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Nondestructive evaluation of cylindrical parts using laser ultrasonics

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Abstract

We applied the laser ultrasonic technique for detecting surface breaking slots in steel cylinders (25 mm in diameter). The observation of the detected signal over a long time (500 μs), shows that the interaction of the two contra-propagating incident Rayleigh waves reinforce the echoes coming from the defect. These echoes are slowly growing with time whereas the main signals decrease. This energy transfer occurring at each revolution of the waves around the cylinder allows the detection of cracks having a depth ($h \approx 80$ μm), very small compared to the Rayleigh wavelength ($\lambda \cong 2$ mm). The evaluation of the material was performed by processing the detected signal in a sliding time window. A cross-correlation is made either between a reference signal and the signal from the tested sample or between two signals probed for two different positions of the sample. In both cases, the slope of the cross-correlation coefficient versus the number of turns is proportional to the depth of the slot.

Keywords: Laser ultrasonics; Surface acoustic waves; Cylinder; Nondestructive evaluation

1. Introduction

In the field of nondestructive evaluation of materials, the need to detect surface breaking defects has motivated extensive work on the interaction of Rayleigh waves with natural and artificial flaws [1,2]. The main advantage of using lasers rather than conventional piezoelectric transducers is that this technique does not require any mechanical contact with the inspected surface [3,4]. In previous works, laser ultrasonics have been used to study the dispersive propagation of Lamb waves in plates [5] and cylindrical shells [6] as well as of surface acoustic waves (SAW) on cylinders and spheres [7]. In this paper we report on the detection and characterisation of slots in cylinders made of steel by laser generated and detected Rayleigh waves.

2. Surface waves on a cylinder

The waves propagating on the free surface of a cylinder of radius a fall into two categories: the Rayleigh wave and the so-called "whispering gallery" waves. The characteristic equation providing the normalised frequency $y = \omega a/V_T$ versus the angular wave number $x = ka$ is given in Viktorov's book [8]. x and y values, calculated for a steel cylinder (bulk wave velocities $V_L = 5910$ m/s and $V_T = 3200$ m/s) are plotted in Fig. 1. An integer value n of ka gives a resonance frequency ω_n. The lowest curve, defined for $n \geqslant 1$, corresponds to the Rayleigh wave and the other, defined for $n \geqslant 0$, to the whispering gallery waves.

Fig. 2 shows, for the Rayleigh mode, the group velocity versus the product ka. As ka tends to infinity, the velocity tends to the value $V_R = 2990$ m/s for a steel plate. The dispersive effect is noticeable for low frequencies such that the Rayleigh wavelength λ_R is larger than $a/2$.

3. Experimental set-up

The surface waves were generated by a Q-switched Nd:YAG laser providing pulses with a 40-ns duration

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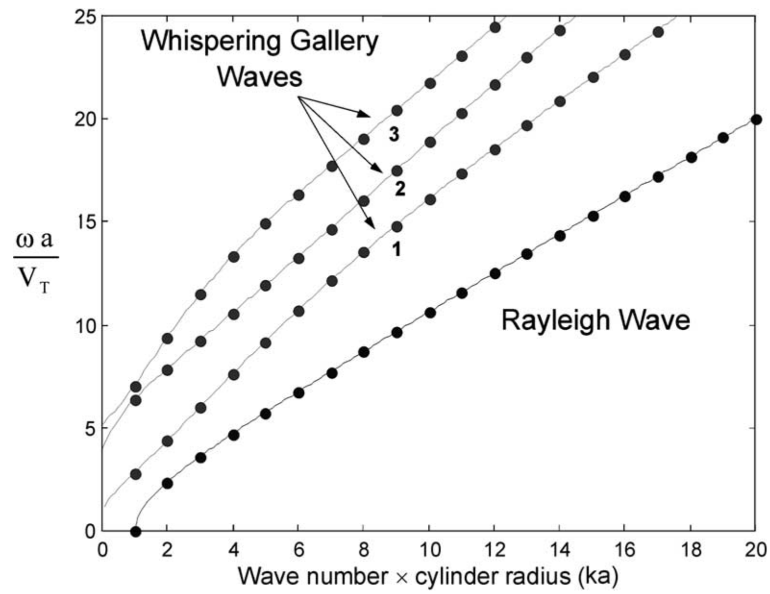

Fig. 1. Surface waves propagating on the free surface of a steel cylinder ($V_L = 5910$ m/s, $V_T = 3200$ m/s). The lowest curve corresponds to the Rayleigh wave, the other curves refer to whispering gallery waves. An integer value n of ka gives resonance frequency ω_n.

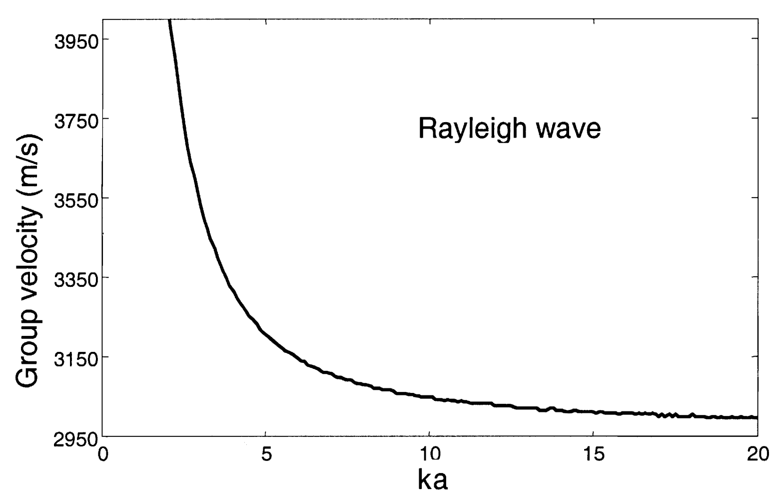

Fig. 2. Rayleigh wave dispersion curve for a steel cylinder.

and a 6-mJ energy. A beam expander and a cylindrical lens (focal length $F = 240$ mm) were used to focus the beam onto a 9-mm width line parallel to the cylinder axis. The mechanical displacement normal to the surface was measured by a heterodyne interferometer [9] equipped with a 100-mW YAG laser (SH 140 optical probe from Thales Laser). The calibration factor, 10 nm/V, was constant in the detection bandwidth (50 kHz–20 MHz). Signals detected by the optical probe are fed into a digital sampling oscilloscope (Tektronix 520D) and transferred to a computer. As shown in Fig. 3, the probe beam is orthogonal to the generation beam. The experiments were performed on steel cylinders of diameter 25 ± 0.1 mm.

4. Experimental results

Fig. 4 shows the signal detected on a cylinder without any defect. Before the first Rayleigh pulse R_1, we observed the head wave (HW) propagating at the longitudinal wave velocity ($V_L > V_R$) and a small depletion (S) at the arrival time of the transverse wave. Whispering gallery modes (WG) appear between R_1 and the second Rayleigh pulse (R_2) which propagates 3/4 turn on the cylinder surface. The rapid evolution of the Rayleigh waveform from a monopolar (R_1) to a dipolar (R_2) waveform demonstrates the dispersive effect due to the curvature of the surface. Low frequency components, travelling faster than high frequency ones, move to the beginning of the R_2 pulse.

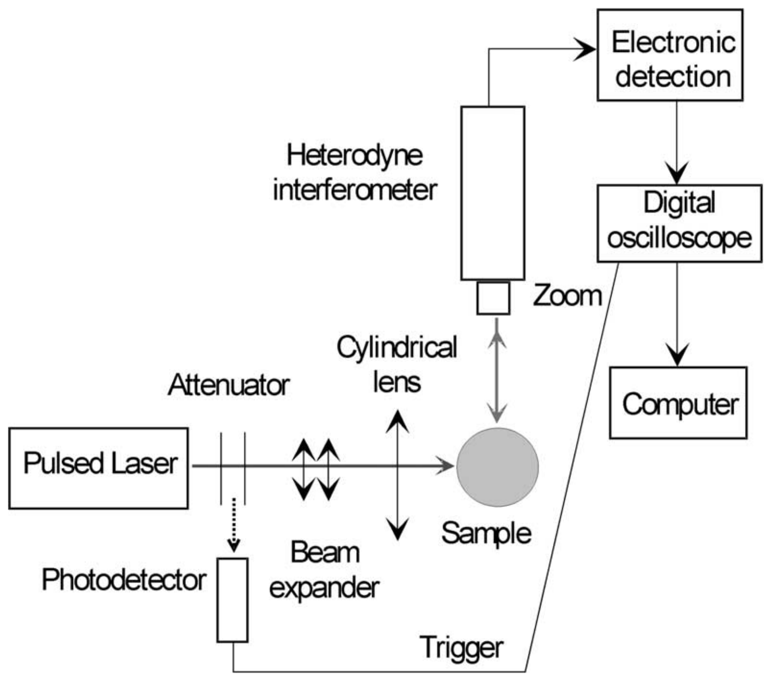

Fig. 3. Experimental set-up.

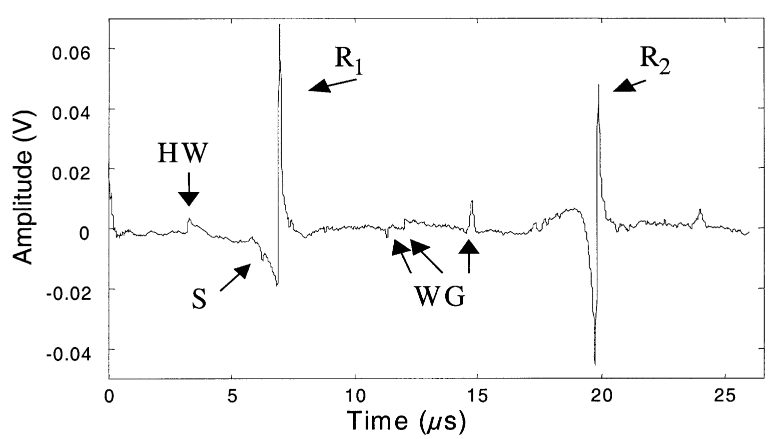

Fig. 4. Pulse waveform detected on a steel cylinder of diameter 25 mm. R refers to Rayleigh wave, HW to the head wave, WG to the whispering gallery waves and S to the shear wave.

Now we investigate the interaction of Rayleigh waves with thin (0.2-mm wide) slots of various depths h. The artificial slots and the thermoelastic line source are parallel to the cylinder axis. We chose this configuration because it corresponds to practical applications and to the simpler case for modelling the interaction between Rayleigh waves and slots [2,10]. The slot and the source make an angle equal to 130°. The time window (26 μs) corresponds to one turn travel time, then the undisturbed (R), the reflected (RR) and the transmitted (TR) Rayleigh pulses can be recorded. Results shown in Fig. 5 are similar to that observed on a plate. According to the mechanism described by Cooper et al. [10], signals RL and RS arise from bulk mode conversion into longitudinal and transverse waves at the tip of the slot. The measured reflection (α) and transmission (β) coefficients are given in Table 1 according to the slot depth h. Defects having depth higher than 0.25 mm are easily detected during the first revolution around the cylinder.

Since the optical probing does not disturb the SAW propagation, we can record many revolutions of the Rayleigh waves. In order to reduce the amplitude of the dispersive low frequency components and the electronic noise, the detection bandwidth was limited from 0.8 to 10 MHz. The signal, sampled at a 100-MHz rate, is displayed over a 500 μs duration which corresponds to

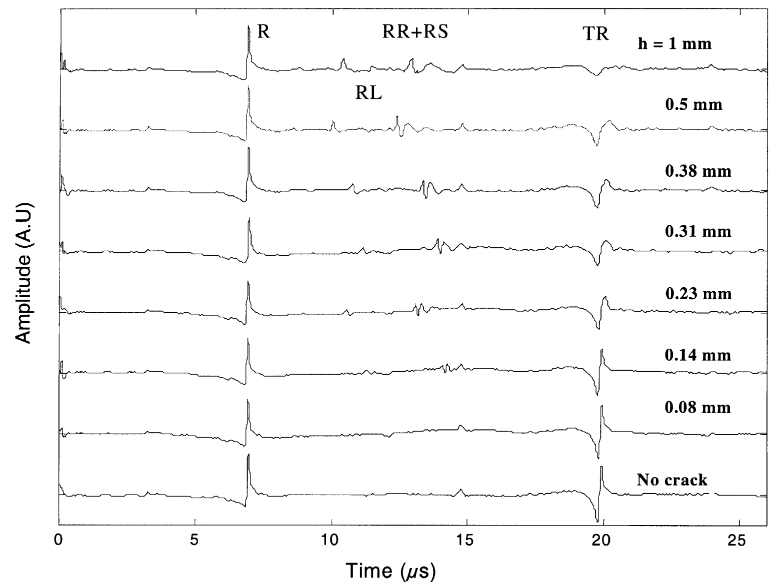

Fig. 5. Interaction of an incident Rayleigh wave (R) with slots of various depth (h).

Table 1

Depth h (mm)	0.08	0.14	0.23	0.31	0.38	0.5	1
Reflection coefficient α (%)	3.4	8	19	23	20	26	23
Transmission coefficient β (%)	93	80	54	33	36	27	3.25

18 turns or 37 Rayleigh wave pulses. In Fig. 6a, it can be observed on the signal acquired on the sample without defect that at a large distance r, the peak-to-peak amplitude varies as $1/\sqrt{r}$. Results of experiments carried out on duraluminum cylinders show almost the same decay in amplitude. We conclude that ultrasonic attenuation and roughness scattering are negligible compared to diffraction effects. The transmitted Rayleigh waves acquired on a cylinder with a 0.14-mm depth slot are strongly attenuated (Fig. 6b). At the end of the signal, the transmitted amplitude almost vanishes. On the other hand, the amplitude of the reflected Rayleigh waves remains constant over the whole signal acquisition duration. Therefore the amplitude ratio between the reflected wave and the transmitted wave increases with the number of propagation revolutions.

In order to describe the phenomenon, we will be primarily interested in waves emitted only towards the right of the line source (Fig. 7). The transmitted waves are characterised by their times of flight $T/4 + (m-1)T$ where m is the number of turns. Their relative amplitudes are β^{m-1}. The echo from the defect appears at a time $T/4 + 2\tau$, where τ corresponds to the time delay

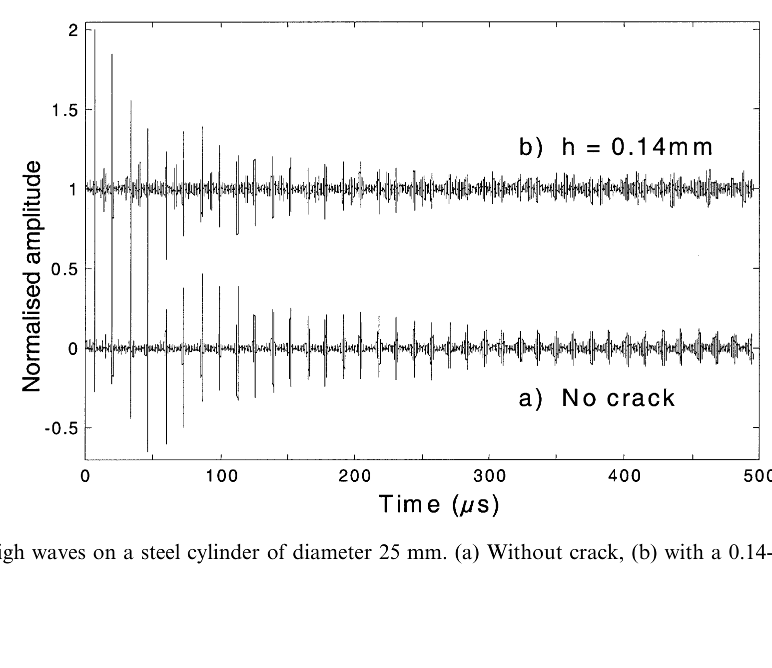

Fig. 6. Rayleigh waves on a steel cylinder of diameter 25 mm. (a) Without crack, (b) with a 0.14-mm depth slot.

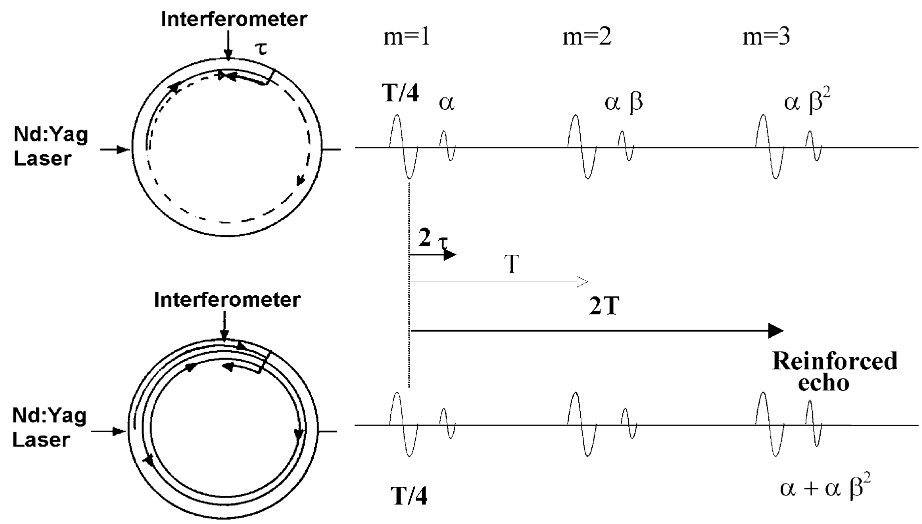

Fig. 7. Description of the cumulative effect on a cylinder.

between the detection point and the defect. The relative amplitude of the first reflected wave detected is α. After a new interaction with the defect, during the following turn, the amplitude of the reflected wave, arriving at time $T/4 + T + 2\tau$, is $\alpha\beta$. On the other hand the reflected wave arriving at time $T/4 + 2T + 2\tau$ takes advantage of two contributions. Classically, the first one comes from the transmitted wave $m = 3$, which gives after reflection the contribution $\alpha\beta^2$. The second one comes from the first reflection which undergoes two total reflections on both sides of the crack (we suppose that the two faces have the same depth). This wave thus brings an additional contribution α to time $T/4 + 2T + 2\tau$. In the same way, with the following turn, we also detect the considered fraction of the transmitted wave $m = 4$ and the additional contribution $\alpha\beta$. In short,

if m odd and $\geqslant 3$, the amplitude of the considered wave is $\sum_{k=0}^{(m-1)/2}\alpha\beta^{2k}$,
if m even and $\geqslant 4$, the amplitude of the considered wave is $\sum_{k=1}^{m/2}\alpha\beta^{2k-1}$.

It should be noted that the same effect exists for the transmitted waves but the contributions brought by the reflected waves are negligible in comparison with the emitted spectrum.

There is thus a cumulative effect which compensates for the attenuation of the reflected waves. Since this phenomenon applies primarily to weak reflective cracks ($\alpha < 0.15$), it makes it possible to highlight low depth cracks.

We must now find a parameter allowing us to estimate the evolution of this amplitude ratio as a function of time. Therefore, we decompose the signal into windows of width $T/2$, centred on each transmitted Rayleigh waves. Then, each window includes a transmitted and a reflected Rayleigh wave. A first method consists in comparing the signal acquired $x(t)$ with a reference signal $y(t)$ obtained on a part without any slot. We calculate the coefficient of correlation Γ, which indicates the degree of resemblance of the two signals detected in the same window N:

$$\Gamma_{xy}(N) = \frac{\max(R_{xy}(\tau))}{\sqrt{R_{xx}(0)R_{xx}(0)}}$$

where R_{xy} and R_{xx} are cross-correlation and auto-correlation functions.

This parameter gives the energy modifications inside this window. Fig. 8 shows the evolution of the coefficient of correlation versus the studied Rayleigh wave N i.e., versus the travel time. The comparison of two parts without crack involves a very slight decrease which can be ascribed to the progressive deterioration of the signal to noise ratio as well as to the amplification of the geometrical differences between the two parts. In the presence of a defect (depth $h = 0.14$ mm), we note a roughly linear decrease of the coefficient. In the same way for $h = 0.08$ mm, the coefficient decrease also linearly until the 18th studied wave. Probably, the geometrical differences dominate the energy differences and produce an additional decrease.

In order to avoid the issue of these geometrical differences, we can evaluate the presence of a crack in a second manner. We acquire two signals on the same part while having carried out a $\pi/2$-rotation of the part between the two acquisitions. Only the positions of the considered waves involve an uncorrelation. Fig. 9 shows the almost stability of the coefficient in the analysis of a part without slot. In the presence of a defect, the decrease is always linear. The slope of uncorrelation is very weak for $h = 0.08$ mm. To accentuate this decrease, we

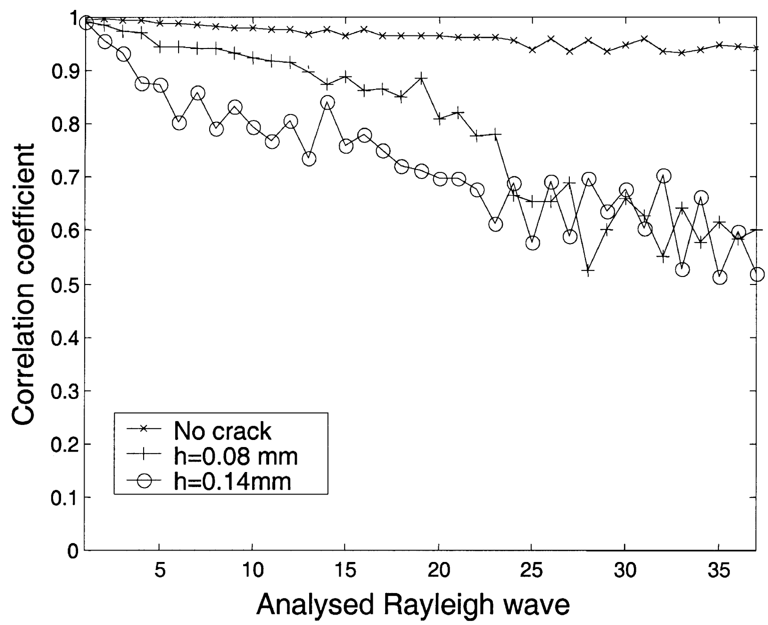

Fig. 8. Evolution of the correlation coefficient versus the analysed Rayleigh wave. First method: comparison with a reference signal.

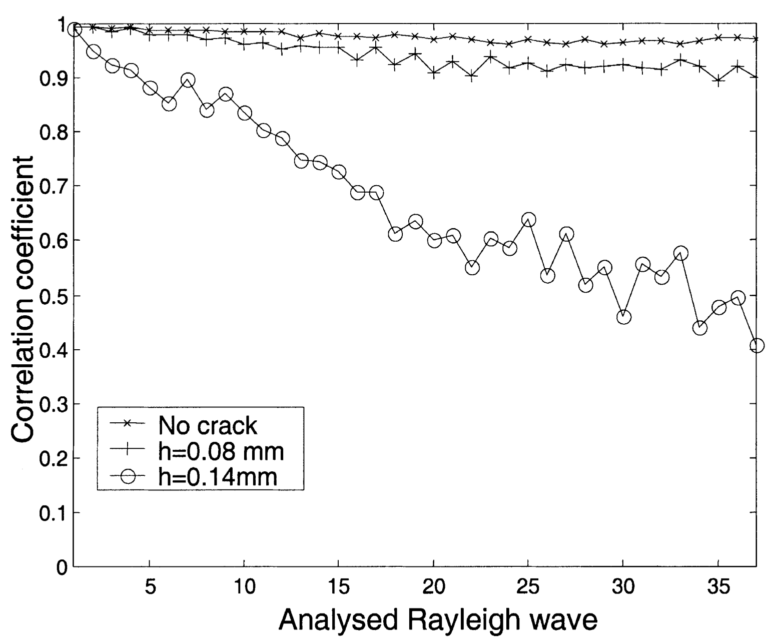

Fig. 9. Evolution of the correlation coefficient. Second method: comparison of two signals acquired on the same cylindrical part.

record a 2-ms signal on the same parts under the same conditions, and we observe 148 Rayleigh waves. Fig. 10 shows that the signals acquired on a part without crack remains identical until the 120th wave. According to the previous results, the defect of depth 0.14 mm produces a linear decrease until the 40th pulse. Then the coefficient remains almost constant around the value threshold 0.4. This value which depends on the signal length and the inspected frequency band corresponds to the correlation coefficient of two white noises. Let us note that, for $h = 0.08$ mm, the cumulative effect is clearly observed for a long travel time: the slope is also linear until the 120th wave. Linear fitting of these various curves gives the dimensionless energy slopes and then the dimensionless amplitude slopes (Table 2). Complementary experiments, where the defect is randomly placed on the

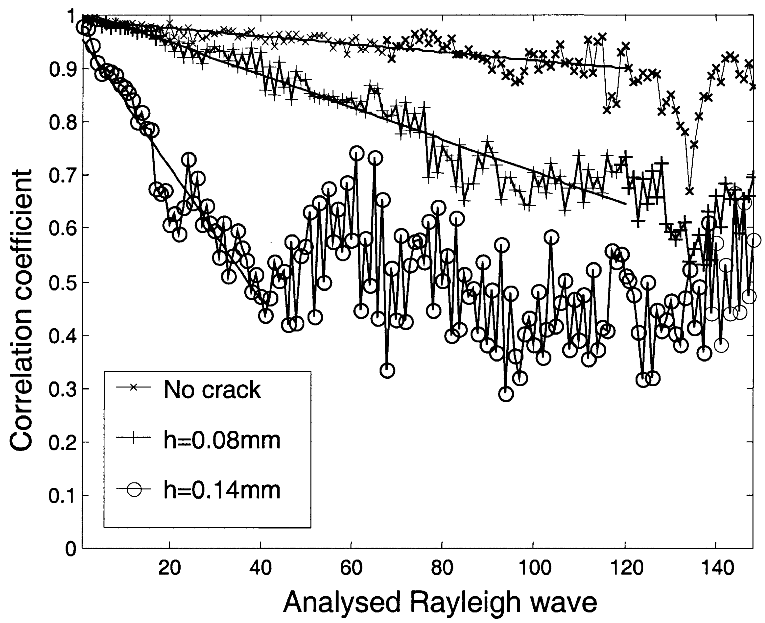

Fig. 10. Second method: comparison of two signals acquired on the same part. Acquisition time: 2 ms.

Table 2

Depth h (mm)	0.0 (No crack)	0.08	0.14
Slope (energy) $\times 10^{-4}$	7.6	30.4	144.4
Slope (amplitude)	0.025	0.055	0.12

section to be inspected, gives the same slope of uncorrelation.

5. Conclusion

The purpose of this study was to analyse the interaction between the Rayleigh waves and a crack on a steel cylinder. By using a pulsed laser as a source of the waves and an heterodyne interferometer as a receiver, placed at 90°, we have shown that it is possible to inspect a section of the cylinder in a single shot and to detect, during the first revolution, defects of depth higher than 0.2 mm. For defects of lower size, we have noted the existence of a cumulative phenomenon on the reflected Rayleigh waves. We have exploited this phenomenon by calculating the evolution of the degree of resemblance of the signals and we clearly distinguished the defects down to 0.08 mm in depth whatever their positions on the section.

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