COMMENTS ON "CALIBRATION OF MARINE SEISMIC SOURCES USING A HYDROPHONE OF UNKNOWN SENSITIVITY" *

BY

A. ZIOLKOWSKI **

Safar's (1976) paper on a proposed technique for calibrating marine seismic sources by comparing their outputs with the output from a single air gun fails to discuss a significant factor which will affect the accuracy of the calibration: the nonlinearity of the air gun bubble oscillations.

Safar has implicitly assumed that the amplitude of the pressure wave radiated by an air gun is linearly related to the distance from the gun. Far away from the gun, where the amplitude of the pressure wave is small, changes in amplitude are linearly related to changes in distance from the gun. Close to the gun, where the amplitudes and velocities of the water particle motions are large, this is not true. The density and bulk modulus of the water are altered as the wave passes through it and the equations describing the radiation are nonlinear. It does not help to put the hydrophone further away for, although the hydrophone itself may be out of the zone of nonlinearity, the pressure waves must pass through this zone to reach the hydrophone.

Safar avoids some of the nonlinearity by suggesting that the first *negative* peak be used for the calibration instead of the first *positive* peak. He does not explain why—and it needs some explanation: the positive peak is much bigger, the error in measuring it would be less and the calibration of the other marine sound source would therefore be that much more accurate. The present author suggests that the positive peak cannot be used if one has only a linear model for the bubble. By choosing the negative peak, Safar is dealing with a portion of the radiation which is generated at a time when the bubble is at its maximum radius, when the motion of the water near to the bubble is much less violent and when the linear equation has the greatest probability of working well.

Another advantage of using the first positive peak would be that the initial internal pressure of the air gun bubble is known at the instant of firing. Unless one goes through the nonlinear equations, proceeding from the known initial firing conditions, one does not know the internal pressure of the bubble when

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it reaches its maximum size. Safar assumes that this pressure is zero. He considers the effect of it being non-zero only on the bubble pulse *period* (which he needs to know in order to be able to estimate the maximum radius using Rayleigh's formula); the effect on the *amplitude* of the radiation at the bubble wall is ignored. By neglecting the internal pressure of the bubble, Safar deduces that the pressure wave generated at this point is $-p_0$ at the bubble wall, where p_0 is hydrostatic pressure.

Calculations (Ziolkowski 1970) using Gilmore's * (1952) theory for the non-linear oscillations of a spherical bubble suggest that the bubble produced by an air gun at 14 m-18 m depth and firing at about 144 bar (roughly the same conditions as in Safar's table 1) would expand to a radius equal to 1.8 R_0, where R_0 is the radius of the bubble when its internal pressure equals hydrostatic pressure. This author (Ziolkowski 1970) also showed that an appropriate equation of state for the air in the bubble is given by:

$$p = p_0 \left(\frac{R_0}{R}\right)^{3.4}$$

where p is the internal pressure and R is the radius of the bubble. Using this equation and $R = 1.8\,R_0$, we find $p = 0.135\,p_0$. If Safar had used this value his predicted amplitudes would have been 13.5 % lower and the agreement between measured and predicted amplitudes would have been almost perfect. In general, to calculate the internal pressure of the bubble at any time after the instant of firing, the nonlinear theory must be used.

In conclusion, a linear radiation theory can be made to work in Safar's calibration technique as long as results from nonlinear theory are included in appropriate places. It almost seems easier to use the nonlinear theory from the beginning. The theory has existed since 1952. A model bubble for an air gun using this theory has existed since 1970. In this author's 1971 paper it was shown, by band-pass filtering the theoretical waveform, that a very accurate approximation to the measured waveform from a small air gun could be obtained. Finally, Smith (1975) showed how this model, combined with the known impulse response of the recording system, could produce a very accurate prediction of the recorded waveform of large air guns as they are being towed through the water—a very significant result.

There is no need to continue to try to fit linear equations to the nonlinear bubble oscillations, when a model exists which takes the nonlinearities into account and which can predict the whole waveform accurately.

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* Gilmore's (1952) theory linearizes the equations, but retains the second-order terms needed to allow for the observed changes in bulk modulus of the water.

References

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REPLY TO A. ZIOLKOWSKI'S COMMENTS

BY

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In reply to Ziolkowski's comments concerning my paper (Safar 1976a), which deals with the calibration of marine seismic sources, I would like to point out that the proposed technique involves the comparison between the output of the marine seismic source with the output from a single air-gun *only* for the case when the marine seismic source is an array of air-guns. However, for the case of marine seismic sources which radiate a bubble pulse such as Maxipulse, Vaporchoc, and Sparker, all that is required is to record the pressure signatures radiated by these sources in the near field i.e. a single air-gun is not required for calibrating Maxipulse, Vaporchoc, and Sparker.

To illustrate the use of the proposed technique for calibrating marine seismic sources other than air-guns array, we consider the pressure signatures recorded (Farriol, Michon, Muniz, and Staron 1970) in the near field of the Sparker and Vaporchoc shown in figures 1 and 2.

The first negative pressure peak radiated by any marine seismic source which radiates a bubble pulse is given approximately by (Safar 1975)

$$p_n \simeq -T(1 + D_s/10)^{3/2}/0.183\, r. \qquad (1)$$

In (1) the pressure p_n is in bar, the distance r of the hydrophone from the seismic source and the seismic source depth D_s are in meters, and the bubble pulse period T is in seconds. From (1) and figures 1 and 2, the predicted first negative pressure peak p_n radiated by the Sparker and Vaporchoc are 250 mbar and 500 mbar at 1 m, respectively. Therefore, the sensitivity of the hydrophone channels used in recording the Sparker and Vaporchoc signatures are 0.3 and

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