the principle of conservation of sound flux in propagation and according to the special construction of the shell. Inspection of artificial base gap on the inner cone and actual measurement on the shells proved its feasibility.

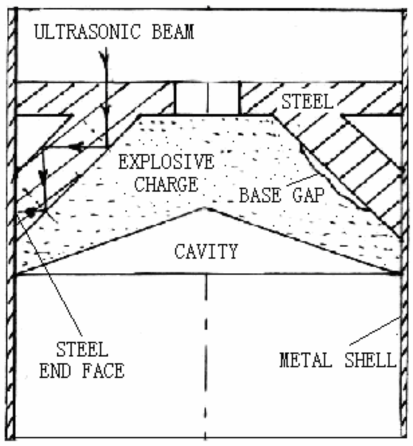


Fig. 1 Abridged general view of shell structure and base gap distribution

2 The Principle and System Design of Ultrasonic Detection

2.1 Principle of ultrasonic detection

In acoustics, medium is divided according to acoustic impedance. Medium boundary of acoustic wave is actually medium boundary with different acoustic impedance. Acoustic wave generates reflection and refraction where: (1) the acoustic impedance of medium is discontinuous; (2) the extent of boundary layer is much larger than the acoustic wavelength and sound beam diameter. When refraction and reflection are generated, those physical quantities such as sound intensity on both sides of the boundary change, but sound pressures are continuous and the normal velocities are continuous, too. Here sound pressure continuity refers to sound pressure on either side of the boundary is equal, and normal velocity continuity refers to the vertical component of velocity of material particle is equal. The two continuity conditions are basic references while studying propagation characteristic of acoustic wave.

When a beam of plane ultrasonic wave arrives at the boundary where the extent of two media is much longer than wavelength, refraction and reflection will occur. This can be shown as Fig.2.

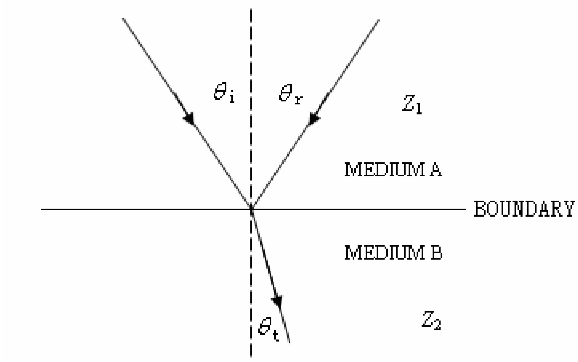


Fig.2 Reflection and refraction of acoustic energy

Where Z_1 is acoustic impedance of medium A; Z_2 is acoustic impedance of medium B; θ_i is the incident angle; θ_r is the angle of reflection; θ_t is the angle of refraction.

Sound intensity reflection coefficient r_I and sound intensity transmission coefficient t_I can be deduced and shown as following separately[5].

$$r_I = \left(\frac{Z_2\cos\theta_i - Z_1\cos\theta_t}{Z_2\cos\theta_r + Z_1\cos\theta_t} \right)^2 \quad (1)$$

$$t_I = \frac{4Z_1Z_2\cos^2\theta_i}{(Z_2\cos\theta_r + Z_1\cos\theta_t)^2} \quad (2)$$

When ultrasonic wave arrives vertically at the interface, from (1) and (2) we have

$$r_I + t_I = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2 + \frac{4Z_1Z_2}{(Z_1+Z_2)^2} = 1$$

The equality shows that conservation of sound intensity lies only when ultrasonic wave arrives vertically and is not observed when ultrasonic wave arrives at other angles. The reasons lie in that intensity only represents energy property at one point if it is used to describe the energy feature. But in practical application, ultrasonic wave beam arrives at the whole boundary, the geometrical property at the boundary has significant effect on ultrasonic energy detection, so it is better to use sound flux to describe the energy transmission feature. Sound flux conservation can be proved when ultrasonic wave arrives at any boundary.

Define the sound flux ϕ as the product of sound intensity *I* and area *S*, suppose that ultrasonic wave arrives at an angle of θ_i and the area of sound beam projection at the boundary is *S*, then incident sound flux $\phi_i = S\cos\theta_i I_i$, back sound flux $\phi_r = S\cos\theta_r I_r$ and transmitted sound flux $\phi_t = S\cos\theta_t I_t$. Reflection coefficient of sound flux r_ϕ and transmission coefficient of sound flux t_ϕ can be deduced as following separately.

$$r_\phi = \frac{\phi_r}{\phi_i} = r_I \frac{\cos\theta_r}{\cos\theta_i} = r_I = \left(\frac{Z_2\cos\theta_i - Z_1\cos\theta_t}{Z_2\cos\theta_r - Z_1\cos\theta_t} \right)^2 \quad (3)$$

$$t_\phi = \frac{\phi_t}{\phi_i} = t_I \frac{\cos\theta_t}{\cos\theta_i} = \frac{Z_1\cos\theta_t}{Z_2\cos\theta_i} \left(\frac{2Z_2\cos\theta_i}{Z_2\cos\theta_r + Z_1\cos\theta_t} \right)^2 \quad (4)$$

From (3) and (4), we can know that $r_\phi + t_\phi = 1$ lies whatever the incident angle is. There is sound flux conservation all the time. This shows that as a parameter of ultrasonic wave energy, sound flux can completely reflect the ultrasonic transmission character at the boundary between two different media; the less difference of acoustic impedance of two media is, the larger transmission sound flux and the smaller reflection sound flux and vice versa. So the magnitude of reflection sound flux can be utilized to distinguish adhesive state at the boundary of two media.

Here, acoustic impedance of steel Z_{st} (Z_1) and that of explosive Z_{ex} (Z_2)are respectively:

$$Z_{st} = Z_1 = c_1\rho_1 = 6000\,\mathrm{m/s} \times 7.8 \times 10^3\,\mathrm{kg/m}$$
$$= 4.68 \times 10^6\,\mathrm{Pa \cdot s/m}$$

$$Z_{ex} = Z_2 = c_2\rho_2 = 2400\,\mathrm{m/s} \times 2.4 \times 10^3\,\mathrm{kg/m^3} = 10^5\,\mathrm{Pa \cdot s/m}$$

Given entrance angle $\theta_i = 45^\circ$, then according to law of refraction $\sin\theta_i / \sin\theta_r = c_1 / c_2$, we can find refraction angle $\theta_t = 18.19^\circ$. Substitute in (3) the value of Z_1, Z_2, θ_i and θ_t, we have

$$r_\phi = 0.69$$

and

$$t_\phi = 1 - r_\phi = 0.31$$

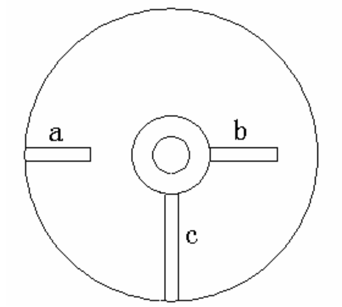
From above results we can see that when the charge explosive is adhered to steel closely, 69% of sound energy is reflected to the steel side and 31% of it is transmitted into the explosive, which results in smaller echo signal at end face of steel. If there is an air gap (base gap) between them, because the sound velocity and acoustic impedance of air are very small as compared to those of steel ($v_{ai} = 340\,\mathrm{m/s}$, $Z_{ai} = 40.7\,\mathrm{Pa \cdot s/m}$), $r_\phi = 1.0$, $t_\phi = 0$, the sound energy is almost perfectly reflected to the steel side ($r_\phi \approx 1$), resulting in larger echo signal at the end face of steel. So we can detect whether base gap exists or not between the inner cone of shell and the explosive charge and identify its size.

According to the design feature of shells and regularities of base gap distribution, only focusing probes normal to the end surface coupled with water can be used to detect base gap at a smaller circular cone surface. Adhesion state detection of element band of conical surface can be realized by multiple reflection as shown in Fig.1 and the whole conical surface realized by rotating the shell about its axis.

2.2 Artificial base gap detection

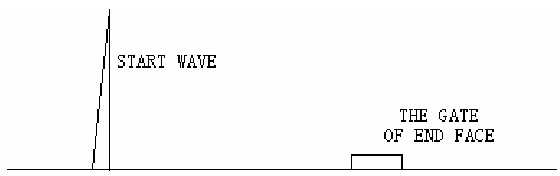
In nondestructive testing, artificial samples need to be made to determine a testing criterion to check the discontinuity in material. According to the particularity of assembly craft between the base of shell and explosive charge, after label paper tape with density far less than the explosive (density $\rho_{pa} = 0.8 \times 10^3$ kg/m^3, sound velocity $c_{pa} = 600$ m/s, reflection coefficient of sound flux $r_\phi = 0.96$) is glued, there will be a paper gap similar to the air gap (reflection coefficient of sound flux $r_\phi = 1.0$) around the paper tape after assembly by normal craft, the width and length of paper tape represent the area of base gap. Paper gaps on inner cone of a shell are distributed as Fig.3.

According to the definition, an air gap means that it is thicker than 0.38mm and wider than 30mm. Glued paper tapes of thickness 0.3mm and width of 3 is chosen as the artificial flaw to imitate the base gaps or smaller deglued flaws strictly. After finding the position of end face echo of steel through calculation (the position is identified by a gate), we observe echoes changing while rotating probe positioner and find out that echo magnitude is bigger where paper tape "a" exists and is smaller or no echo where paper tape does not exist. Two peak values observed from crack detector have a difference of 6dB, which can obviously identify whether paper gap exists or not. If paper gap "a" in size of 0.3mm×3mm×20mm ($t \times w \times l$) is chosen as the testing criterion, three paper gaps on circular cone all reach the criterion and give an alarm, but there is no echo where pasting is normal. Detected waveforms from crack detector are shown as Fig.4. It can be found out from Fig.4 that the detected echo of end face of steel where paper tape "a" exists is the same as that where paper tape "b" exists because of their same size although they are at different radial positions and that where paper tape "c" exists is bigger because of its longer length. The magnitude of echo generally represents the length of paper gap and duration of echo represents the width of paper gap.

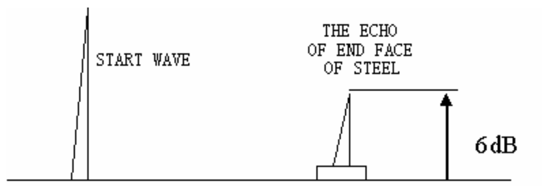


(a): 0.3mm×3mm×20mm($t \times w \times l$)
(b): 0.3mm×3mm×20mm
(c): 0.3mm×3mm×30mm

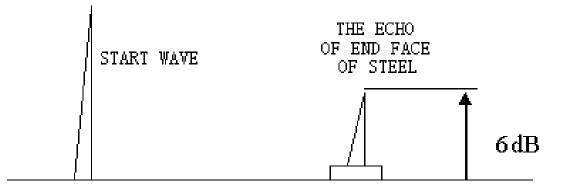
Fig. 3 Abridged general view of distribution of paper gaps on inner cone



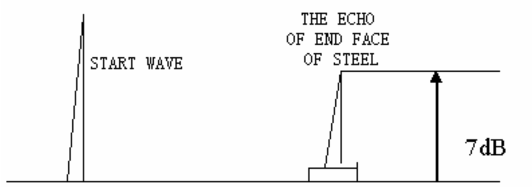
(a) Waveform without paper tape



(b) Waveform with paper tape "a"



(c) Waveform with paper tape "b"



(f) Waveform with paper tape "c"

Fig. 4 Detection of artificial base gap

2.3 Design of detecting system

To realize above detecting principle and the on-line detecting demand, the detecting system is shown in Fig. 5. The system has realized automatic checking and real-time alarm under the control of chip microcomputer. With artificial sample as testing criterion, shell type A is detected and found out to be normal. As for other shell type B, under low temperature some of them reflect existence of deglue (the magnitude and duration of their echoes are both less than those in case of a base gap), but under high temperature no abnormality are detected.

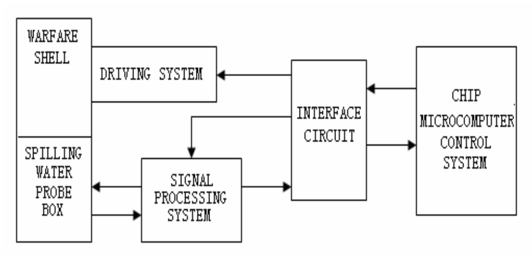


Fig. 5 Block diagram of detecting system

3 Conclusion

Batch experiments have been done on shells with above method and the received results are good. This detecting method can reflect safety features of shells better. The exploited system of detecting base gap of shells based on above detecting principle can realize on-line base gap detection with high speed.

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