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Modeling air gun signatures in marine seismic exploration considering multiple physical factors*

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Abstract: Based on analyzing the limit of Ziolkowski's bubble oscillation formulation, a new model with various physical factors is established to simulate air gun signatures for marine seismic exploration. The practical effects of physical factors, such as heat transfer across the bubble wall, air gun port throttling, vertical rise of the bubble, fluid viscosity, and the existence of the air gun body were all taken into account in the new model. Compared with Ziolkowski's model, the signatures simulated by the new model, with small peak amplitude and rapid decay of bubble oscillation, are more consistent with actual signatures. The experiment analysis indicates: (1) gun port throttling controls the peak amplitude of air gun pulse; (2) since the hydrostatic pressure decreases when the bubble rises, the bubble oscillation period changes; (3) heat transfer and fluid viscosity are the main factors that explain the bubble oscillation damping.
Keywords: heat transfer, port throttling, fluid viscosity, marine exploration, air gun signature

Introduction

Air gun transient excitation releases high-pressure gases into the surrounding infinite water medium. Keller and Kolodner (1956) regarded the high-pressure gases as a free oscillation spherical bubble and presented a "free oscillation bubble theory". Based on the theory, Ziolkowski (1970) formulated the first physical model to be used for simulating air gun signatures. However, compared with actually measured signature, the initial pulse amplitude of the signature calculated by Ziolkowski's model is far too high and the decay of the bubble oscillations is much too slow (Ziolkowski et al., 1982; Chen and Ni, 2008; Chen et al., 2008). The reasons are: (1) the model assumes that all the air is released from the gun chamber instaneously, without being concerned about gun port throttling; (2) the model only accounts for amplitude damping via acoustic radiation without considering the viscosity of surrounding fluid and the heat transfer between bubble and fluid; and (3) the model assumes that the bubble is at rest, without considering the vertical rise of the bubble and existence of the gun body in the simulation of the air gun signature. Since then, many studies have been done to improve Ziolkowski's model. Schulze-Gateman (1972) deduced a new bubble oscillation formulation assuming the gun body shape is spherical. Johnston (1994) and

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Liu (2005) simulated the pressure waves of a single gun by considering the bubble oscillation as a spring-mass system. Ziolkowski (1998) presented an air gun simulation method from pressure measurements made in the vicinity of the gun port. In addition, Langhammer (1993) performed an experimental study to quantify the influence of viscous terms on the air gun signature. Ziolkowski (1984) and Laws et al. (1990) provided a detailed analysis of the physical mechanism of gun port throttling and heat transfer and concluded that the air in the gun chamber is not released into the bubble instantaneously and that the air release process controls the signature behavior.

In this paper, based on the analysis of Ziolkowski' s model and taking into account various practical factors such as the existence of the gun body, gun ports throttling, heat transfer between bubble and surrounding fluid, the vertical rise of the bubble, fluid viscosity, and bubble wall surface tension, we establish a new model and numerically simulate the signature. Satisfactory consistency between numerical simulation and actual measurements is achieved.

Basic equations

Ziolkowski's model for a single air gun is based on Gilmore's equation for a large bubble of air oscillating in an infinite, compressible liquid, the equation of motion for the bubble is:

$$\ddot{R} = \frac{(1+\frac{\dot{R}}{C})H + (1-\frac{\dot{R}}{C})\frac{R}{C}\frac{dH}{dt} - \frac{3}{2}(1-\frac{\dot{R}}{3C})\dot{R}^2}{R(1-\frac{\dot{R}}{C})}, \quad (1)$$

where R is the bubble radius, C is the velocity of sound in the water, and H is the enthalpy at the bubble wall. In this equation H and C are expressed as:

$$H = \frac{n(p_\infty + B)}{(n-1)\rho}[(\frac{p(R,t)+B}{p_\infty + B})^{(n-1)/n} - 1], \quad (2)$$

$$C = c_\infty(\frac{p(R,t)+B}{p_\infty + B})^{(n-1)/2n}, \quad (3)$$

and

$$c_\infty{}^2 = \frac{n(p_\infty + B)}{\rho_\infty}, \quad (4)$$

where $p(R,t)$ is the pressure in the liquid at the bubble wall, p_∞ is the hydrostatic pressure, ρ is the water density, and c_∞ is the sound velocity at infinite distance from source. Gilmore suggests that $n \approx 7$ and $B \approx 3000$ for water. The hydrostatic pressure p_∞ is given by

$$p_\infty = p_0 + \rho g h, \quad (5)$$

where p_0 is the atmospheric pressure, g is the acceleration due to gravity, and h is the depth of the air bubble.

The vertical rise of the air gun bubble should be taken into account during the bubble oscillation. The buoyancy of the air bubble causes it to rise to the surface as it oscillates. The resulting change in hydrostatic pressure affects the bubble period. The vertical velocity of the bubble is expressed as

$$\frac{dh}{dt} = \frac{2g}{R^3}\int_0^t R^3 dt. \quad (6)$$

If the relation between the pressure at the bubble wall $p(R,t)$ and the radius of the bubble R in the water can be found then the radiated pressure waveform from a spherical air bubble oscillating in water can be determined as follows:

$$P - p_\infty = \rho_\infty(\frac{y}{r} - \frac{u^2}{2}) + \frac{\rho_\infty}{2c_\infty}(\frac{y}{r} - \frac{u^2}{2})^2, \quad (7)$$

where r is the distance between detector and air gun. The velocity u, the quantity y, and K_3 are given by:

$$y = R(H + \frac{U^2}{2}), \quad (8)$$

$$K_3 = \frac{c_\infty{}^3 R^2 U}{y^2}(1 - \frac{U^2}{2c_\infty{}^2}) - \frac{c_\infty{}^2 R}{y}(1 - \frac{U}{c_\infty}), \quad (9)$$

$$u = \frac{y}{c_\infty r} + \frac{K_3 y^2}{c_\infty{}^3 r^2}(1 - \frac{y}{c_\infty{}^2 r} + \frac{K_3{}^2 y^4}{2c_\infty{}^8 r^4}). \quad (10)$$

In Ziolkowski's model, neglecting the air flow and heat transfer makes it only appropriate for a fixed volume of air in a closed thermodynamic system. However, the air gun bubble is clearly an open thermodynamic system with the air-mass ejected from the gun chamber and the air bubble heat is lost to the surrounding water across the bubble wall. The energy gained by the air gun bubble, due to mass transfer and conductive heat loss, must be balanced by the change in internal energy of the bubble. Their relation is:

$$c_p T dm + dQ = dw + pdV, \tag{11}$$

where m is the mass of air contained in the bubble, T is the temperature in the bubble, $w=mc_vT$ is the internal energy of the bubble, c_p and c_v are the heat capacity of the air at constant pressure and volume, respectively, V is the volume of the air in the bubble, and dQ is the heat transfer into the air bubble. Another additional physical effect, which cannot be neglected in reality, is the existence of the gun body. Now the volume of the bubble is total volume of the gun body and the air released into the bubble. Assuming the radius of the gun body is $\bar{R}$, the volume of air in the bubble can be expressed as:

$$V = \frac{4}{3}\pi R^3 - \frac{4}{3}\pi \bar{R}^3. \tag{12}$$

If the air inside the bubble is assumed to obey the ideal air law then equation (11) can be re-written in terms of the universal air constant $R_G=c_p-c_v$:

$$\frac{dT}{dt} = \frac{R_G T \frac{dm}{dt} - \frac{dQ}{dt} - p\frac{dV}{dt}}{mc_v}. \tag{13}$$

Assuming a spherical bubble and introducing a heat transfer coefficient k, the rate of heat transfer across the air bubble wall can be expressed as:

$$\frac{dQ}{dt} = k \times 4\pi R^2 (T - T_w), \tag{14}$$

where $\Delta T=T-T_w$ is the temperature difference between the bubble and the surrounding water and the value can be determined by fitting the model with experimental data.

To derive the mass-transfer equation, a throttling constant τ is introduced which specifies the rate of flow through the air gun port:

$$\frac{dm}{dt} = \tau \sqrt{\frac{(p_g - p)m_g}{V_g}}, \tag{15}$$

where $\Delta p=p_g-p$ is the pressure difference between the gun chamber and the air bubble, m_g is the mass of air inside the gun chamber, and V_g is the gun chamber volume.

Note that the port area has been absorbed into the throttling constant τ since the area of the gun ports is fixed. Thus, the rate of mass ejection depends on the air gun volume according to the power law:

$$\tau = \tau_0 (V_g)^{\beta}, \tag{16}$$

where τ_0 is the volume-independent port-throttling constant and β is a power law exponent that must be determined by comparison with experimental data.

There is another marine air gun named GI which has two chambers: the G and I chambers. The G chamber initially releases air as air gun fires. Later when the bubble is formed and the air volume reaches maximum, the I chamber begins to release air. The GI air gun main feature is that the bubble created by the gun is stabilized by the injection of extra air from the second chamber at a later time (Landro, 1992). The rate of air release from the two chambers in the GI gun is described by:

$$\frac{dm}{dt} = \begin{cases} \tau_1 (V_{g1})^{\beta 1} \sqrt{\frac{(p_g - p)m_{g1}}{V_{g1}}}, \; for \quad 0 \le t \le t_1 \\ \tau_2 (V_{g2})^{\beta 2} \sqrt{\frac{(p_g - p)m_{g2}}{V_{g1}}}, for \;\; t_0 \le t \le t_0 + t_2 \end{cases}, \tag{17}$$

where m_{g1} and m_{g2} are the masses of air in the G and I chambers, respectively, V_{g1} and V_{g2} are the volumes of the two chambers, τ_1, β_1 and τ_2, β_2 are the chamber's volume-independent constants, t_1 and t_2 are the corresponding injection periods, and t_0 denotes the starting time for the air release from I chamber.

The liquid pressure just outside the bubble wall $p(R,t)$ is connected to the pressure $p_i(R,t)$ acting on the inner side and the internal pressure $p_i(R,t)$ can be split into the particle pressure of air and water vapor p_s and p_v (Prospereti, 1984). The relations can be expressed as:

$$p(R,t) = p_i(R,t) - \frac{2\sigma}{R} - \frac{4\mu \dot{R}}{R}, \tag{18}$$

$$p_i(R,t) = p_s + p_v, \tag{19}$$

$$\frac{p_s V}{T} = mR_G, \tag{20}$$

where σ is the surface tension coefficient and μ is the liquid viscosity.

For a real air gun, the air in the gun chamber is not completely released after firing. Some air remains in the gun chamber after the air gun is fired and the gun ports close. In the model, this effect is denoted by the efficiency parameter η. η is the ratio between the released air-mass from the gun chamber and total air-mass within the gun chamber:

$$\eta = \frac{m_{t=\infty}}{m_g}, \tag{21}$$

where $m_{t=\infty}$ is the air-mass released into the bubble and m_g is the total air-mass in the gun chamber.

Now that the rate of mass-ejection from air gun chamber dm/dt and the heat lost term dQ/dt is known, the state of the air inside the bubble, including the pressure $p(R,t)$ at the bubble wall, can be determined completely with an iterative numerical integration procedure. We now have all the equations necessary to predicate the air gun signature and finally estimate the bubble pressure, bubble temperature, bubble size, and pressure variation at the bubble wall in water using these equations.

The source ghost amplitude produced at the water-air interface is smaller than the direct arrival because of the difference in the travel paths of the two signals. For a given source and hydrophone depth, the ghost amplitude can be expressed as a percentage of the direct arrival amplitude (Fricke and Davis, 1985).

$$R = \frac{D-d}{D+d} \times 100\% , \tag{22}$$

where D is the hydrophone depth and d is the source depth. The far-field signature emitted from the air gun source is represented by a superposition of direct arrival and source ghost:

$$F(t) = f(t) - R * f(t+\Delta t), \tag{23}$$

where $f(t)$ is the source direct arrival, $f(t+\Delta t)$ is the source ghost, $\Delta t = 2d/c_\infty$ is the time delay, and c_∞ is the speed of sound in water.

Numerical simulation and discussion

Initial conditions

(Prospereti, 1984). The relations can be expressed as:

$$p(R,t) = p_i(R,t) - \frac{2\sigma}{R} - \frac{4\mu\dot{R}}{R}, \tag{18}$$

The addition of new parameters requires a different set of initial conditions from those of Ziolkowski's model:

(1) The initial volume of the air in the bubble is set equal to that of the air gun chamber: $V = V_g$.

(2) The initial bubble volume is set equal to the total volume of air gun chamber and air gun body: $V'|_{t=0} = V_g + \frac{4}{3}\pi\bar{R}^3$, where $\bar{R}$ is the radius of the air gun body. Thus the initial radius of the bubble is $R|_{t=0} = \left(\frac{3V'|_{t=0}}{4\pi}\right)^{1/3}$, and the initial velocity and acceleration of the bubble wall are set to zero.

(3) The initial pressure inside the bubble $p|_{t=0}$ is set to the hydrostatic pressure p_∞ and the initial temperature inside the bubble is set to the surrounding water temperature T_w so the bubble is filled with an initial mass $m_0 = \frac{p_\infty V_g}{R_G T_w}$.

(4) Because of the extremely high pressure of air in the gun chamber, the initial temperature in the air gun is $T_g = T_w(1 + \frac{p_g}{p_c})$, depending on the pressure of the gun chamber, with the constant $p_c = 139MPa$ for air. Therefore, the initial mass of the gun chamber is:

$$m_g = \frac{p_g V_g}{T_g R_G}.$$

(5) After air ejection from the gun chamber, the mass of the air in the bubble remains constant $m_g' = m_g\eta$ and the equilibrium radius of the bubble is:

$$r_0 = \left(\frac{3m_g' R_G T_w}{4\pi p_\infty}\right)^{1/3}.$$

Numerical resolution

With the use of an interactive numerical integration procedure, the pressure wavelet radiated from a spherical oscillating air bubble can be determined by resolving equations (7) to (10). In order to calculate the enthalpy H at the bubble wall, it is necessary to calculate the pressure $p(R, t)$ at the bubble wall, the bubble radius R, and the velocity of bubble wall $\dot{R}$ at any time.

Using the equations (18) to (20), the pressure at the bubble wall $p(R, t)$ can be described as:

$$p(R,t) = \frac{mR_G T}{V} + p_v - \frac{2\sigma}{R} - \frac{4\mu\dot{R}}{R}, \tag{24}$$

In this equation, the mass of air in the bubble m, the temperature in the bubble T, and the volume of air V are the functions of time. During the air gun firing procedure, the mass of air in the bubble can be determined with equation (25):

$$\frac{dm}{dt} = \tau_0 (V_g)^\beta \sqrt{\frac{(p_g - p)m_g}{V_g}}, \quad m_{new} = m + \Delta m. \tag{25}$$

After air injection from the gun chamber, the mass of air in the bubble remains constant, and the time derivative $dm/dt = 0$. The air volume variation in the bubble can be written as:

$$\frac{dV}{dt} = 4\pi R^2 \Delta R. \quad (26)$$

In order to determine the variation of bubble radius ΔR, equation (1) can be altered to:

$$\frac{dU}{dt} = \frac{(1+\frac{U}{C})H + (1-\frac{U}{C})\frac{R}{C}\frac{dH}{dt} - \frac{3}{2}(1-\frac{U}{3C})U^2}{R(1-\frac{U}{C})}. \quad (27)$$

Here, the time derivative dH/dt may be found by the relation $dH/dt = dH/dp \cdot dp/dt$. While p is a function of m, T, and R, we can re-write dp/dt in terms of the particle derivative. The bubble radius R and the bubble wall velocity U at any time can be calculated from equations (28) and (29):

$$\Delta U = \frac{dU}{dt}.\Delta t + \frac{d^2U}{dt^2}.\frac{\Delta t^2}{2}, \quad U_{new} = U + \Delta U. \quad (28)$$

$$\Delta R = U\Delta t + \frac{dU}{dt}\frac{\Delta t^2}{2}, \quad R_{new} = R + \Delta R. \quad (29)$$

Concerning the effect of the air gun body on the signature, the volume of air in the bubble can be described as:

$$V_{new} = \frac{4}{3}\pi({R_{new}}^3 - \bar{R}^3). \quad (30)$$

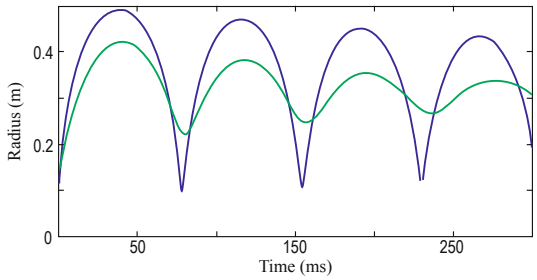


Fig. 1 Comparison of Ziolkowski's model (blue line) and the improved model (green line) for the bubble radius.

The heat conduction velocity dQ/dt is given in equation (14). By substituting equations (14), (25), and (26) into equation (31), the temperature variation in the bubble at any time can be obtained:

$$\frac{dT}{dt} = \frac{R_G T\frac{dm}{dt} - \frac{dQ}{dt} - p\frac{dV}{dt}}{mc_v}, \quad T_{new} = T + \Delta T. \quad (31)$$

Since the air mass m, the temperature T, and the air volume V in the bubble is known at any time, the pressure at the bubble wall $p(R, t)$ can be determined using equation (24).

Because of buoyancy, the bubble rises to the surface during oscillation. The air bubble depth can be described as:

$$\Delta h = \frac{2g}{{R_{new}}^3}\sum_{n=0} R(n\Delta t)\Delta t, \quad h_{new} = h + \Delta h. \quad (32)$$

The time-varying hydrostatic pressure p_∞ can be obtained by substituting equation (32) into equation (5). With the use of equations (2), (28), and (29), we can calculate the enthalpy H at the bubble wall, the bubble radius R, and the bubble wall velocity $\dot{R}$ at any time and then substitute these results into equations (7) to (10) to yield the radiated pressure waveform from the spherical oscillating air bubble.

A value for Δt must be chosen to be suitably small compared with the period T of the bubble oscillation. Typically, T is on the order of 10-100 ms. Therefore, $\Delta T = 10^{-5}s$ is probably good enough for most purposes.

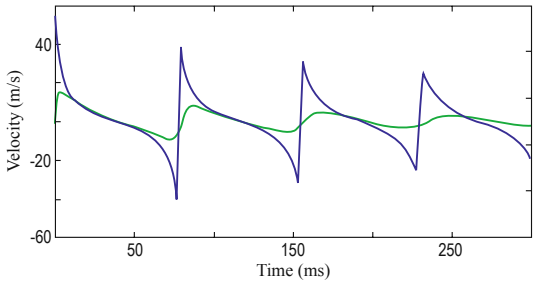


Fig. 2 Comparison of Ziolkowski's model (blue line) and the improved model (green line) for the bubble wall velocity.

Results and discussion

Assuming that the air in the bubble obeys the ideal gas law, equations (18) to (32) can be discretized and resolved numerically by integration to obtain the bubble radius, bubble wall velocity, mass of air in the bubble, and bubble temperature as a function of time. The solutions are shown in Figures 1 to 6 using Ziolkowski's model with and without considering the practical physical parameters. Given that the volume of the air gun is 80 in^3, firing depth is 8 m, firing pressure is 2000 psi, reflection coefficient of the ocean surface is -1, water velocity is 1483 m/s, and water temperature is 20°C.

The comparison of Ziolkowski's model (blue line) and the improved model (green line) for bubble radius is shown in Figure 1 and the comparison for bubble wall velocities of the two models is shown in Figure 2. We see that the velocity of the bubble wall is subdued faster and the bubble radius damped considerably after considering the practical physical parameters. Thus, we have the confidence to say that the bubble oscillation decays not only from acoustic radiation but also from the energy lost due to heat transfer. The water viscosity plays an essentially important role on the dynamics of the bubble. As the viscosity of fluid surrounding the bubble generated by the air gun increases, more energy is transferred from the bubble into the turbulent motion of the liquid. Therefore, we conclude that fluid viscosity, together with heat transfer are the main physical effects that explain the damping of an air gun signature.

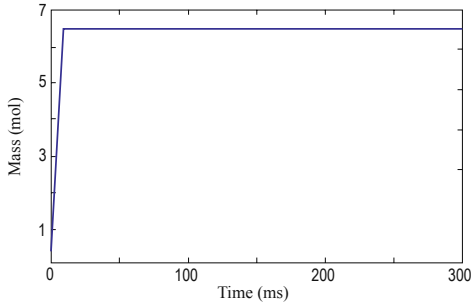


Fig. 3 The mass of air in the bubble calculated by the improved model.

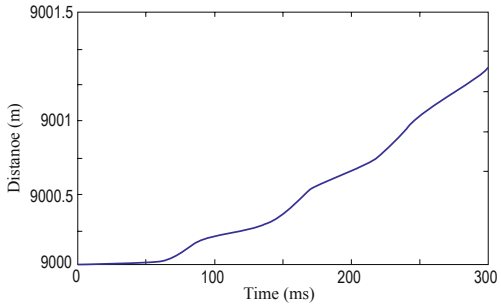


Fig. 4 The distance between detector and air gun calculated by the improved model.

Figure 3 shows the change of air mass in the bubble calculated by the improved model. It is obvious that the air in the gun chamber is not released into the bubble instantaneously. When the air gun is initially fired, the air is injected from the pressurized gun chamber into the bubble via a throttled flow through the gun ports. The rate of air-flow from the air gun chamber controls the peak amplitude of the air gun pulse. For the GI gun, there are two ejection phases: first, the initial air release from the G chamber and then the ejection phase. The main effect of the ejection of extra air is to stabilize the bubble radius when approximately reaching the maximum bubble radius. This reduces the bubble oscillations amplitude which also means the acoustic signal from the GI gun is characterized with a clear primary pulse followed by very small bubble oscillation side lobe.

Figure 4 shows the change of distance between detector and air gun calculated by the improved model. The buoyancy of the air bubble causes it to rise to surface as the bubble oscillates. The distance from the detector increases while the hydrostatic pressure decreases and, thus, the period of bubble oscillation changes.

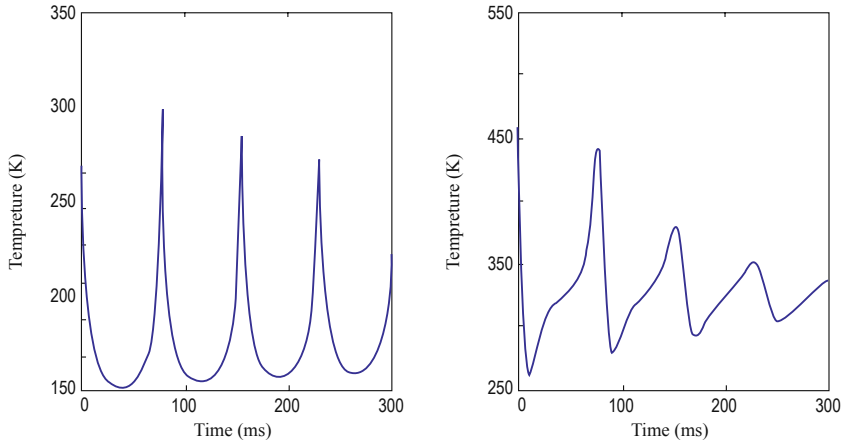
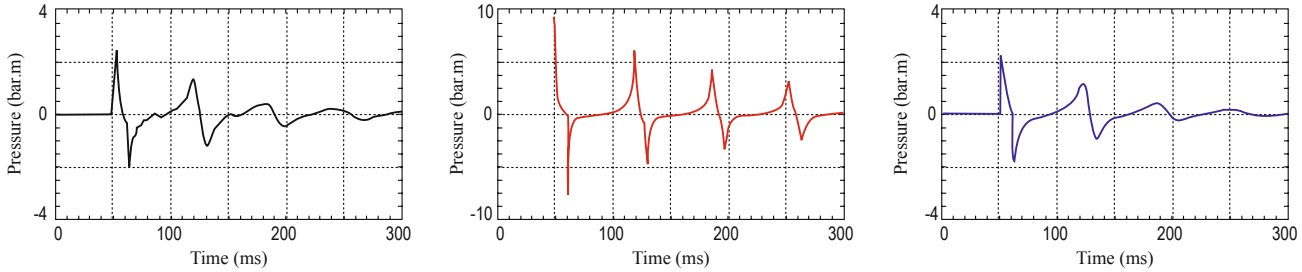


Fig. 5 Comparison of Ziolkowski's model (left) and the improved model (right) for the bubble temperature.

Figure 5 shows the temperature in the bubble calculated by Ziolkowski's model and the improved model. We can see that Ziolkowski's model has failed to describe the bubble oscillation, with the

result that the equilibrium temperature in the bubble is unrealistically low (-80°C). However, when the practical physical parameters is incorporated into the model, the equilibrium temperature in the bubble is nearly to the water temperature, which is true in reality.

Figure 6 shows the comparison of air gun signatures from Ziolkowski's model, the improved model, and actual measurement. Figure 6a is the actual measured signature and Figure 6b is from Ziolkowski's model. We see that the initial pulse amplitude in Figure 6b is far too high because Ziolkowski's initial conditions assume that all the air is instantaneously released from the gun chamber into air bubble. This assumption is not realistic because the gun ports throttle the air flow from the gun chamber. As well, the decay of the bubble oscillations in Figure 6b is much too slow because the model only accounts for damping via acoustic radiation. In reality, significantly more energy is lost from the air gun bubble due to heat transfer and water viscosity. Thus, the additional practical physical parameters must be incorporated into the basic model in order to correctly simulate real air gun behavior. Figure 6c is the signature simulated from improved model. With the addition of the practical physical parameters to the model, the initial pulse amplitude is considerably subdued and the bubble oscillation decays faster. All these are consistent with the measured signature in Figure 6a.



(a) Actual measured signature. (b) Signature from Ziolkowski's model. (c) Signature from the improved model.

Fig. 6 Signatures from actual measurement (a), from Ziolkowski's model(b), and from improved model(c).
Gun depth is 8 m, gun volume is 80in^3, and the firing pressure is 2000 psi.

Conclusions

Based on an analysis of the limitations of Ziolkowski's model, a new improved model is established to simulate the effects of multiple practical physical factors on air gun signatures such as the existence of the gun body, gun port throttling, heat transfer, the vertical rise of the bubble, fluid viscosity, and bubble wall surface tension. Some conclusions are derived from an analysis of the experiments:

(1) The main physical effect that explains the damping of an air gun signature is fluid viscosity, together with heat transfer.

(2) The air is ejected from the pressurized chamber into the bubble via a throttled flow through the gun ports and the rate of air-flow from the chamber controls the peak amplitude of the air gun pulse.

(3) The buoyancy of the air bubble causes it to rise to the surface as it oscillates and the resulting change in hydrostatic pressure affects the bubble oscillation period.

(4) When incorporating the heat transfer across the bubble wall into the model, the simulated equilibrium temperature in the bubble is nearly equal to the water temperature, which is true in reality.

(5) Considering these factors, the signatures predicted by the improved model shows remarkably good similarity with measured signatures, with the initial pulse amplitude considerably subdued and the oscillation of the bubble decays faster.

The energy of a single air gun is too weak to produce a high primary / bubble peak amplitude ratio, which makes its signature far from being an ideal impulsive seismic wavelet. The problem can be improved using the tuned air-gun array, in which many guns of different volumes are fired simultaneously. Because of the difference in bubble periods, the side lobes of bubble pulses cancel each other in the far field and the peak amplitude is enhanced. The accurate signature simulation for an air gun lays the groundwork for modeling the signature of air-gun array.

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