Computer modeling of the acoustic path of a normal probe in cast iron with globular graphite

V N Danilov¹ and L V Voronkova²

¹JSC “CNIITMASH”, Moscow, Russia
²JSC “CNIITMASH”, Moscow, Russia
vadnicdan@yandex.ru, voronkova-lv@yandex.ru

Abstract. Using the previously developed model for estimating the attenuation coefficient of elastic longitudinal waves in cast iron due to their Rayleigh scattering on graphite inclusions, we studied the influence of such attenuation for cast iron with spherical graphite on the characteristics of signals with frequency spectra of different widths depending on the cast iron models and the distance traveled by the ultrasonic wave.

1. Introduction

Cast iron with spherical graphite is a high-strength structural material that has good performance characteristics [1]. A feature of this cast iron is a good combination of casting properties and high strength, [2]. This material is very plastic, so it is well processed by cutting, has high values of tensile, compression and bending strength, satisfactory casting properties, it is well machined, can be welded, has high wear resistance, etc.

Production of high-strength and durable water supply pipes, pipes for gas and oil pipelines, as well as transport and packaging containers for storing nuclear waste from nuclear power plants makes cast iron with spherical graphite an indispensable structural material [3–6]. Ultrasonic testing of the structure of cast iron with spherical graphite is an urgent task, but the theoretical basis of methods for its testing has not yet been developed to the proper extent.

In this article, we study the relationship between the content and size of spherical graphite inclusions and the acoustic parameters of cast iron, the spectral characteristics of the acoustic field and directional diagrams in order to study the possibilities of testing such cast iron.

The mass content of graphite (carbon), depending on the grade of cast iron with spherical graphite [7], significantly affects the speed of elastic longitudinal waves in cast iron \( c_l \). This rate is also related to the average linear size of graphite inclusions \( \bar{D}_G \) [8]. Computer modeling of the attenuation coefficient \( \delta_l \) of longitudinal waves in cast iron with spherical graphite and a metal ferrite base for the proposed models (1–3, see table 1) was carried out according to the formulas of [9], and instead of the attenuation coefficient \( \delta_{MF} \) (I. N. Ermolov) for low-carbon steel, the coefficient \( \delta_{MFI} \) for steel with metal ferrite base with an average grain size \( \bar{D}_{MF} \) of 0.1 mm was used [10].
Table 1. Models of cast iron with spherical graphite.

| № | number of graphite $\delta M_G$, % | 1   | 2   | 3   |
|---|----------------------------------|-----|-----|-----|
|   | velocity of longitudinal wave $c_l$, mm/µs | 5.7 | 5.5 | 5.3 |
|   | size of graphite $D_G$, mm         | 0.04| 0.09| 0.14|

Frequency dependences of the coefficient $\delta_l (f)$ for models 1–3 of cast iron with spherical graphite (table. 1) and the attenuation coefficient $\delta_M$ for low-carbon steel (model of I. N. Ermolov [(3) 10]) with a grain size $\overline{D}_M = 0.05$ mm are shown in figure 1.

Figure 1. Frequency dependences of attenuation coefficients $\delta_l$ and $\delta_M$:

1 – $\delta_l$, model of cast iron with spherical graphite 1; 2 – $\delta_l$, model of cast iron – "– 2;

3 – $\delta_l$, model of cast iron – " – 3; 4 – $\delta_M$ – model of I. N. Ermolov for low-carbon steel.

The study of the effect of attenuation of elastic longitudinal waves in cast iron with spherical graphite on the characteristics of signals was carried out for models of elastic pulses of different lengths radiated into cast iron, similar to those used in [9].
2. Methods
When a longitudinal wave pulse propagates in cast iron with spherical graphite, the shape of the spectrum will change due to a greater attenuation of high-frequency components, the frequency of its maximum will decrease, the value of the maximum itself will decrease, and the width of the spectrum will change with a corresponding decrease in the pulse amplitude and a change in its shape due to a higher attenuation coefficient because of scattering on graphite inclusions. In figure 2 the frequency spectra of a medium-length pulse with form 2 \((S_{c2}^N)\) for the nominal frequency \(f_0 = 2.5\ \text{MHz}\), normalized to the maximum of the spectrum of the transmitted signal \((S_{t2}^N)\) (see [9]) that passed the distance \(d = 300\ \text{mm}\) in models of cast iron with globular graphite 1–3 (see table 1) are shown. The shape of the transmitted signal is shown in figure 4, pulse 1.

As can be seen from figure 2, frequency-dependent attenuation leads to a shift of the maximum of the spectrum to the frequency range less than the nominal \(f_0\).

The shorter the pulse (wider the spectrum) is, the greater the offset is. Changing the distance \(d\) passed by the ultrasonic pulse in cast iron leads to a corresponding change in the effect of attenuation on the shape of its spectrum, as well as on the appearance of the signal itself. In figure 3 the signal spectra \(S_{c2}^N\) for the cast iron model 3 and various values of the distance \(d\) are given, as well as the spectra of the transmitted pulse \(S_{t2}^N\) [9].

As can be seen from figure 3 an increase in the distance \(d\) leads to a noticeable decrease in the maximum of the spectrum to the value \(S_{c3}^N \approx 0.23\) (dependence 6) and the maximum frequency \(\approx 2.33\ \text{MHz}\).
A decrease in the amplitude of the pulse propagating in cast iron due to attenuation reduces the sensitivity of the control at a long distance to defects, and a decrease in the frequency of the maximum spectrum expands the directivity characteristic of signal reception and makes it difficult to use DVG-diagrams [10]. Therefore, when testing cast iron with spherical graphite with high attenuation for the operating frequency of 2.5 MHz and long distances (300-600 mm), it is advisable to use medium-length pulses $A_{t2}^N$ [9]. The value $d = 600$ mm corresponds to the distance to the reflector when checking the echo method [10] - 300 mm. According to experimental data, practical ultrasonic testing of castings made of cast iron with spherical graphite at a frequency of 2.5 MHz can be performed at ranges up to 300 mm, which is estimated to correspond to the results.

The form of transmitted pulse $A_{t2}^N$ and signal pulse $A_{c3}^N$ that have passed a distance of $d = 600$ mm in cast iron with spherical graphite model 3 ($f_0 = 2.5$ MHz) are shown in figure 4. The relative value of the positive maximum $A_{c3}^N$ is 0.3.

![Figure 3](image)

*Figure 3. Pulse Spectra: 1 – transmitted $S_{t2}^N$; 5 signals $S_{c2}^N$ passed in cast iron model 3: 2 – $d = 100$ mm, 3 – $d = 200$ mm, 4 – $d = 300$ mm, 5 – $d = 400$ mm, 6 – $d = 600$ mm.*

In the process of computer modeling of the acoustic path of a normal probe, the influence of attenuation of elastic longitudinal waves in cast iron with spherical graphite on the pulse pattern of a circular piezo plate according to I. N. Ermolov [3] $|\Phi_n| = \left| \frac{2 J_1 ( q J )}{q} \right|$ was studied ($J_1$ is the cylindrical Bessel function of the first order, $q$ is a dimensionless parameter). Pulse directivity characteristics $|\Phi_n|$ (q) for the emission of a medium-length pulse (form 2, $A_{c3}^N$) ($f_0 = 2.5$ MHz) and
various distances $d$ traveled by an ultrasonic wave in cast iron model 3 are shown in figure 5. For comparison, there is also a directivity graph for the continuous-wave mode.

In the course of experimental studies of the possibilities of narrow cast iron with spherical graphite, a sample (A) with dimensions of $30 \text{ mm} \times 30 \text{ mm} \times 59 \text{ mm}$ was used.

3. Results and discussion

Experimental estimation of the longitudinal wave velocity in this sample showed that it is $5.5 \text{ mm} / \mu \text{s}$, which corresponds to the value $c_l$ for cast iron with spherical graphite model 2 (table 1).

The calculated pulses of the bottom signal of the P111-2.5-K12-002 probe model at a distance of $h = 59 \text{ mm}$ for steel $A_{c2}^N$ (CO-2 sample) and cast iron of the model 2 $A_{c2}^N$ (“A” cast iron sample) are shown in figure 6(a), and the pulse amplitude for cast iron on maximum exceeds the pulse amplitude for steel by 1 dB.

Experimental pulses of bottom signal probe P111-2.5-K12-002 for steel sample (CO-2) and the sample of cast iron, “A”, at distance $h = 59 \text{ mm}$ and with same gain of the signal detector are shown in figure 6b, c. The amplitude of the signal in the sample of globular cast iron “A” (figure 6c) is about 1.5 dB more than in a standard steel sample (CO-2, figure 6b), which exceeds the calculated value, which is apparently due to limitations of the computational model of the attenuation that takes into account only the average size of the scattering elements of carbon in iron.

The lower impedance of cast iron than steel leads to a better matching of the probe with such a medium and a greater transmitted signal to cast iron than to steel. Therefore, despite the greater attenuation of the elastic wave in cast iron due to scattering and absorption for relatively small depths (several tens of mm), the recorded bottom signal for cast iron samples may even slightly exceed the
amplitude of the signal received from the same depth in steel, which was established by calculation and confirmed experimentally. The limitations of the calculated attenuation model, which takes into account only the average size of carbon scattering elements in cast iron, explained that the difference in bottom signals for cast iron and steel in the experiment even exceeded the same theoretical value.

Figure 5. Directivity characteristics $|\Phi_n|$ : 1 – continuous mode of radiation; 2 – for a signal pulse $A_{c3}^N$ that has passed the distance $d = 100$ mm model 3 ; 3 – - "- distance $d = 200$ mm - "-; 4 – - "- distance $d = 400$ mm - "-; 5 – - "- distance $d = 600$ mm - "-.

Figure 7 shows DVG diagrams (dependences of the pressure normalized to the maximum of the reflected wave on the probe from the depth $h$) of the bottom signal of the probe P111-2,5-K12-002 for steel and models 1-3 of cast iron with globular graphite (see table 1).

4. Conclusion
4.1 A satisfactory quantitative agreement has been found between the results of calculations of spectra and pulse signals with experimental results for sample of cast iron with spherical graphite with different velocities and attenuation of longitudinal waves. It is shown that the amplitude of the bottom signal in cast iron with spherical graphite can exceed its values for structural steel.
4.2 The features of the effect of attenuation of longitudinal waves in cast iron with spherical graphite on the directivity graph of their transmutations for model 3 of cast iron, and depending on the distance traveled by the wave in cast iron are shown.
4.3 The value of the damping coefficient of longitudinal waves has the main influence on the difference between DVG diagrams for steel and cast iron, which depends on the operating frequency.
Figure 6 (a). Pulses of the bottom signal of the probe model P111-2,5-K12-002 at a distance of $h = 59$ mm: 1 – for steel $A_1^N$; 2 – for cast iron model 2 $A_{c2}^N$.

Figure 6 (b) (c). Experimental pulses of the bottom signal of the probe P111-2,5-K12-002 for a sample of CO-2 steel (b) and a sample of cast iron with globular graphite “A” (c) for the distance $h = 59$ mm.
Figure 7. DVG-diagrams of the bottom signal of the probe P111-2,5-K12-002: 1 – steel; 2 – model of cast iron with spherical graphite 1; 3 – model 2; 4 – model 3.

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