Detection of small cracks by forward or backward ultrasonic wave in threads

순방향 또는 역방향 초음파 신호에 의한 나사산의 미세한 결함검출

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ABSTRACT

It is difficult such to detect flaws as stress-corrosion cracking and corrosion wastage(loss of bolt diameter) in the threads during the in-service inspection using conventional ultrasonic testing method. In many cases, the critical size of the flaw is very small. At critical size, the crack tends to propagate rapidly through the bolt under stress, resulting in total fracture. As regarding ultrasonic testing technique, a normal-beam or longitudinal wave technique and an angle-beam or shear-wave technique are generally used. In such a method a small flaw can not be distinguished from the complicated signals reflected from threads since the fine echo produced by a flaw is nearly equal to the noise level. A new method is proposed to separate the crack reflection from the multiple thread signals. The forward or backward scattered waves from the crack tip are useful for recognizing the fine flaw echoes and evaluating the thread crack size.

요 약

볼트와 넛트에 대한 초음파비파괴검사는 종파와 사각 횡파 기술을 사용하고 있는데 작은 결함신호는 나사산의 신호와 크기가 비슷해 구분이 되지 않는다. 본 논문에서는 나사산의 다중반사신호로 부터 결함신호를 구분할 수 있는 방법을 제시한다. 종파를 사용하였을 경우 균열의 선단신호와 코너에서 반사되는 신호는 진행시간이 거의 같아 중첩되어 나타나지만 균열로 인한 Rayleigh파는 균열의 선단신호와 코너에서 반사되는 신호다음에 결함길이에 따른 미세한 진행시간을 가지고 나타난다. 이와는 다르게 횡파를 사용하였을때의 균열의 선단신호는 코너에서 반사되는 신호보다 앞에 나타난다. 이러한 나사산에 존재하는 결함의 선단신호를 기준으로 순방향 또는 역방향으로 반사되는 신호로 부터 작은 결함신호도 구분할 수 있고 그 크기를 정량적으로 계산할 수 있다.

I. Introduction

In the industry and particularly in the nuclear power plants many kinds of bolts, ranging in size from small to large, are used. But bolting degradation problems in the primary coolant pressure boundary applications have become a major ooncern in the nuclear industry. It is difficult to detect such flaws as stress-corrosion cracking or corrosion wastage(loss of bolt diameter) in the threads using conventional ultrasonic testiong

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method during the inservice inspection prior to failure. In many cases, the critical size of the flaw is very small. At critical size, the crack tends to propagate rapidly through the bolt under stress, resulting in total fracture.(1-5) Generally, ultrasonic examination, magnetic particle examination and penetrant examination are carried out as in-service inspection technique. Of these methods, ultrasonic inspection technique is the only testing method which is able to detect crack of the thread region, under the condition of the stud bolts in position.(6)

In such a method a small flaw can not be distinguished from the complicated signals reflected from threads since the fine echo produced by a flaw is nearly equal to the noise level. In some cases, the critical flaw size is so small that its reflected signal amplitude is hidden in the noise level. Thus, these facts demand us a new technique or the modification of an existing technique. The weak and small tip signals from the threads of the bolt are useful for distinguishing the fine flaw echoes from the threads echoes, and to evaluate thread crack size. The forward or backward scattered signals between thread echoes can easily resolve the small crack in the stud (bolt) threads. This technique can be used to detect the fine flaw in threads.

Ⅱ. Forward or backward scattered wave in threads

The shear-wave angle-beam technique of the pulse-echo method is suitable for the studs with heater holes, while the 0-degree longitudinal-beam(0-deg.L) technique of the pulse-echo method is suitable for the studs without heater holes.

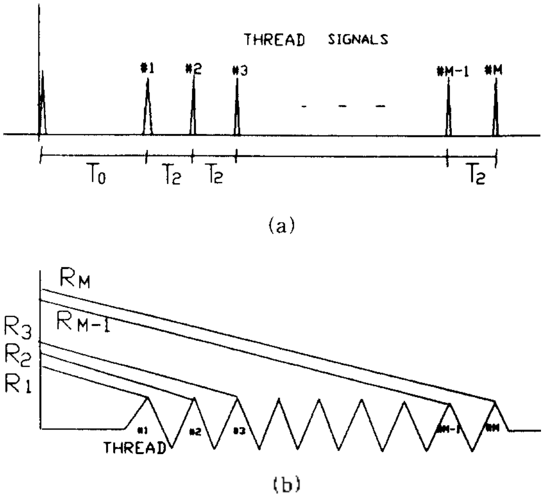


Fig 1. Illustration of the time-of-flight difference (TOFD) of thread signals

(a) The signal trace illustrates the signals obtained from the threads.

(b) Ultrasonic beams are traveling into the threads of stud(bolt) in parallel.

If an ultrasonic beam is emitted from a source, and reflected from each successive thread, then the interval between any two corresponding signals from the successive threads, are almost the same. These displays are observed from small studs(bolts) as well as large stud bolts. The thread signals become smaller and less well defined due to ultrasonic attenuation caused by specimen material and thread noises. We assume that when ultrasonic beams are travelling into threads in parallel, without loss of generality, then the reflected wave from tilt face or diffracted wave from the tip of threads have the same time-of-flight difference(TOFD) as indicated in Fig. 1. If the incident beam angle to the thread tilt face is less than 90 degree in the 0-degree longitudinal-beam and shear-wave angle-beam technique and the incident beam is perpendicular to the thread tilt face, the echo signals are reflected wave, diffracted and mode-converted wave as shown in Fig.2 and 3. We may assume the M threads have equal interval. We denote the common one-way travel time of thread to thread by T_1 and the two-way travel time by $T_2 = 2\ T_1$. As an impulse $\delta(t)$ is from the top on the M Tips or tilt faces of threads, there will be immediately a reflected wave from threads. When the wave reaches thread #1, the reflection will be occurred at time T_0. Similarly, the sucessive wave will be returned from the thread #2, this wave will return T_2

seconds later and the successive signals will add to the wave at time interval T_2 as shown in Fig.1. When we add the contributions of all the returned waves we see that the reflection response will be a linear superposition of returned impulses

$$R(t)=\sum_{k=0}^{\infty} R_k\, \delta(t-kT_2)$$

It has a Fourier transform expressible more conveniently as the z-transform

$$R(z)=\sum_{k=0}^{\infty} R_k\, z^{-k} \qquad \text{where } z=e^{j\omega T_2}$$

Observe that R is periodic in frequency ω with period $2\pi/T_2$, which plays a role analogous to the sampling frequency. Therefore, it is enough to specify R within the Nyquist interval $[-\pi/T_2, \pi/T_2]$.[7] That is, resonance frequency of transducer must be at least 2 times greater than pulse train frequency of reflected signals due to neighboring thread to get the TOFD from threads echo. If the resonance frequency is nearly equal wave train frequency, it is impossible to discriminate the thread interval effect from the reflected signal dispay.

We can obtain the crack or corrosion wastage (loss of bolt diameter) information from the travel time between the thread intervals as follows. The TOFD of thread signals is changed by the flaw in the thread root. If a stud is normal without any crack, the time interval(T_2) between thread to thread travel time is same. But if there is a small crack in the thread which start at the bottom of the thread and proceed at right angles to the axis, the times of arrival of thread signals is different from those of normal threads signals. Fig.2 shows 0-degree longitudinal-beam technique of pulse-echo method. When acoustic waves encounter crack-like threads in stud, some of the energy is converted into multiple reflected or diffracted wave mode from both the tip of the crack and the corner of the thread as shown in Fig.2(b). First, a longitudinal wave scatters from

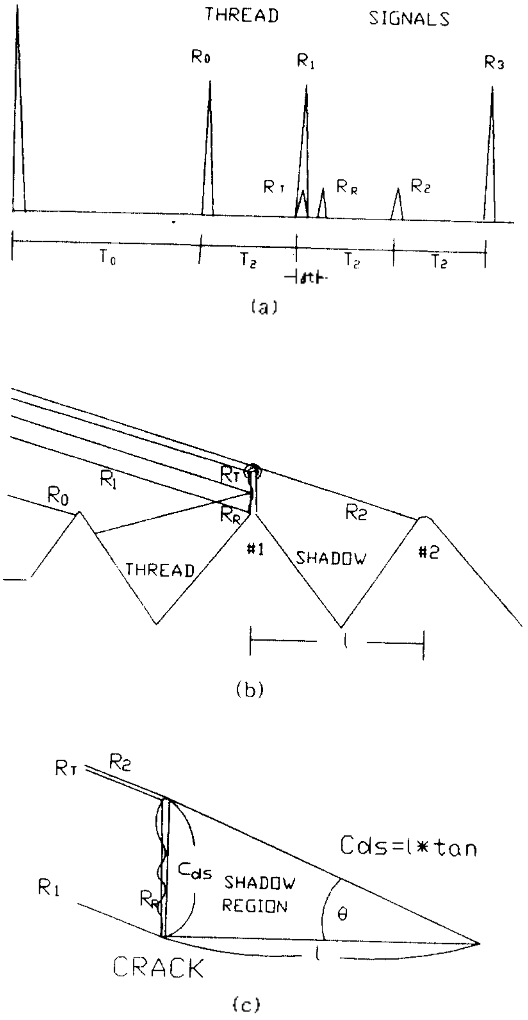


Fig 2. The interaction of 0-degree longitudinal-wave in the threads without heater hole.

(a) The signal trace illustrates the signals obtained from threads. The crack size be can evaluated by the time-of flight difference(TOFD) of thread signals and the backward scattered Rayleigh wave.

(b) The interaction of longitudinal wave in the crack, resultiong in a large reflected ulse(R_1) and a backward scattered Rayleigh wave (R_R).

(c) The minimum detectable flaw(C_{ds}) depends on the angle (θ) (between incident beam and stud wall) and pitch to pitch interval(l) of threads.

the crack tip(R_T) and reflects from the corner of the crack(R_1)$^{(8, 9)}$ and notch ; second, a Rayleigh wave(R_R) travels a shallow trajectory skimming along the surface of the crack and reflects from the corner of the crack and thread root. The reflected signal from the thread #1 is shifted and reinforced by the crack, but the metal path(T_0) is not changed. And this main signal is overlapped in time with the forward scattered tip signal(R_T). When the crack size is bigger than minimum detectable size(Cds) by TOFD of thread signals, the R_2 signal from the thread #2 is disappeared due to the interruption of sound path by a crack. The minimum detectable flaw(Cds) by TOFD of thread signals depends on the angle(θ) between incident beam and stud wall and thread to thread interval(l)

Cs : crack size

$$Cds \geq l^* \tan\theta$$

And the crack size can be calculated by delay time Δt of main reflected signal(R_1) and Rayleigh wave(R_R).

$$C_s = \frac{\Delta t^* v^* \sin\theta}{2}$$

where v : wave velocity(Rayleigh wave)
Cs : crack size

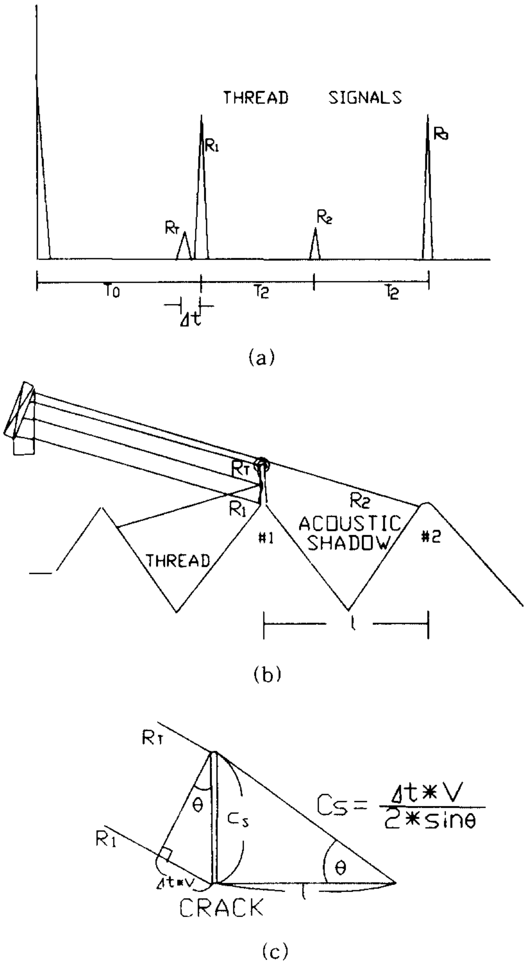


Fig 3. The interaction of 60-degree shear-wave in the threads with heater hole.
(a) The signal trace illustrates the signals obtained from the threads. The crack size can be evaluated by the time-of-flight difference(TOFD) of thread signals and the fordward scattered tip signal(R_T).
(b) The interaction of shear-wave in the crack, resulting in a large reflected pulse (R_1) and fordward scattered tip signal (R_T).
(c) The fordward scattered tip signal(R_1) can be used in the crack sizing.

And if there is a small crack(Cs) at thread root in the shear wave angle-beam technique as shown in Fig. 3, the echo signal(R_1) is fully reflected at tilt face and reinforced by the crack(Cs) as shown in Fig.3(b). On the other hand, forwardscattered tip-diffracted wave at the crack tip will be occured and this forward-scattered signal preceded the R_1 signal by delay time Δt. The Rayleigh wave travels along the surface of the crack and reflects from the corner and thread root. But this signal is overlapped in time with the main reflection from the corner. If the crack size(Cs) is bigger than the C_{ds}, the echo signal(R_2) is disappeared due to interruption of sound path by crack. The crack size(Cs) is given by

$$C_s = \frac{\Delta t^* v_s}{2^* \sin\theta}$$

where Δt : delay time between thread and tip diffracted signal

v_s : shear-wave velocity(3.2 mm/μsec) in steel

Ⅲ. Experimental results

To test the theory, test specimen were fabricated from carbon steel and notches were cut into the test specimen(NC 40 M 4, manufactured by Framatome, France), as shown in Fig.4. The lower 210 mm of this were threaded at a pitch of 8 threads per inch(25.4 mm). The interval of pitch to pitch is 3.2 mm. We have to select the center frequency of transducer by $f_0 > 2f_t$, is the center frequency of transducer and f_t is the pulse train frequency.

The pulse train frequency f_t is calculated by

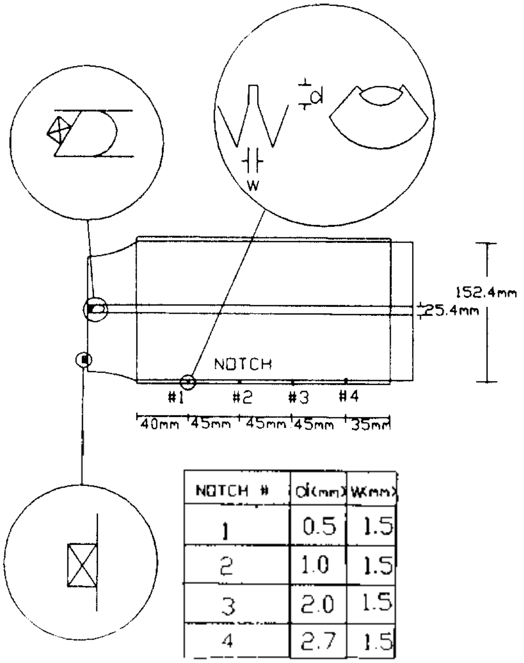
$$f_t = \frac{v}{l \cdot \cos\theta}$$

where l : interval of pitch to pitch

θ : angle between incident wave and thread wall

v : shear wave velocity in steel(3.2 mm/μsec) or longitudinal wave velocity in steel(5.8mm/μsec)

If the interval of pitch to pitch (l) is 3.2 mm, the angle between incident wave and thread wall (θ) is nearly zero in the zero-degree longitudinal wave and 30 degree in the shear-wave angle-beam technique, the pulse train frequency is 2 MHz in the zero-degree longitudinal-wave and 1 MHz in the shear-wave technique. The center frequency of transducers used in the test were 5 MHz(Bandwidth 1.5 MHz) and 2.25 MHz(Bandwidth 0.9 MHz).



NOTCH #	d(mm)	W(mm)
1	0.5	1.5
2	1.0	1.5
3	2.0	1.5
4	2.7	1.5

Fig 4. Illustration of transducer and notch size. (material : NC 40 M 4, manufactured by framatome, France)

The Fig.5 shows the A-scan display from stud thread including notches in the zero-degree longitudinal-wave technique. We can hardly differentiate small crack signal from normal signal as shown in the A-scan display. But if the crack flaw(C_s) is larger than the minimum detectable flaw(Cds), R_T signal will be displayed in A-scan even this signal is very weak. The minimum detectable size(Cds) by T TOFD of thread signals is depend on the angle between incident wave and thread wall(θ).

$$Cds \geq l \cdot \tan\theta$$

In the Fig.5, notch signals(0.5, 1 mm depth) are very small, while the signals due to 2 and 2.7 mm notches are larger than threads noise for the 0-degree longitudinal-wave heater hole. We can expand the A-scan display including 0.5 mm notch signal as illustrated in Fig.6. The notch signal R_I is fully reflected at the corner of the notch and thread root and reinforced by the notch. Even if there is a small crack at thread root, backward scattered Rayleigh wave(R_R) occured

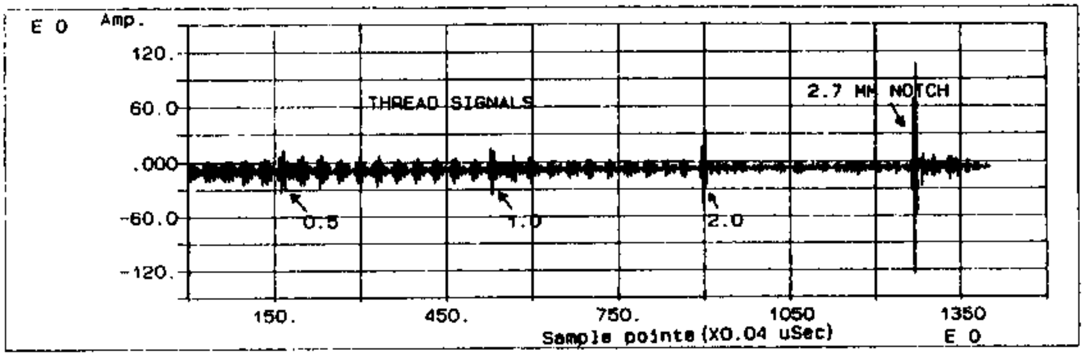


Fig 5. A-scan display from threads including notches in 0-degree longitudinal-wave technique.

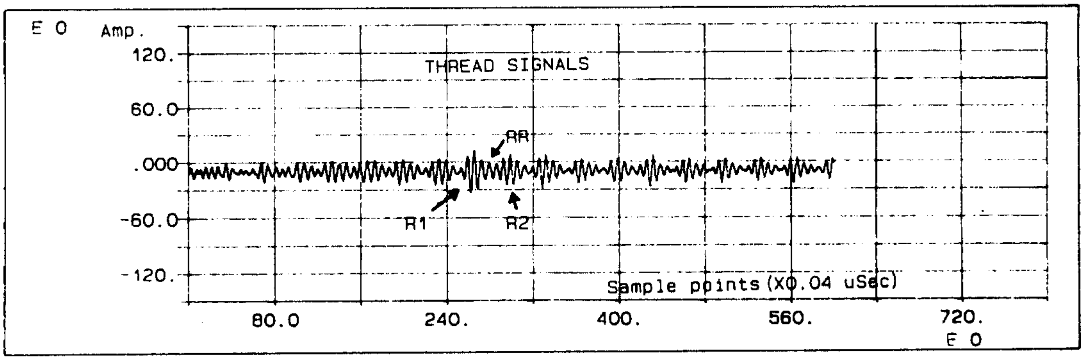


Fig 6. A-scan display including 0.5 mm notch from threads in 0-degree longitudinal-wave technique.

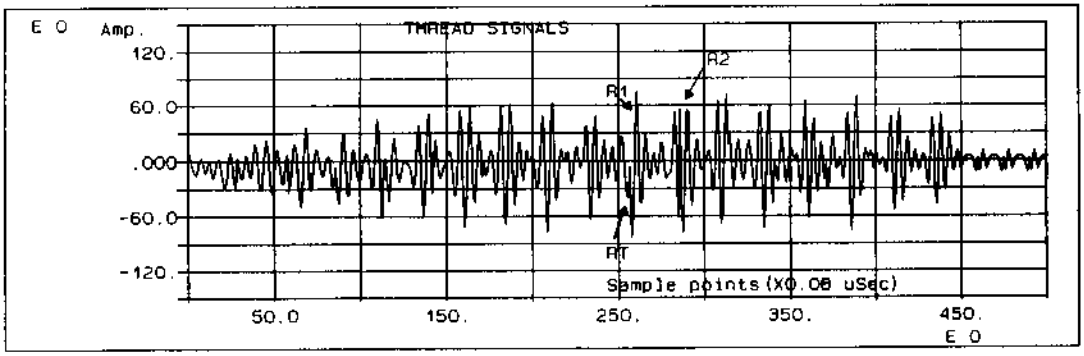


Fig 7. A-scan display including 0.5 mm notch from threads in 60-degree shear-wave technique.

between forward thread(R_1) and backward thread signal(R_2). The tip diffracted signal(R_T) is normally overlapped with R_1 signal and the reflected signal from forward notch face is overlapped with backward notch signal(R_2) also in time. The successive signal(R_2), however, is decreased because the sound path is interrupted by the notch. The bigger crack size is, the smaller the echo signal(R_2) is and eventually R_2 can be disappeared with big enough crack size.

For the shear-wave angle-beam with heater hole, the 60-degree transducer was inserted into the heater hole of stud. The A-scan display is the thread signals including 0.5 mm notch as shown Fig.7. The notch signal(R_1) is reflected at the corner of the notch and thread root. However, the forward scattered tip signal(R_1) precedes the notch signal(R_1) in time. But the second reflection signal by notch is overlapped with next thead signal(R_2). It is difficult to discriminate forward diffracted tip signal in the A-scan display, but the crack is larger than $l^* tan\ \theta$, the next thread signal(R_2) is disappeared due to interruption of sound path the notch. While the second reflection signal by the notch is displayed in R_2 signal position in time.

The small crack(smaller than $l^* tan\ \theta$, 0.5-1.0 mm) can be evaluated by the forward or backward scattered wave. And the large crack(larger than $l^* tan\ \theta$, 2-3 mm) can be evaluated by TOFD of thred signals. Table 1 shows the experimental results obtained from the use of the forward or backuard scattered wave and TOFD of thread signals technique.

Table 1. Estimates crack size by forward or backward scattered signals

Actual height (mm)	Estimated height(mm)	
	0-degree L-wave	60-degree shear-wave
0.5	0.8	0..7
1.0	0.9	1.1
2.0	1.7	1.6
2.7	2.5	2.4

The mimimum detectable size(C_{ds}) by TOFD of thread signals

0-deg. : $C_{ds} = l^* tan\ \theta = 0.56$ mm($l = 3.2$ mm, $\theta = 10$)

60-deg. : $C_{ds} = l^* tan\ \theta = 1.85$ mm ($l = 3.2$ mm, $\theta = 30$)

Ⅳ. Discussion and conclusions

It is difficult to discriminate a forward or a backward scattered signal from the composite stud(bolt) threads signals in A-scan display. Ultrasonic beams, however, are travelling into threads in parallel with angle, then the reflected wave from tilt faces or tip of threads have the same time-of-flight difference(TOFD) of thread signals. This TOFD, corresponding to the thread interval, is changed by crack in thread root. If a crack is large enough to interrupt the sound path of a thread, the next signal is disappeared in A-scan display due to the shadow effect of the crack. But if a crack is not large enough to interrupt a thread signal, the forward and backward scattered signals, depending on transducer position and incident angle, occur between the threads signals. A small crack(< 1mm) can be discriminated by this scattered signals.

For a long stud(bolt), without heater holes, the forward or backward scattered signals and disappeared thread signal will be occured in main echoes(longitudinal wave) as well as the mode-converted secondary echoes(longitudinal to shear wave). But the multiple reflections from the thread root and crack cannot be resolved by normal means. The use of ultrasonic signal and image processing to identify various reflectors in stud(bolt) threads will be required.

We have found a method which detects very small cracks in stud(bolt) threads. Although there are multiple geometric features in threads of stud, the forward or backward scattered signals technique can identify a small crack in the threads of the stud(bolt).

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