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Simulation Study on the Acoustic Field from Linear Phased Array Ultrasonic Transducer for Engine Cylinder Testing

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Abstract: Ultrasonic phased array inspection technology is widely used in non-destructive evaluation (NDE) applications and it has been proved to be an effective method for flaw detections in industry. In our study, this nondestructive evaluation method is proposed to detect the corrosion defects on engine cylinders. In order to demonstrate its feasibility, it is necessary to study the characteristics of the acoustic field produced by a linear phased array ultrasonic transducer in the engine cylinders. In this paper, according to multi-Gaussian beam model and ray acoustics theory, we derive the expression of the acoustic field from a linear phased array ultrasonic transducer under condition of the concave cylindrical interface on engine cylinder. The acoustic field simulations in the engine cylinders are carried out and analyzed. Our results indicate that the method of ultrasonic phased array inspection is feasible in the engine cylinder testing. Besides engine cylinders with different inside radius need different array element lengths to get best focusing beam and the optimal element length can be obtained by our simulation study.

Keywords: engine cylinder, linear phased array ultrasonic transducer, acoustic field, multi-Gaussian beam model, simulation

1 Introduction

With the increase of usage time, engine cylinder can be corroded by cooling liquid, which may cause driving force and security problems. In response to this situation, researchers focused on the study of corrosion behavior and anticorrosion cooling liquid[Mercer (1985); Beal (1999); Yang, Marinho, and Gershun (2008); Xu, Wu, Xu, Jin, and Wang (2011)], however, those methods can not monitor the corrosion condition in real time, i.e., the location, size and so on. Therefore, nondestructive

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evaluation methods should be developed to serve in the corrosion inspection for engine cylinders.

Ultrasonic phased array inspection technology is gaining a great attention in non-destructive evaluation applications recently [Zhong, and Mei (2002)]. The most attractive features of phased array inspection is flexibility, instantaneity, high-accuracy, safety, and it has outstanding performances in flaw detections for weld joint, composite material and various components in aerospace or nuclear industry [Freemantle, Hankinson, and Brotherhood (2005); Kramb (2007); Yang, Yoon, and Kim (2009); Lu, Deng, and Li (2012)]. So, in our study, we attempted to demonstrate its feasibility in engine cylinder testing by acoustic field simulations in the detected engine cylinder.

In actual testing, wedges are always used to couple the array to the tested structures. In the inspection of engine cylinder, according to its cannular shape convex wedges are needed to fit different inner diameters. So, the acoustic field simulations are carried out under the concave cylindrical interface between the wedge and inner surface of the engine cylinder. In the present study, the phased array ultrasonic transducer is placed along the central axis of the concave cylindrical interface. The top view of the engine and the transducer on the concave cylindrical interface are shown in Fig.1. (a) and (b).

In order to simulate acoustic field from phased array ultrasonic transducers accurately, various models have been developed [Ramm, and Smith (1983); Clay, Wooh, Azar, and Wang (1999); Wooh, and Shi (1999); Azar, Shi, and Wooh (2000); Guz (2005); Belgroune, Belleval, and Djelouah (2008); Chen (2008); Du, Jensen, and Jensen (2009); Luo, and Wang (2009)]. An outstanding simulation model should have the characteristics of high accuracy and efficiency. Song and Kim have calculated 3-D radiation beam model propagated through a planar interface from ultrasonic phased array transducers based on Rayleigh-Sommerfeld integral [Song, and Kim (2002)]. However, Rayleigh-Sommerfeld integral requires lengthy calculation time and their model is not appropriate for the focusing curved interfaces like condition in our study [Schmerr, and Song (2007)]. These problems can be eliminated by expanding the wave field in terms of Gaussian beams. Ding and his co-workers have proposed an approach that calculate the acoustic field from a rectangular transducer by superposition of two-dimensional Gaussian beams, and the coefficients are obtained from Wen and Breazeale's study [Ding, Zhang, and Liu (2003)]. This model is called expanded multi-Gaussian beam model and has been proved high accuracy and efficiency. With these advantages, multi-Gaussian beam model have been widely studied recently and used to calculate the acoustic field from phased array ultrasonic transducers [Park, Kim, and Song (2005); Huang, Schmerr, and Sedov (2006); Park, Song, and Kim (2006); Kono, and Baba

(2007); Zhao, and Gang (2009)]. Up to now, however, there has been no simulation and systematic investigation of the acoustic field characteristics from phased array ultrasonic transducer under condition of concave cylindrical interfaces.

In this paper, acoustic field produced by a linear phased array ultrasonic transducer is simulated and analyzed in the detected engine cylinder. Firstly, the expression of the acoustic field under condition of a concave cylindrical interface will be derived according to multi-Gaussian beam model and ray acoustics theory, and then the acoustic field simulations in the engine cylinder will be carried out. Finally, according to the simulation results, the feasibility of this method will be analyzed and the optimal transducer parameters will be chosen for engines with different sizes.

2 The acoustic field produced by a single element of the phased array

In our study, the solid wedge is considered as an equivalent fluid medium because the liquid couplant between the wedge and the detected engine cylinder can not carry any shear stresses. Thus, the issue about the phased array ultrasonic detection with a wedge can be reasonably simplified into a liquid-solid interface problem, that is to say, in our model, the convex wedge is perceived as liquid medium and the detected engine cylinder is the solid medium. The transmission of multi-Gaussian beam through the interface in plane x-z is shown in Fig.2.

2.1 Multi-Gaussian beam model in liquid medium

The acoustic field produced by a circular piston source can be calculated by superposition of a series of Gaussian beam functions [Wen, and Breazeale (1988)], and a rectangular piston source can be expressed as the product of two circular piston sources, i.e., the acoustic field from a rectangular transducer can be calculated by superposition of two-dimensional Gaussian beams. Thus, in the liquid medium, i.e. in the convex wedge in our study, the expression of acoustic field from the nth single element can be written as:

$$p_n(x_1,y_1,z_1) = \rho_1 c_1^P \sum_{m=1}^{10} \sum_{j=1}^{10} \frac{A_m A_j exp(ik_1^P z_1)}{\sqrt{1+iB_m z_1/D_1}\sqrt{1+iB_j z_1/D_2}} \times exp\left(-\frac{B_m \frac{x_1^2}{a^2}}{1+iB_m z_1/D_1}\right) exp\left(-\frac{B_j \frac{y_1^2}{b^2}}{1+iB_j z_1/D_2}\right) \quad (1)$$

where ρ_1,c_1^P are the density and longitudinal wave velocity of the fluid medium, A_m and B_m are complex constants obtained by Wen and Breazeale [Wen, and Breazeale (1988)], $2a$ and $2b$ are the width and length of the rectangular element, $D_1 = k_1^P a^2/2$ and $D_2 = k_1^P b^2/2$ are Rayleigh distances,$k_1^P = \omega/c_1^P$ is the wave number in liquid.

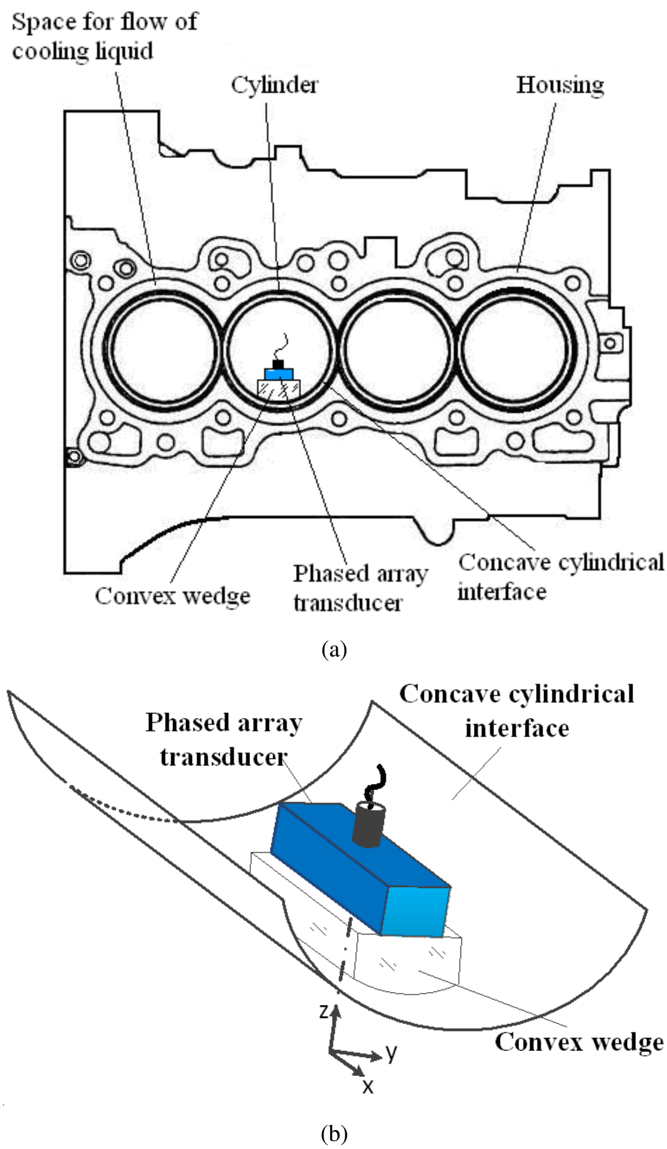


Figure 1: The phased array ultrasonic transducer is placed along the central axis of the concave cylindrical interface (a) The top view of the engine; (b) The transducer placed on the concave cylindrical interface

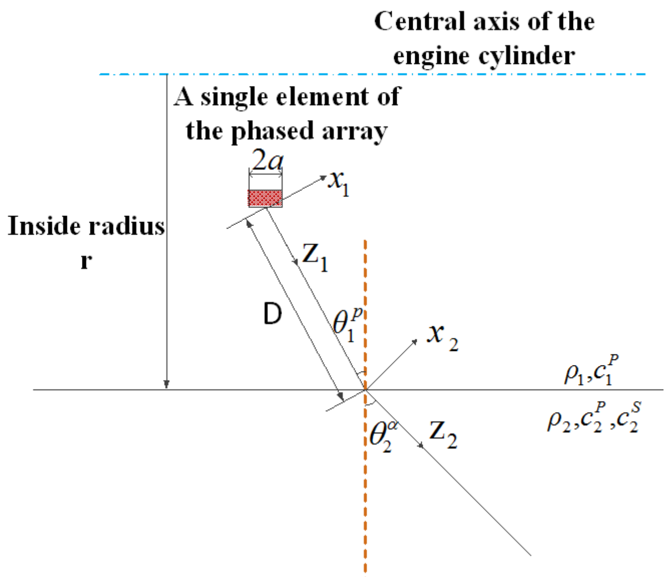


Figure 2: Multi-Gaussian beam propagates through the interface in plane x-z

2.2 *Acoustic field in solid medium under condition of a concave cylindrical interface*

In the solid medium, i.e. in the detected engine cylinder in our study, the acoustic field from a single rectangular element can also be calculated by superposition of two-dimensional Gaussian beams [Kim, Park, Song, and Schmerr (2004)]. Thus, in the solid medium, the expression of acoustic field from the nth single element can be written as:

$$\frac{-i\omega u_n^\alpha(x_2,y_2,z_2)}{v_0} = T_{12}^{\alpha:p}\sum_{m=1}^{10}\sum_{j=1}^{10} d^\alpha \frac{A_m}{1+iB_mD/D_1}\frac{A_j}{1+iB_jD/D_2}$$

$$\times \exp(\mathrm{i}k_1^P D+\mathrm{i}k_2^\alpha z_2)\frac{\sqrt{\det G_2^\alpha(0)}}{\sqrt{\det G_2^\alpha(\mathrm{z}_2)}} \tag{2}$$

$$\times \exp(\frac{\mathrm{i}k_1^P X^T[G_2^\alpha(z_2)]^{-1}X}{2})$$

where α=P means longitudinal wave, α=S means shear wave, u_n^α is the displacement vector, v_0 is the velocity on the face of the transducer, d^α is polarization vector,$T_{12}^{\alpha:p}$ is the transmission coefficient based on a velocity ratio, $D$is the propagation distance in the liquid medium, k_2^{α}=ω/c_2^{α} is the wave number of longitudinal wave (α=P) or shear wave (α=S) in the solid medium, $X^T=[x_2\ y_2]$ is position vector. When the phased array ultrasonic transducer is placed along the central axis of the concave cylindrical interface. $G_2^{\alpha}(0)$ and $G_2^{\alpha}(\mathrm{z}_2)$ are matrixes in 2D and can be expressed as:

$$[G_2^{\alpha}(0)]_{11}=\frac{\cos^2\theta_2^{\alpha}}{\cos^2\theta_1^{P}}[G_1^{P}(D)]_{11}$$

$$[G_2^{\alpha}(0)]_{22}=\frac{[G_1^{P}(D)]_{22}}{1+\kappa(\cos\theta_1^{P}\text{-}\frac{c_1^P}{c_2^{\alpha}}\cos\theta_2^{\alpha})[G_1^{P}(D)]_{22}}$$

$$[G_2^{\alpha}(0)]_{12}=[G_2^{\alpha}(0)]_{21}=0$$

$$G_2^{\alpha}(z_2)=G_2^{\alpha}(0)+\frac{c_2^{\alpha}}{c_1^{P}}z_2 I \tag{3}$$

where $[G_1^{P}(D)]_{11}$=-$\frac{iD_1}{B_m}$+D, $[G_1^{P}(D)]_{22}$=-$\frac{iD_2}{B_j}$+D, $[G_1^{P}(D)]_{12}$=$[G_1^{P}(D)]_{21}$=0, θ_1^{P} is the incidence angle of longitudinal wave in liquid medium, θ_2^{α} is the refraction angle of longitudinal wave (α=P) or shear wave (α=S) in the solid medium, I is unit matrix in 2D, κ is the interface curvature in plane y-z, i.e., the curvature of the concave cylindrical interface. In our present study, κ is a negative value because the interface is raised from the liquid side to the solid.

3 The acoustic field from a linear phased array transducer

3.1 The acoustic field from array transducers

A phased array transducer utilizes the wave physics principle of phasing, pulsing the individual probe elements at slightly different times in such a way that the individual wave fronts generated by each element in the array combine with each other to add or cancel energy in predictable ways that effectively steer and shape the sound beam. Thus, we can predict the acoustic field generated from an array transducer by superposition of the beam field from each element with appropriate time delays. So the acoustic field from a linear phased array transducer in the liquid and solid medium can be expressed respectively as:

$$p(x_1,y_1,z_1)=\sum_{\mathrm{n=1}}^{N} p_n(x_1,y_1,z_1)\exp(\mathrm{i}\omega t_n) \tag{4}$$

$$\frac{\text{-}i\omega u^{\alpha}(x_2,y_2,z_2)}{v_0}=\sum_{n=1}^{N}\frac{\text{-}i\omega u_n^{\alpha}(x_2,y_2,z_2)}{v_0}\times\exp(\mathrm{i}\omega t_n) \tag{5}$$

where t_n is the time delay of the nth element, N is the number of elements.

3.2 Time delays of individual elements

3.2.1 Time delays for the steering beam

Time delays are calculated based on ray acoustics theory. The steering beam is shown in Fig.3.

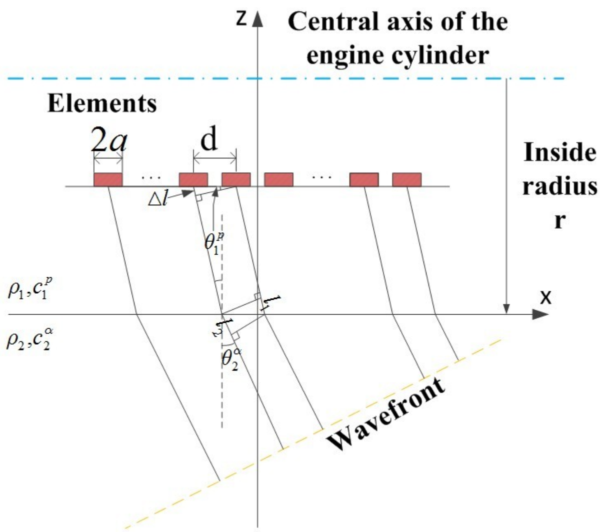


Figure 3: Steering beam from the linear phased array transducer

According to Snell's law, the wave propagation time through l_1 distance in liquid is the same as through l_2 distance in solid. Thus, the path difference between two adjacent elements can be written as:

$$\triangle l = d sin\theta_1^P \tag{6}$$

and the time delay of the nth element relative to the first one can be written as:

$$t_n = \frac{(n\text{-}1)d\sin\theta_1^P}{c_1^P} \tag{7}$$

where d is the inter-spacing between centers of adjacent elements.

3.2.2 Time delays for the focusing beam

The focusing beam is shown in Fig.4.

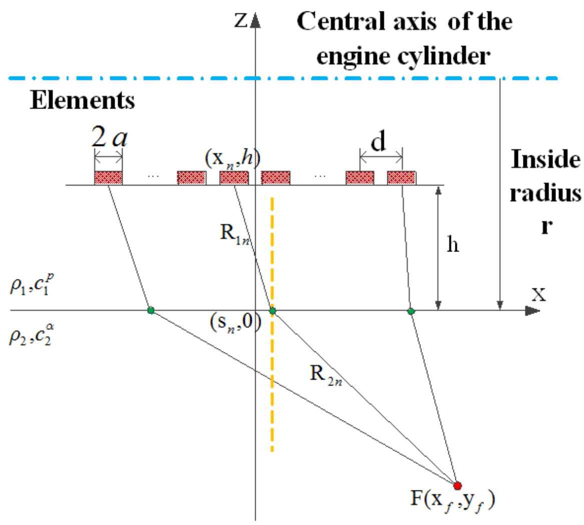


Figure 4: Focusing beam from the linear phased array transducer

The center coordinates (x_n,h) of the nth element can be calculated using the inter-spacing d and center coordinates of the array $(0,h)$. Assume the focus point of the beam is $F(x_f,y_f)$, the intersection point of beam generated by the nth element with the interface is$(s_n,0)$, the wave propagation distances in liquid and solid are R_{1n} and R_{2n}, respectively. According to Snell's law and the geometric relationships, equations can be written as:

$$\frac{s_n - x_n}{R_{1n}} c_2^\alpha = \frac{x_f - s_n}{R_{2n}} c_1^P$$

$$R_{1n} = \sqrt{h^2 + (s_n - x_n)^2}$$

$$R_{2n} = \sqrt{y_f^2 + (x_f - s_n)^2} \qquad (8)$$

R_{1n} and R_{2n} can be calculated by the above equations and then the total propagation time through the liquid and solid medium for the nth element can be written as:

$$T_n = \frac{R_{1n}}{c_1^P} + \frac{R_{2n}}{c_2^\alpha} \qquad (9)$$

Assume the total propagation time of the first pulsed element is T_{max} and then the delay time for nth element relative to the first one can be written as:

$$t_n = T_{max} - T_n \qquad (10)$$

4 Simulation results and analysis

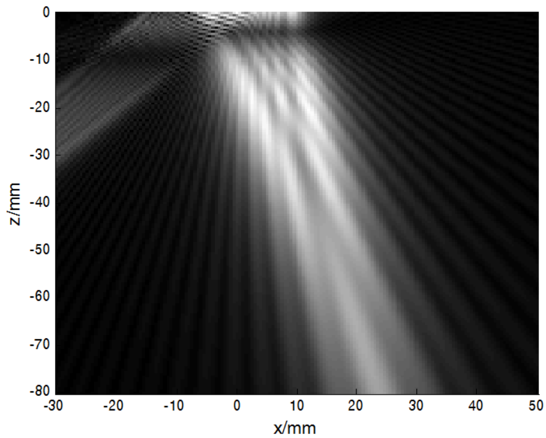
Taking longitudinal wave as the representative, acoustic field simulations are carried out in the engine cylinder using the model derived above. The inside radius of the cylinder is 55mm, and the material of the cylinder is steel of which the density is $7.8kg/m^3$ and the velocities of longitudinal and shear waves are 5900 and 3230m/s, respectively. The wedge is 20mm thickness (h=20mm) and made of plexiglas of which the density is $1.18kg/m^3$ and the velocity of longitudinal wave is 2330m/s. The major parameters of the linear phased array ultrasonic transducer adopted in this simulation are as followed: center frequency is 5 MHz, number of elements N is 32, element width 2a is 0.49mm, element length 2b is 13mm and the inter-spacing between centers of adjacent elements d is 0.59mm.

Acoustic field distributions of beams with different time-delay laws are shown in Fig.5.

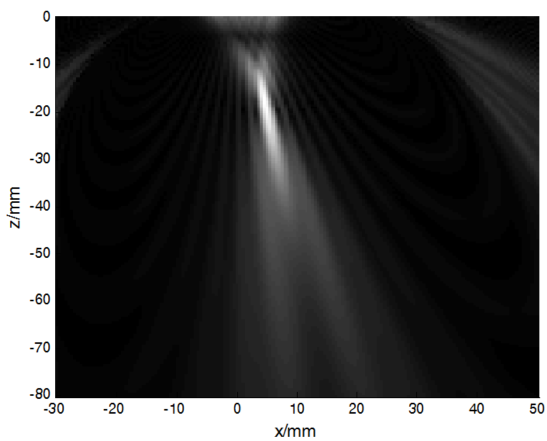
Fig.5.(a) shows the distribution of steering 10°, and Fig.5.(b) shows the distribution of steering 10° and focusing in 20mm depth in the meantime. It is shown that a linear phased array ultrasonic transducer can produce routine steering and focusing beam in the engine cylinder under condition of the concave cylindrical interface, and the energy is concentrated near the expected focal point. This result demonstrates that the method of phased array inspection is feasible in the engine cylinder testing.

In order to choose optimal transducer parameters for engine cylinders with different inside radiuses, the field distributions on acoustic axis are analyzed. Fig.6. shows the focused field distributions on acoustic axis, and comparison is carried out among different element length 2b. The inside radiuses of the engine cylinders are 50mm, 60mm and 70mm as shown in Fig.6.(a), (b) and (c), respectively. The depth of focus point is 20mm. The other parameters of phased array transducer adopted are the same as described above.

The results in Fig.6 show that, in condition of focusing in 20mm depth, the optimal element length 2b which shapes the best focus result is different among radiuses. When the inside radius is 50mm, best focus result is formed at 14mm element length and the focusing behavior will fail when the length is more than 16mm; when the inside radius is 60mm, best focus result is shaped at 12mm element length and focusing beam can not be formed when the length is more than 14mm; when the inside radius is 70mm, 11mm element length make the optimal focus result and we can not get an expected focusing beam when the length is more than 13mm. That is to say, engine cylinders with different inside radius need different element lengths to get best focusing beams and the optimal element length can be obtained by our simulation study.



(a)

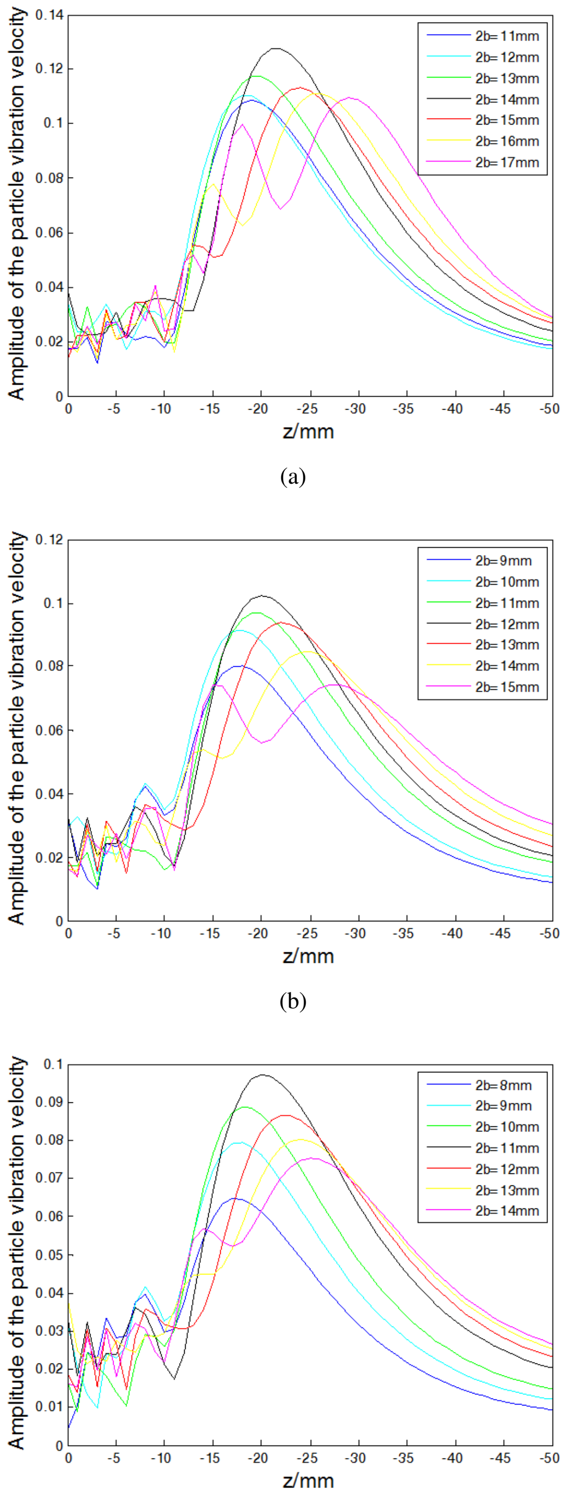


(b)

Figure 5: (a) Acoustic field distribution of steering 10°. (b) Acoustic field distribution of steering 10° and focusing in 20mm depth.

5 Conclusions

With the increase of usage time, engine cylinder can be corroded by cooling liquid, which may cause driving force and security problems. In response to this situation, ultrasonic phased array inspection technology is proposed to detect the corrosion defects on engine cylinders in real time. For the reliable application, we demonstrate its feasibility in engine cylinder testing by acoustic field simulations in the



(c)

Figure 6: Focused acoustic field distributions on acoustic axis (a) Inside radius is 50mm (b) Inside radius is 60mm. (c) Inside radius is 70mm

detected engine cylinder. The calculated model is built based on multi-Gaussian beam model and ray acoustics theory. Then, the acoustic field simulations in the engine cylinders are carried out and the results are analyzed. The simulation results indicate that a linear phased array ultrasonic transducer can produce routine steering and focusing beams in the cylinders, which have indicated the method of ultrasonic phased array inspection is feasible in the engine cylinder testing. The simulation results on acoustic axis show that engine cylinders with different inside radius need different element lengths to get best focusing beams and the optimal element length can be obtained by our simulation study. In the future work we will take inspection experiments for the typical corrosion defects on the engine cylinders using the optimized linear phased array ultrasonic transducer and further research will be carried out.

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