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Effect of Temperature on Ultrasonic Velocities, Attenuations, Reflection and Transmission Coefficients between Motor Oil and Carbon Steel Estimated by Pulse-echo Technique of Ultrasonic Testing Method

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Abstract: In this research, the dependence of the velocities and the absorption coefficients of ultrasonic waves propagated in 1018 low carbon steel on temperature range from 0 ^{o}C to 50 ^{o}C was investigated. The coefficients of the temperature dependence of the ultrasonic longitudinal wave and ultrasonic shear wave were estimated to be -0.8 m/s.^{o}C and -0.44m/s.^{o}C, respectively. The acoustic impedances of this carbon steel were also investigated and effected much by temperature. Simultaneous, the effect of temperature on the acoustic impedances and ultrasonic attenuations of the motor oil was also determined. As the results, reflection and transmission coefficients at the interface between the carbon steel and motor oil were estimated. It is concluded that the ultrasonic attenuation of the motor oil is one of the main reasons for the behavior of the ultrasonic absorption coefficients propagated in the steel sample.

Keywords: Ultrasonic, Nondestructive Testing, Reflection and Transmission coefficients, Longitudinal Wave, Shear Wave, Ultrasonic Velocity, Low carbon steel, Ultrasonic Attenuation, Reflection and Transmission Coefficients, Pulse-echo Technique

1. Introduction

Non-destructive testing methods are very popularly used to evaluate the properties of materials, components or systems without damages. The most common application is checking of defects. When the defects are detected, their location, dimension, orientation, and shape are required to determine. Nowadays, there are several non-destructive techniques, such as X-ray images [1], thermographic imaging [2], ultrasonic testing methods [3], *etc.* In these methods, the ultrasonic testing method is widely used to analyze and characterize some important properties of materials such as microstructure, mechanical properties of materials, thermal damage [4-8].

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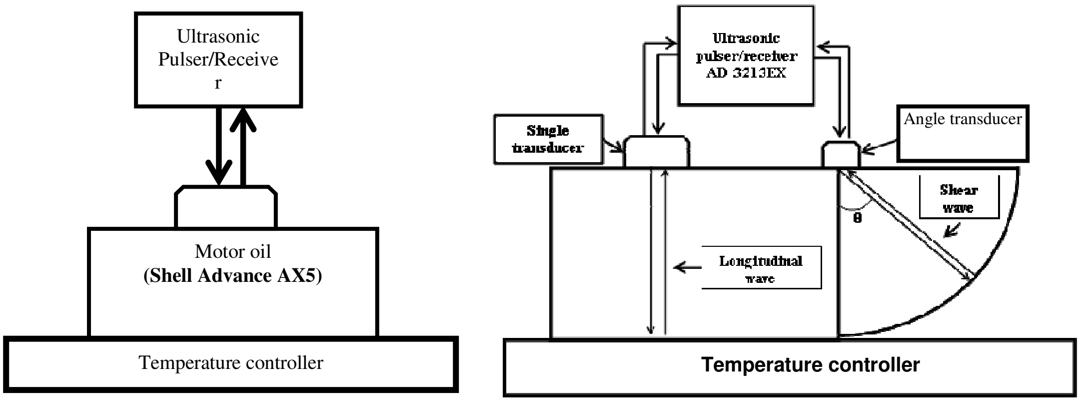
Recently, carbon steels have many applications in different fields such as ship building, goods fabrication, home appliances, ship sides, low carbon wire; the reason for these popular applications is due to the good properties of the steel materials such as their good strength, good toughness and ductility [9]. In order to investigate properties of steel, ultrasonic non-destructive testing method was widely used. A. Ruiz *et al* used the ultrasonic method for early detection of thermal damage in steel [8], Vera Lúcia de Araújo Freitas *et al* showed that the nondestructive characterization of microstructures and determination of elastic properties of the carbon steel can be utilized by the ultrasonic method [10]. Changzhou Yan *et al* and Liu Zenghua *et al* reported the dependences of the ultrasonic properties of steels on temperature [11, 12]. Notably, in the direct contact method of pulse-echo technique, if there is an air gap between test object and the ultrasonic transducer, the ultrasonic energy is highly loosed. Therefore, a couplant material between ultrasonic transducer and steel sample is needed. Some materials could be used as couplant material such as water, motor oil, glycerin, silicon oil, *etc.* In these couplant materials, the motor oil is suitable couplant material between the transducer and steel sample because it would not rust or corrode the steel's surface.

In this research, effect of temperature on properties of ultrasound propagated in motor oil were investigated. Furthermore, velocities and attenuation of ultrasonic wave propagated in the low carbon steel AISI 1018 test sample were characterized with sample's temperature increasing from 0 to 50 ^{o}C. Based on the experimental longitudinal ultrasonic velocities in the motor oil and carbon steel, the acoustic impedances of these materials were estimated. And then reflection and transmission coefficients at boundary between them were also estimated.

2. Experimental methods

Type 1018 low carbon steel was used as a test sample in this study with the following chemical compositions in %wt: 0.17 C, 0.816 Mn, 0.01 P, 0.005 S, 0.07 Ni, 0.06 CR, 0.01 Mo, 0.2 Cu, 0.022 Al, and 0.01 N. The mass density of this steel type is 7800 kg/m^3. The motor oil of Shell Advance AX5 was used as couplant material between ultrasonic transducers and steel sample.



(a) (b

Figure 1. The experimental set-up of ultrasonic measurements propagated in (a) the motor oil (Shell Advance AX5) and (b) in AISI 1018 low carbon steel.

Figure 1(a) shows the experimental set-up for ultrasonic measurement of longitudinal velocities propagated in the motor oil with its basic properties shown as Table 1. Figure 1(b) shows the schematic diagram of the experimental set-up to investigate the ultrasonic properties of the AISI 1018 steel sample. In these diagrams, the Ultrasonic Flaw Detector AD 3213EX was used as a pulser/receiver ultrasonic system. The pulse-echo technique and direct contact method were used to characterize the velocities and attenuation of the ultrasound. A single transducer with 5 MHz center frequency was used to generate an ultrasound and then receive echo for the ultrasonic longitudinal wave; otherwise, a single 70^o angle transducer with 5 MHz center frequency was used for ultrasonic shear wave measurements. The temperature of samples was controlled by the temperature controller FOX2005 and Peltier chips with ± 0.2 ^oC of accuracy. The samples' temperature changed in the range of 0 to 50 ^oC with 5 ^oC for each raising step and waiting about 20 minutes for each step to obtain temperature stability. The samples' temperature must be smaller than 55 ^oC because the ultrasonic transducers could be damaged with high temperature [13].

Table 1. Properties of motor oil Shell Advanced AX5 [14, 15]

Density (kg/m^3) @ 15 ^oC	870
Pour Point (^oC)	-30
Kinetic viscosity (mm^2/s) @40 ^oC	106.2
Kinetic viscosity (mm^2/s) @100 ^oC	14.3
Volumetric thermal expansion (1/^oC)	0.0007

3. Temperature Dependence of Ultrasonic Wave Propagation

The mechanical properties and dimensions of a steel sample will change because of its temperature dependence. A linear dependence of each property on temperature is assumed as following equation [12, 16, 17]:

$$P(T) = P(T_0) + \frac{\partial P(T)}{\partial T}\Delta T , \qquad (1)$$

where P is one of the mechanical properties of sample, such as Young's modulus E, Poisson's Ratio v, shear modulus G, and bulk modulus K; T is sample's temperature, T_0 is reference temperature, and $\frac{\partial P(T)}{\partial T}$ is temperature dependence coefficient, i.e., sensitivity of the material property of sample to temperature.

The dependence of ultrasonic wave velocities on temperature can be obtained by following relations [10, 17]

$$C_l = \sqrt{\frac{E(1-v)}{\rho(1+v)(1-2v)}}, \qquad (2)$$

$$C_t = \sqrt{\frac{G}{\rho}}, \qquad (3)$$

where C_l and C_t are velocity of ultrasonic longitudinal wave and one of ultrasonic shear wave, respectively; ρ is mass density of material, and G is modulus of shear. And acoustic impedance Z of material can be obtained as

$$Z = \rho C \qquad (4)$$

where C is velocity of ultrasound propagated in sample and can be determined by pulse-echo technique using relation

$$C = \frac{2d}{t} \qquad (5)$$

where d is thickness of sample and t is transit time of ultrasonic wave.

In the case of liquid materials, their bulk modulus K could be obtained as the following relation [18]

$$K = \rho C^2 \qquad (6)$$

The attenuation coefficient α of the ultrasonic waves propagated in elastic materials can be obtained by measuring the peak amplitude of the echoes from observed time domain traces by the relation [19, 20]

$$\alpha = \frac{-20}{2(m-n)d}\log\left(\frac{I_m}{I_n}\right) \qquad (7)$$

where I_n and I_m are the the maximum amplitude of the m^{th} and n^{th} pulse echoes, d is the thickness of sample. Notably, thermal expansion α of carbon steel is small value of 1.2×10^{-5} /°C [21]; therefore, the temperature dependence of mass density ρ of this 1018 carbon steel sample will be ignored and considered as constant value of 7800 kg/m^3 within a range of temperature from 0 to 50 °C [9, 12].

Furthermore, when the ultrasonic wave transmits from medium 1 to medium 2, reflection and transmission coefficients at boundary between them of ultrasonic wave could be estimated as:

$$R = \frac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2} \qquad (8)$$

$$T = 1 - R \qquad (9)$$

where R and T are the reflection coefficient and transmission one; Z_1 and Z_2 are the acoustic impedance of the medium 1 and the medium 2, respectively; these acoustic impedances could be calculated by using Eq. (4) when the ultrasonic velocities and mass densities of mediums were known.

4. Results and discussion

Firstly, the effect of temperature on ultrasonic properties of motor oil Shell Advance AX5 was investigated. The experiment set-up was shown in Figure 1(a), the thickness of this motor oil layer was fixed to be 4 cm. By using pulse-echo technique, the velocities and attenuation of the ultrasonic wave propagated in this oil were obtained and shown in Table 2. When the temperature of motor oil increased from 0 to 50^{o}C, the ultrasonic velocities decreased from 1476 down to 1289 m/s with accuracy of ±1 m/s; the thermal coefficient of these experimental velocities was determined to be -3.65 m/s.^{o}C by using linear fitting approach (Figure 2.(a)). From Eq. (4), bulk modulus K_{oil} of this motor oil was also calculated to be in the range from 1.915 down to 1.412 GPa, and the coefficient of temperature dependence of this bulk modulus is about - 0.01 GPa/^{o}C (Figure 2.(b)). Simultaneously, acoustic impedance of this oil was investigated to be in the range of 12.97 $\times 10^5$ down to 10.95 $\times 10^5$ kg/m^2.s, it is clearly observed that the acoustic impedance of this oil is also linearly dependent on the temperature with its thermal coefficient being about -0.04$\times 10^5$ kg/m^2.s.^{o}C (Figure 2(c)).

Table 2. Ultrasonic properties of the motor oil Shell Advance AX5

The Oil's Temperature T (^oC)	Ultrasonic velocity C_{oil} (m/s)	Bulk modulus K_{oil} (GPa)	Acoustic impedance Z_1 ($\times 10^5\ kg/m^2.s$)	Attenuation α_{oil} (dB/cm)
0	1476	1.915	12.97	4.718
5	1433	1.800	12.56	4.308
10	1414	1.746	12.35	4.312
15	1393	1.687	12.12	3.720
20	1384	1.661	12.00	3.486
25	1356	1.589	11.72	3.642
30	1333	1.531	11.48	3.389
35	1317	1.487	11.30	3.062
40	1303	1.452	11.14	3.071
45	1298	1.436	11.06	2.810
50	1290	1.412	10.95	2.708

The attenuations of ultrasound propagated in the motor oil was also clarified by using Eq. (7) for the echo-peaks of the pulse-echo technique. The effect of temperature on these ultrasonic attenuations was clearly shown in Figure **2**(d). It was seen that when motor oil's temperature increased from 0 to 50 ^{o}C, the attenuation α_{oil} of the ultrasonic wave decreased from 4.718 down to 2.708 dB/cm. The well-known description of the ultrasonic attenuation α propagated in liquid material is given by [22]

$$\frac{\alpha}{f^2} = 2\pi^2 \frac{\eta}{\rho C^3} \qquad (10)$$

where f is frequency of the ultrasonic wave, C is ultrasonic velocity, and η is the viscosity of liquid material. This equation showed that the ultrasonic attenuation propagated in liquid materials is strongly depended on ratio of η/C^3. Notably, the dynamic viscosity of the motor oil is effected much by temperature and it was decreased about 7.4 times when the oil's temperature increased from 40 to 100 ^{o}C (Table 1). While the decrease of velocity is small as 12% when the oil's temperature increased from 0 to 50 °C. Therefore, it is believed that the change of viscosity of the motor oil is a main reason of the behavior of this ultrasonic attenuation as shown in Figure 2(d).

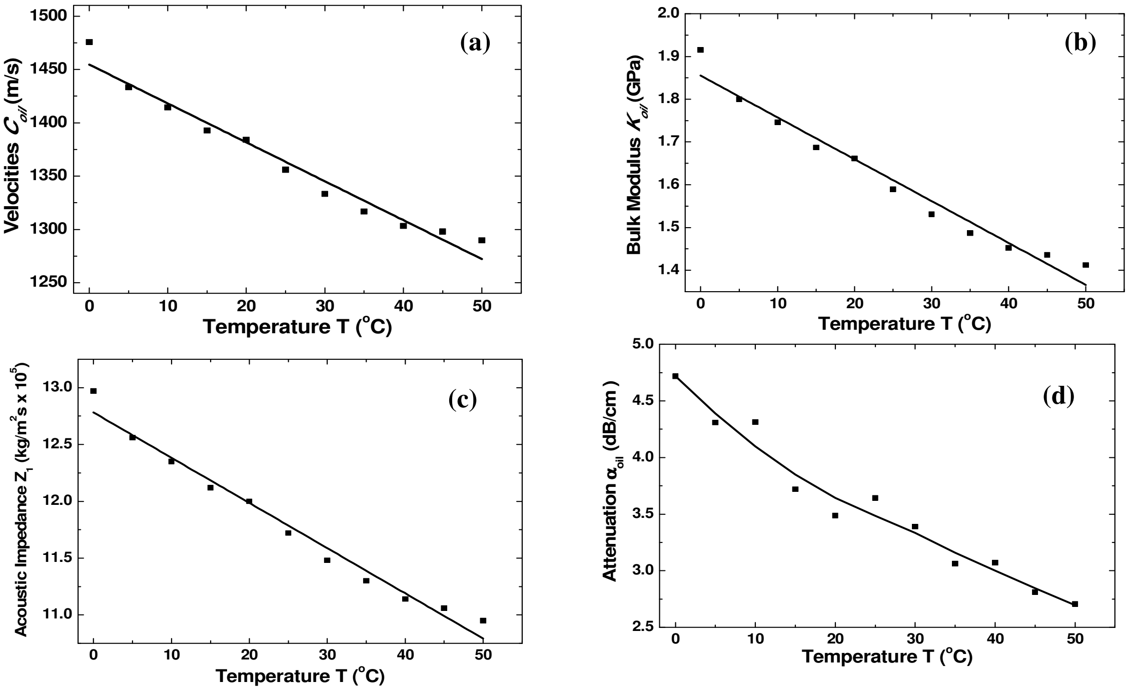


Figure 2. The experimental ultrasonic velocities (a), bulk modulus (b), acoustic impedance (c), and attenuation of ultrasound propagated in motor oil vs temperature.

Secondly, the influence of temperature on characteristics of ultrasonic wave propagated in the AISI 1018 low carbon steel was also characterized. The length change of propagation distance in steel sample of ultrasonic waves is linear with temperature and could be expressed as [12, 21]

$$\Delta l = l_T - l_{T_o} = \alpha(T - T_o)l_{T_o}, \qquad (11)$$

where l_{To} and l_T are reference and final length for temperature changing from T_o to T, respectively. For example, with temperature raising from the room temperature 23 to 50 °C the prolongation of propagation distance was calculated to be 0.03 mm which is very smaller than 99.8 mm. Hence, the effect of temperature on the length change of propagation distance can be considerably ignored.

Table 3 showed the ultrasonic properties of the AISI 1018 steel sample. Based on Eq. (1) and Eq. (2), it is concluded that the longitudinal velocity strongly depends on the sample's temperature. By using the pulse/echo technique [3], the experimental longitudinal velocities C_l were obtained and shown as triangle line of Figure 3 (a); these velocities increased in the range of 5894 to 5931 m/s with accuracy of ±1 m/s when sample's temperature decreased from 50 down to 0 °C (Table 3). By using linear fitting, the coefficient of temperature dependence of these experimental velocities was obtained to be −0.8 m/s.°C. Simultaneously, the ultrasonic shear velocities are also clearly depended on the sample's temperature. The experimental shear velocities C_t were obtained in the range of 3214 to 3237 m/s with ± 1 m/s of accuracy and shown square line of Figure 3(a) with sample's temperature decreasing from 50 down to 0 ^{o}C. By using the linear fitting approach of these experimental results, the coefficient of temperature dependence of these velocities was estimated to be –0.44 m/s.^{o}C. These experimental values of the longitudinal ultrasonic velocities and the shear ones propagated in this AISI 1018 steel sample are comparable with ones of other researches for carbon steels [8, 10-12], hence these experimental results are reliable.

Table 3. Ultrasonic properties of the AISI 1018 steel

The steel's temperature T (^{o}C)	Longitudinal velocity C_l (m/s)	Shear velocity C_t (m/s)	Acoustic impedance Z_2 ($\times 10^5$ $kg/m^2.s$)	Reflection Coefficient between Oil and Steel R (%)	Transmission Coefficient between Oil and Steel T (%)	Ultrasonic Attenuation α_{steel} (dB/cm)
0	5931	3229	462.618	89.4	10.6	0.401
5	5929	3227	462.462	89.7	10.3	0.326
10	5924	3224	462.072	89.9	10.1	0.288
15	5922	3222	461.916	90.0	10.0	0.275
20	5917	3220	461.526	90.1	9.9	0.278
25	5913	3218	461.214	90.3	9.7	0.280
30	5909	3215	460.902	90.5	9.5	0.284
35	5905	3213	460.590	90.7	9.3	0.277
40	5903	3210	460.434	90.8	9.2	0.274
45	5900	3208	460.200	90.8	9.2	0.264
50	5894	3206	459.732	90.9	9.1	0.242

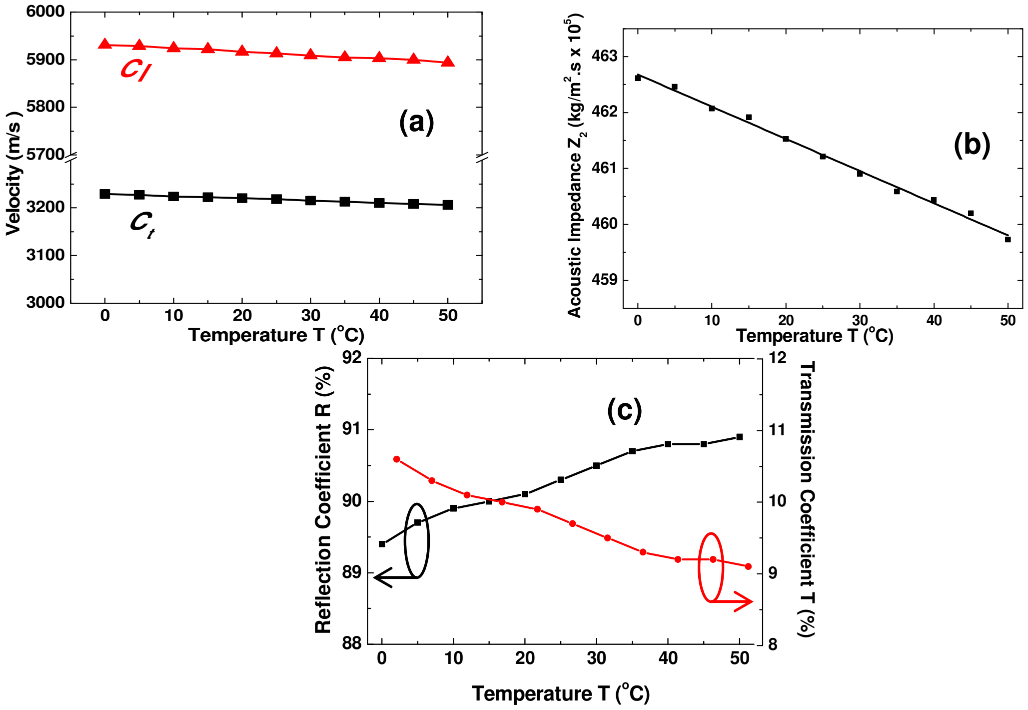


Figure 3. Effect of temperature on (a) longitudinal ultrasonic waves velocities C_l (red-cycle line) and shear ultrasonic waves ones C_t (black-square line), (b) acoustic impedance of steel, and (c) reflection and transmission coefficients at boundary between the motor oil and the steel.

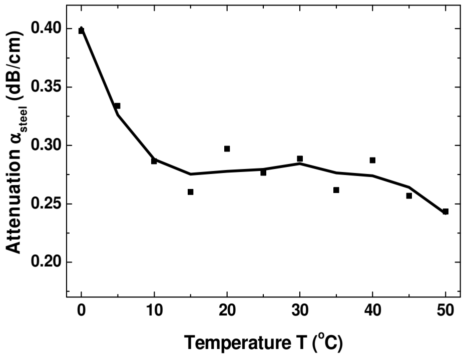


Figure 4. Attenuation α_{steel} of ultrasound propagated in the AISI 1018 steel sample vs temperature.

In addition, by using Eq. (4) for the experimental longitudinal velocities, the longitudinal acoustic impedance of this carbon steel were estimated and shown in Figure 3(b). It was also linearly dependent on the sample's temperature with temperature dependent coefficient of -0.058×10^{5} kg/m^{2}.s.^{o}C. Based on estimated acoustic impedances of the steel and the motor oil used as couplant material (Figure 2(c)), the reflection and transmission coefficients between them were calculated and shown in Figure 3(c). The reflection coefficient R was increased from 89.4% to 90.9% while the transmission coefficient T was decreased from 10.6% to 9.1% when the samples' temperature was raised from 0 to 50 ^{o}C.

The ultrasonic attenuation α_{steel} propagated in this AISI 1018 steel was also determined by using Eq. (7) for echo-peaks of pulse-echo technique and shown in Figure 4. It is observed that this attenuation was decreased when the sample's temperature increased. The dependence of this attenuation on temperature is very complicated to explain. P. Palanichamy *et al* showed that the attenuation of ultrasonic beam is influenced by the grain size of steel [23], M. Molero *et al* though that the attenuation must be effected by the frequency of ultrasonic wave [20], Devraj Singh *et al* showed that the attenuation of ultrasonic longitudinal wave depended on C_l^{-3} [7], while N. Guo *et al* and ER. Generazio thought that the attenuation of ultrasonic beam is influenced by the thickness of coupling material in the direct contact technique and unsteady pressure applied to the transducer and roughness [24]. In this research, it is believed that this ultrasonic attenuation is strongly dependence on properties of motor oil used as coupling material. At low temperature, the ultrasonic attenuation of motor oil is larger leading to the larger absorption coefficient of ultrasound propagated in steel. At high temperature region, it is smaller, therefore the ultrasonic attenuation of steel is also small. The reflection coefficient is also believed to effect on this ultrasonic attenuation, however the change of this coefficient is small of 1.5% when the sample's temperature in the range from 0 to 50 ^{o}C, hence it is difficult to observe this effect clearly.

5. Conclusion

In this research, the effect of temperature on the acoustic impedances and ultrasonic attenuations of the motor oil was determined. When the motor oil's temperature was increase from 0 to 50 ^{o}C, the ultrasonic velocities propagated in motor oil decreased from 1476 down to 1289 m/s with the thermal coefficient of -3.65 m/s.^{o}C. The bulk modulus K_{oil} of this motor oil was calculated in the range from 1.915 down to 1.412 GPa with the coefficient of temperature dependence of - 0.01 GPa/^{o}C. The acoustic impedance of this oil was estimated in the range of 12.97 ×10^5 down to 10.95 ×10^5 kg/m^2.s with thermal coefficient being -0.04×10^5 kg/m^2.s.^{o}C. The attenuation α_{oil} of the ultrasonic wave was investigated and decreased from 4.718 down to 2.708 dB/cm. Simultaneous, dependences of the velocities and the absorption coefficients of ultrasonic waves propagated in 1018 low carbon steel were characterized with the steel sample's temperature in the range from 0 to 50 ^{o}C. The temperature dependence coefficients of the ultrasonic longitudinal wave and ultrasonic shear one were estimated to be -0.8 m/s.^{o}C and -0.44m/s.^{o}C, respectively. The acoustic impedances of this carbon steel were also calculated and almost linearly dependent on the sample's temperature with the temperature dependent coefficient of -0.058×10^5 kg/m^2.s.^{o}C. Furthermore, the attenuation of the ultrasonic longitudinal wave was also studied and it was decreased when sample's temperature increased. It is concluded that the ultrasonic attenuation of the motor oil is one of the main reasons for the behavior of the absorption coefficients of the ultrasonic longitudinal wave propagated in the steel sample when its temperature was changed in the range from 0 to 50 ^{o}C. Based on the experimental acoustic impedances of the steel sample and motor oil used as couplant material, the effect of temperature on the reflection and transmission coefficients at the boundary between them were also estimated.

Acknowledgments

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