Study on Characteristic of Thin layer Rubber Based on Ultrasonic Echo Testing

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Abstract:

With ultrasonic echo method, characteristic of rubber thin layer was investigated, and theory of a survey the thin layer medium characteristic of frequency spectral analysis was deduced. A method is proposed to establish restoration function of frequency spectrum ratio of ultrasonic echoes under the condition of substrate material is covered and uncovered with the rubber thin layer. The results show that $H(f)$ contains information on the acoustic properties of the substrate and the thin layer, not only the supersonic wave propagation velocity in the rubber thin layer can be acquired, but also its acoustic impedance and density. The results of this method accord with the time frequency compound method, of which ascertains performance of a thin layer without damaging its usability of a detected component.

Keywords: ultrasonic testing, thin rubber, acoustic impedance, restoration function

1. Introduction

In recent years, the rubber thin layer is extensively applied to the surface of the roller which is used to convey paper. For example, the roller of automatic ticket clipper, mail processing machine, overlaps cash splitter and so forth. At the same time, the rubber thin layer with higher quality is required. Whether the characteristic of the rubber thin layer is controlled reasonably will effect its service life, accuracy of convey counting and reliability directly. Therefore, it is indispensable to evaluate the surface characteristic of a roller.

However, conventional testing method to the thin layer characteristic is complex and its testing cycle is long and also has to damage the thin layer component to be tested [1]. The ultrasonic testing echo signal method ascertains performance of a thin layer without damaging its usability of a tested component. This method has such advantages as high accuracy and rapid testing [2]. N. F. Haines etc [3] examined the epoxy resin lining on the surface of aluminum component and resorted to the reflection coefficient spectrum to obtain the acoustic velocity, density and decay coefficient in the thin layer. But because the thin layer's thickness is much shorter than the length of ultrasonic wave, multiple echo don't occur in thin layers at a sufficient number of times to produce a resonance spectrum [4], therefore, the conventional methods can't evaluate and detect thin layer's characteristic.

This article will discuss the method of frequency spectrum analysis which is applied to conduct evaluation and detection of a thin layer. A frequency domain recovery function is deduced by using the ratio of frequency spectrum that is created by the echo signal within substrate material, which is covered and uncovered with rubber thin layer. And an ultrasonic inspection method to evaluate thin layer's characteristic is also obtained.

2. The theory of ultrasonic echo propagation in thin layer

Fig.1 shows the geometry of the system to be analyzed, where the system is composed of three mediums: substrate (sound velocity υ_1, wave number k_1, density ρ_1, acoustic impedanceZ_1,), thin layer (sound velocity υ_2, wave number k_2, density ρ_2, acoustic impedanceZ_2,), air (sound velocity υ_3, wave number k_3, density ρ_3, acoustic impedanceZ_3,). The boundaries of three mediums are planes parallel to each other; the thin layers adhere perfectly to the substrate and the absorption of the energy of propagation waves is negligible due to the thinness of the thin layer, and acoustic impedance Z_3 of air is zero. Reflection coefficients and transmission coefficients of the ultrasonic wave are R and T .These terms are expressed according to principle of reflection and transmission [5]

$$R_1 = (Z_2 - Z_1)/(Z_1 + Z_2), T_1 = (2Z_1)/(Z_1 + Z_2)$$
$$R_2 = -R_1, T_2 = (2Z_2)/(Z_1 + Z_2) \qquad (1)$$
$$T_1 = 1 - R_1, T_2 = 1 - R_2$$

where, R_1 and T_1 are the reflection coefficients and transmission coefficients from the substrate to the thin layer, and from the thin layer to the substrate as R_2 and T_2 respectively.

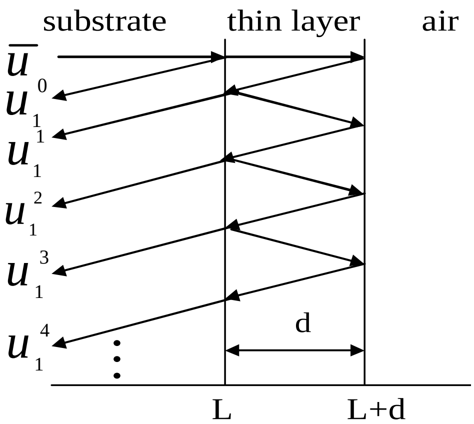

Fig. 1. Schematic illustration of the model of reflection of ultrasonic wave by a thin layer.

Incident wave is planes longitudinal wave, which propagate upright between two boundaries [6, 7].

$$\bar{u}(t) = A_1 \exp(ik_1 x - i\omega t) \qquad (2)$$

A_1 is incident wave amplitude. Echo and transmission wave located at the boundary the substrate and the thin layer X = L are expressed as follow

$$u_1^0 = A_1 R_1 \exp(-ik_1 x - i\omega t)$$
$$u_2 = A_1 T_1 \exp(ik_2 x - i\omega t) \qquad (3)$$
$$u_1^1 = A_1 T_1 T_2 \exp(ik_2 \cdot 2d - ik_1 x - i\omega t)$$

L L L

We can obtain ultrasonic echo expression in the substrate without the thin layer

$$u(t) = A_1 \exp(-ik_1 x - i\omega t) \qquad (4)$$

3. Testing of thin layer characteristic by frequency spectrum and simulation results

3.1. Building restoration function

It can be from Fig.1 that when ultrasonic incident wave located at the boundary the substrate and the thin layer, reflection echoes will come into existence at up-surface of the thin layer firstly, which denotes u_1^0. A portion of ultrasonic incident wave that continues propagate in the thin layer engender echo when ultrasonic incident wave barge up against down-surface besides reflection echo, according to principle of reflection and transmission. We can obtain echo of backtrack sensor, if multiple reflections echoes u_1^1、$u_1^2 \ldots\ldots u_1^n$ that come from down- surface of the thin layer add one after the other

$$r(t) = u_1^0 + u_1^1 + u_1^2 \ldots\ldots + u_1^n \qquad (5)$$

If propagation time of the wave in the thin layer with sound velocity υ_2 is denoted by τ, the time of echo u arrival at sensor without thin layer earlier $(2d \cdot N)/\upsilon_2$ than multiple reflections echoes u_1^n of down-surface with thin layer, at the same time, $(2d \cdot N)/\upsilon_2$ is denoted u_1^0. Amplitude change following invariable principle. If we define that amplitude of u is unit amplitude, echoes u_1^n amplitude of the thin layer down- surface are summarized as follow

$$K_n = T_1 T_2 (-R_1)^{n-1}, \quad n = 1, 2 \cdots\cdots N \tag{6}$$

Substituting eqs(4) (5) and (6) into eq(7)

$$r(t) = A_1 R_1 \exp(-ik_1 x - i\omega t) + \sum_{n=1}^{\infty} K_n A_1 \cdot \exp(-ik_1 x - i\omega t) \cdot \exp(-2nik_2 d) \tag{7}$$

We known that $k_2 \cdot 2d = 2\pi f \tau$, and $r(t)$ is changed with Fourier transform.

$$R(f) = U(f)[R_1 + \sum_{n=1}^{\infty} K_n \cdot \exp(-2i\pi f n\tau)] \tag{8}$$

where, $U(f)$ is Fourier transform of $u(t)$. We define $H(f) = R(f)/U(f)$, then eq(8) change into eq(9)

$$H(f) = R_1 + \frac{T_1 T_2 \cdot \exp(-2i\pi f \tau)}{1 + R_1 \cdot \exp(-2i\pi f \tau)} \tag{9}$$

where, $H(f)$ is restoration function, if we put in the above equation

$$\frac{(R_1 + (T_1 T_2 \times \exp(-2i\pi f \tau)))}{(1 + R_1 \times \exp(-2i\pi f \tau))} = R(f) \times \exp(-i\theta(f)) \tag{10}$$

where, $R(f)$ is always real and positive , we can obtain $R(f) = 1$, $u(t)$ is ultrasonic echo wave without thin layer. Eq(9) is transformed

$$\cos\theta(f) = \frac{Z_1^2 - Z_2^2 + (Z_1^2 + Z_2^2) \cdot \cos 2\pi f \tau}{Z_1^2 + Z_2^2 + (Z_1^2 - Z_2^2) \cdot \cos 2\pi f \tau}, \qquad \sin\theta(f) = \frac{2Z_1 Z_2 \cdot \sin 2\pi f \tau}{Z_1^2 + Z_2^2 + (Z_1^2 - Z_2^2) \cdot \cos 2\pi f \tau} \tag{11}$$

Substituting eqs. (9) and (11) into eq.(12)

$$H(f) = \frac{Z_1^2 - Z_2^2 + (Z_1^2 + Z_2^2) \cdot \cos 2\pi f \tau}{Z_1^2 + Z_2^2 + (Z_1^2 - Z_2^2) \cdot \cos 2\pi f \tau} - i \cdot \frac{2Z_1 Z_2 \cdot \sin 2\pi f \tau}{Z_1^2 + Z_2^2 + (Z_1^2 - Z_2^2) \cdot \cos 2\pi f \tau} \tag{12}$$

Formula (12) contains information on the acoustic properties of the substrate and the thin layer. We could expect to extract these properties by analyzing $H(f)$, include sound velocity υ_2 in the thin layer and density ρ_2 and so on, where $\cos\theta(f)$、$\sin\theta(f)$ are periodical function, and both of their periods are $2\pi/\tau$, τ is twice as long as the one during which ultrasonic travels in the rubber thin layer. Because thickness d is invariable, τ is fixed value. If we choose $2\pi f\tau = n\pi$, therefore, $\cos\theta(f) = -1$, where, n denotes a positive integer. We can assume $n = 1$, then frequency corresponding f' to the first minimum of $\cos\theta(f)$ figures out, and $\tau = 1/(2f')$, τ is obtained, so sound velocity in the thin layer υ_2 can be obtained. We can assume $\sin\theta(f) = 1$, acoustic impedance ratio of the thin layer and the substrate can be obtained. Because Z_1 is known (It can be obtained when substrate by ultrasonic testing echo without the thin layer [5]), Z_2 can be obtained. On account of $Z_2 = \rho_2 \cdot \upsilon_2$ and $\upsilon_2 = 2d/\tau$, therefore, $\rho_2 = (Z_2 \cdot \tau)/(2d)$ and $E_2 = \rho_2 \cdot \upsilon_2^2$, we can obtain the thin layer density ρ_2, modulus of elasticity E_2.

3.2. Simulation results

With PZflex finite element analysis software, the thin layers which thicknesses are 0.3mm、0.6mm、0.9mm are detected by ultrasonic echo respectively, as a result simulation data of ultrasonic echo were acquired. Simulations parameters include mean frequency of sensor is 1MHz and sampling frequency is 250MHz. The thin layer echo signal for 0.3mm、0.6mm、0.9mm thickness (a) and restoration function $H(f)$ (b) are shown in Fig2~Fig4. It can be seen from Fig2a~Fig4a that multiple echoes in each waveform reflected by the thin layer can not be separated. A frequency domain recovery function $H(f)$ is deduced by using the ratio of frequency spectrum that is created by the echo signal within substrate material, which is covered or uncovered with the thin layer, where real line denote $\cos\theta(f)$, similarly broken line denote $\sin\theta(f)$. We can know that periods of $\cos\theta(f)$、$\sin\theta(f)$ increase with the increase in the thin layer thicknesses from Fig.2b~Fig5b, which is accord to the resultant of analytical formula.

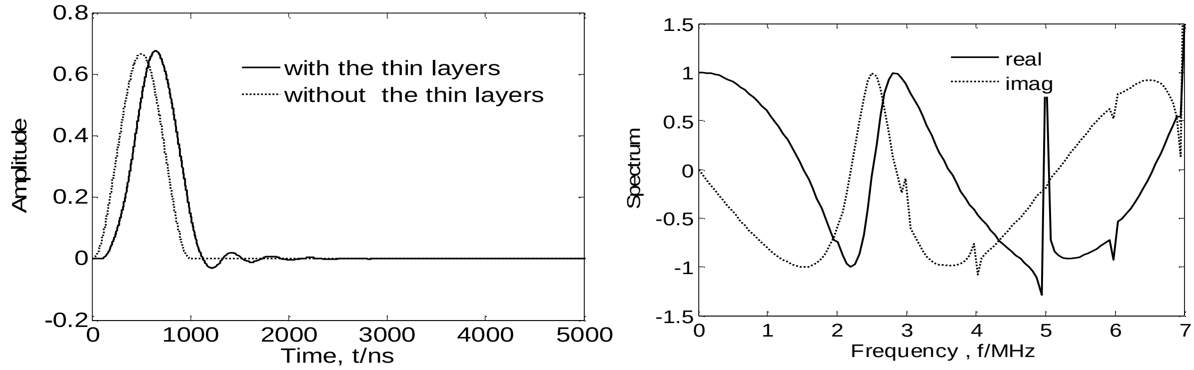

Fig.2. Ultrasonic detecting for 0.3mm echo waves and restoration function $H(f)$

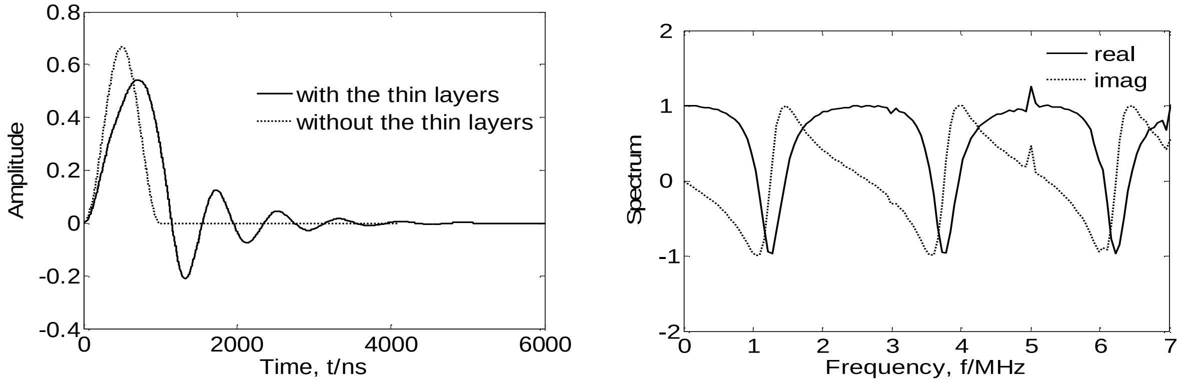

Fig.3. Ultrasonic detecting for 0.6mm echo waves and restoration function $H(f)$

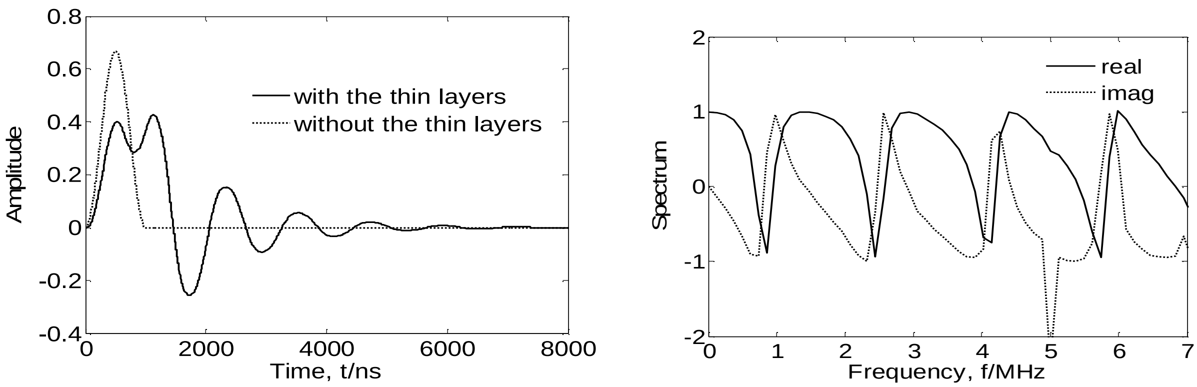

Fig.4. Ultrasonic detecting for 0.9mm echo waves and restoration function $H(f)$

With expressions (11) we can obtain physics characteristic of the thin layer, include velocity of ultrasonic in the thin layer, acoustic impedance and density etc. Table 1 presents the results of the analysis. Relationship between the propagation time in the thin layer and their thickness are shown in Fig 5. The propagation time τ is proportional to thickness d using the least-squares method

$$d = 0.06(\pm 0.023) + 1.66(\pm 0.05)\tau \tag{13}$$

They are the straight line relationship between variables from expressions (12). This means is applicable to the sound velocity measurements for the thin layers $2d/\tau = 3.32(\pm 0.1)$. The accuracy of the value for sound velocity in thin layer is within 1%.

Table 1 Results of characteristic of thin layer with frequency analysis

No	d (mm)	f' (MHz)	τ (us)	v_2 (mm/us)	ρ_2 (g/cm^3)	E_2
1	0.3	2.25	0.22	2.73	1.1	8.2×10^9
2	0.6	1.28	0.39	3.07	1.2	11.3×10^9
3	0.9	0.85	0.58	3.10	1.2	11.5×10^9

4. Experimental results and discussion

A schematic diagram for the measurement is shown in Fig.6, which indicates to detect the rubber thin layer characteristic of the roller surface of overlaps cash splitter. Ultrasonic testing device is material superficial sound examine that is manufactured by TOSHIBA, namely USH-B. Performance parameters of device technology: rectangle pulse、pulse/receiver of frequency spectrum70kHz～15MHz, sampling rate 100MHz. Substrate of thickness 30mm is epoxy, the thin layer is about 1mm Ethylene- Propylene-Diene Monomer (EPDM). Coupler of colophony and rubber is water. Y-1, Y-2, Y-3 are used to denote as choosing rubber the thin layers with three different stuffing. Y-1 is treated with nothing; Y-2 is strengthener of Si; Y-3 is strengthener of carbon. We define the two mean frequencies to detect three rubber thin layers as A (1MHz resonance sensor) and B (1-8MHz resonance sensor). Fig.7 and Fig.8 can tell that mean frequency 1MHz and 1-8MHz detect echo waveforms forY-3 and restoration function $H(f)$, respectively. Reflected waves that stern of which without miscellaneous waves indicate broken line without the rubber thin layer, moreover, real line indicate reflected waves with the rubber thin layer, stern of which take on thin miscellaneous waves due to ultrasonic multiple reflection in the thin layer as illustrated in Fig 7(a) and 8(a), which contain mechanics parameters particular information of the rubber thin layer [8] (for instance density and modulus of elasticity etc). Restoration function curve can be obtained by frequency analysis for signal of Fig 7(a) and 8(a). We apply the theory developed in §2.1 elasticity modulus of the thin layer and propagation velocity of ultrasonic wave in the thin layer. Table 2 presents the results of the analysis. When mean frequency of senor is 1MHz, curve of Fig.7(b) can be acquired. When frequency is rather high, amplitude rapidly decrease with number of frequency increasing. Curve appears Singular point of 'saw tooth' figure round 2.3MHz. Moreover, Fig.8(b) shows that waveforms can be obtain by mean frequency 1-8 MHz broadband sensor, which in the frequency spectrum is smooth.

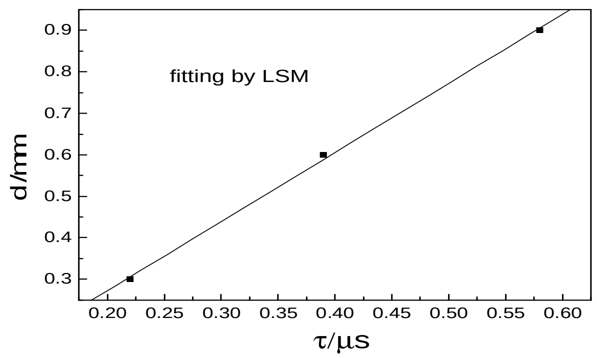

Fig.5. Relationship between the thicknesses d and the propagation time τ

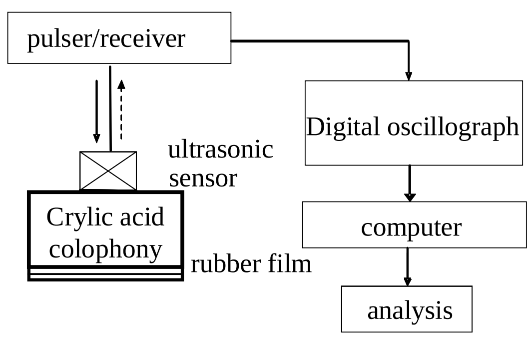

Fig.6. Schematic diagram for the measurement system for ultrasonic

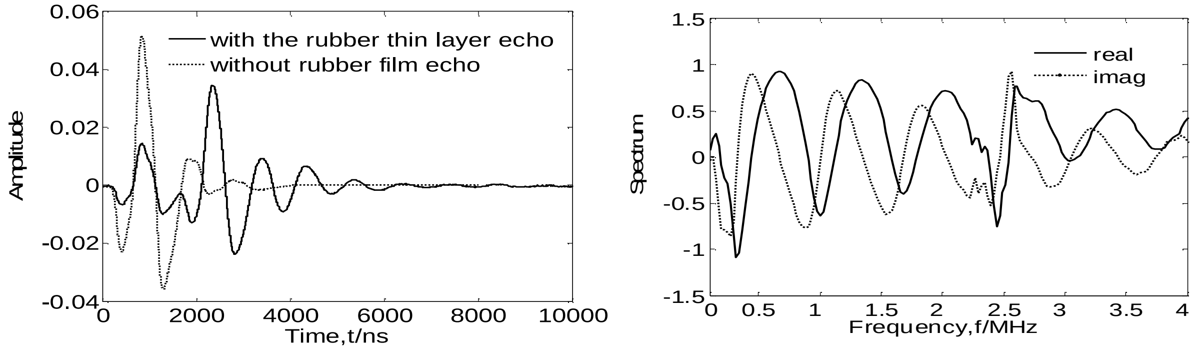

Fig.7. Mean frequency 1MHz detecting echo waveforms for Y-3 and restoration function $H(f)$

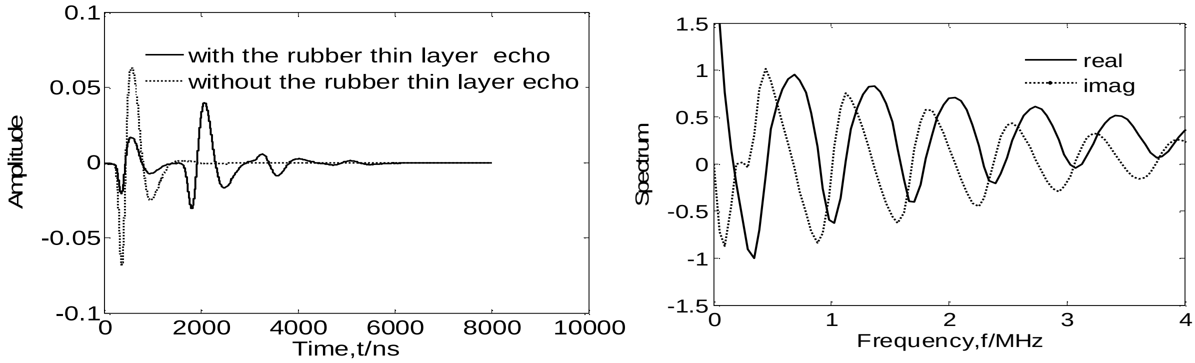

Fig.8. Mean frequency 1-8MHz detecting echo waveforms for Y-3 echo waves and restoration function $H(f)$

Table 2 Results of characteristic of rubber thin layer with frequency analysis

No		d (mm)	f' (MHz)	τ (us)	v_2 (mm/us)	ρ_2 (g/cm^3)	E_2
	Y-1	1.008	0.41	1.21	1.67	1.14	3.2×10^9
A	Y-2	1.318	0.29	1.72	1.53	1.09	2.6×10^9
	Y-3	1.206	0.34	1.47	1.64	0.90	2.4×10^9
	Y-1	1.008	0.37	1.35	1.49	1.06	2.4×10^9
B	Y-2	1.318	0.30	1.67	1.57	0.90	2.2×10^9
	Y-3	1.206	0.33	1.52	1.59	1.05	2.6×10^9

5. Conclusions

Characteristic of the rubber thin layer is investigated base on ultrasonic echo method. A method is proposed to establish restoration function of frequency spectrum ratio with the and without thin layer ultrasonic echo. With this method, propagation velocity of ultrasonic wave in the thin layer, density and modulus of elasticity are estimated. This method avoids the conventional one can't evaluate and detect performance of the thin layer that its thickness to be smaller than far the wave length, which ascertains performance of a thin layer without damaging its usability of a detected component.

References

[1] PATRICK J. GOLDEN， MICHAEL J. SHEPARD. Life prediction of fretting fatigue with advanced surface treatments. Materials Science and Engineering: A 15 (2007)15-22．

[2] ROBIN P， ROMMERT， JAN M． A comparison of models for measurable deterioration：An application to coatings on steel structures．Reliability Engineering & System Safety，92(12)(2007) 1635-1650．

[3] HAINES N F， BELL J C， M CLNTYRE P J．The application of broadband ultrasonic spectroscopy to the study of layered media[J]．The Journal of the Acoustical Society of America, 64 (6)(1978)1645-1651．

[4] COX R L，D.P.ALMOND，H.REITER．Ultrasonic attenuation in plasma-sprayed coating materials [J]．Ultrasonics， January，1981，17-22．

[5] SHINOBU，SUGASAWA．Measurements of Elastics of Plasma-Sprayed Coatings Using Bulk Ultrasonic Pulses[J]．Japanese Journal of Applied Physics， 2004，43：3109-3114．

[6] Nondestructive Testing Institution of Chinese Mechanical Engineering Society，Ultrasonic testing．Mechanical Industry Press, Beijing, 2000．

[7] CHANG JUN JIE， NI Q， IWAMOTO M． Physical Properties of Thin Layer Material Evaluated by

Ultrasonic Propagation [J] . JSMS Composites , 2005 , 34 : 196-200 .
[8] J.J. Chang, Evaluation of the Al_2O_3 Coating by Ultrasonic Wave Propagation Character, Material for mechanical engineering , 31(2)(2007) 62-64 .