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SIGNATURES FROM SINGLE AIRGUNS*

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ABSTRACT

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The far-field signatures from a comprehensive and systematic airgun pulse test have been analyzed. Empirical relations between the characteristic signature parameters and depth (5–12 m), pressure (100–137 bar = 10–13.7 MPa) and total chamber volume (0.65–9.5 l) have been derived. Also, the influence of using waveshape kits in different positions within the chamber has been tested.

The results indicate that:

(1) The amplitude is proportional to chamber pressure to the power 3/4.
(2) The bubble period is nearly independent of the position of the waveshape plate.
(3) The increase in primary/bubble amplitude ratio is inversely proportional to the chamber volume above the waveshape plate.
(4) The amplitude is independent of airgun depth.

INTRODUCTION

Airgun arrays are one of the most widely used energy-sources in today's marine seismic exploration. Such arrays are designed to give a resulting signature which is optimal according to one or more criteria. The most commonly used criteria are the length and amplitude of the primary pulse and the primary-to-bubble amplitude ratio (Giles and Johnston 1973, Nooteboom 1978, Brandsæter, Farestveit and Ursin 1979).

In order to design optimal arrays, the knowledge of how single airgun signatures depend on the basic initial parameters is of vital importance.

In this paper the results from an airgun pulse test undertaken on board the R/V *Håkon Mosby* of the University of Bergen in November 1980 are presented. In most

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of the experiments PAR (Trade mark of Bolt Associates, Inc.) 1500 C airguns were used, although a PAR 1900 C airgun was included in some of the measurements.

The experiment was designed to measure the far-field signatures of airguns with varying chamber volume V, airgun depth D, air pressure P, and position of the waveshape plate.

We would like to stress that the objective of this paper is mainly to present the experimental results from the test and compare them with published theoretical and experimental relations. Thus, comprehensive discussions of the physical nature of any discrepancies is beyond the scope of this paper. In addition, representative amplitude spectra (of the primary pulses) will be shown. The raw records have been used, i.e. without de-ghosting. This was done for practical reasons, since records from more than 2000 shots have been analyzed, and to de-ghost this number of records is a very time-consuming task. We will briefly discuss how the presence of the ghost signal influences the results:

Amplitude A. As a standard, an airgun depth of 7.5 m was used. This gives a delay of the ghost signal of about 10 ms relative to the primary pulse. As can be seen from fig. 1. (which is typical) the peak positive amplitude of the signal is reached

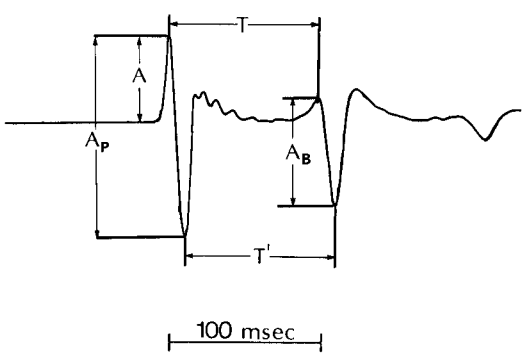


Fig. 1. Definitions of signature parameters.

approximately 5 ms after the onset, which implies that the ghost signal does not affect measurements of A as long as the airgun depth is greater than about 4 m. The standard deviation (SD) in A within a series of 5–10 shots was 2–4%.

Bubble period T. If T is measured between the peak positive amplitude in the primary and bubble pulse, it will not be affected by the ghost, since the ghost/bubble relation is comparable to the ghost/primary relation. In some cases, however, it was difficult to define the peak positive amplitude of the bubble from the records and thus T' (see fig. 1) was used instead of T. In signals where both T and T' could be measured we found $T = T'$ within 1 ms. SD-calculations show that T is the most stable of the measured parameters, with SD values of about 1–2%.

Primary/bubble ratio R. The difficulties in picking the positive peak in the bubble signal forced us to use peak-to-peak values in the calculations of R. The ghost signal therefore influences the results, but since we are looking for variations in R as a

function of chamber volume, pressure, etc. we believe that the trend in the results is correct, although the SD in the measurements of R is as high as about 10%. This indicates that the relations concerning R are the most uncertain.

Amplitude spectra. Since we compare spectra of signatures recorded with constant airgun depth (7.5 m), the ghost will introduce the same modification on all spectra. The modification consists of notches in the signal spectra at frequencies of about $n \cdot 100$ Hz, where $n = 0, 1, 2, \ldots$ Thus, any differences in the spectral content of the signals are caused by differences in the signals themselves and not by the ghost.

Theoretical and Experimental Relations

For the far-field signatures of airguns the following relations have been derived for the primary amplitude A and bubble period T (Kramer, Peterson, and Walter 1968, Giles and Johnston 1973, Nooteboom 1978, Johnston 1980):

$$A \propto C_1 V^{1/3} \tag{1}$$

for constant P and D,

$$T \propto C_2 \frac{P^{1/3} V^{1/3}}{(D + D_0)^{5/6}} \tag{2}$$

with $D_0 = 10$ m; (Giles and Johnston 1973):

$$A \propto C_3 P; \tag{3a}$$

and (Johnston 1980):

$$A \propto C_4 P^{0.551} \tag{3b}$$

for constant V and D in equation (3). In equations (1)–(3), D is depth in meters and C_1, C_2, C_3 and C_4 are constants depending on airgun design and the units used for pressure P and volume V.

Equation (3b) is an experimental result covering the pressure range 13.7–41.1 MPa (2000–6000 p.s.i.), i.e. outside the range considered in this paper.

We have not been able to find published results for the primary/bubble ratio R as a function of the parameters considered in this paper.

Data

The data were recorded by a calibrated hydrophone at approximately 150 m depth (depth to the sea floor was approximately 500 m) and a DFS V (Trade mark of Texas Instruments Inc.) recording system with sample interval 1 ms. The experiment was carried out under static conditions, i.e. without any ship movements. For each parameter setting (i.e. depth, volume, pressure, etc.), 5–10 shots were fired, and the signature parameters were averaged. In the spectral analysis, signals recorded with a 360 Hz high-cut frequency filter (72 dB/octave) have been used. In all other compu-

tations, signals filtered with a 128 Hz high-cut and 72 dB/octave filter have been analyzed.

A typical example of a recorded signature is shown in fig. 1. The parameters used to characterize the pulses are:

A: primary amplitude defined as the peak value of the first positive peak.
T: bubble period.
$R = A_P/A_B$: primary/bubble amplitude ratio, when
A_P and A_B are both maximum peak-to-peak values.

Results and Discussion

Chamber volume V. Chamber volumes in the range 0.65–9.5 l (40–580 in^3) were included in the test. Waveshape kits were not used.

Variations in A, T, and R as functions of V are shown in fig. 2(a–c). Curves satisfying equation (1) and (2) are drawn in figs 2(a) and (b), respectively. As can be seen from the figures, the fit of T to the line is excellent, confirming the relation in equation (2). For the amplitude A there is a reasonably good fit to the theoretically predicted relation $A \propto V^{1/3}$. This result is also in agreement with the experimental relation found by Giles and Johnston (1973) and Johnston (1980). The variation in primary-to-bubble ratio R (fig. 2c) can be approximated by

$$R \propto V^{0.25} \tag{4}$$

which is a purely empirical relation. However, we stress that equation (4) is derived from a limited data base, and from only one type of airgun (PAR 1500 C). In any case, equation (4) should not be extrapolated outside the volume range considered here.

Normalized (relative to their maximum value) amplitude spectra of signatures from the two extreme chamber volumes are shown in fig. 2(d). As can be seen from the curves, the frequency content is identical within a few dB up to about 200 Hz.

Depth D. Airgun depth was varied between 5 and 12 m, and 10 test series covering the volume range 0.65–9.5 l were carried out. Airguns both with and without waveshape kits were used.

The results, with standard deviations, are shown in fig. 3(a–c). The primary amplitude (fig. 3a), corrected for spherical divergence, is independent of depth in the considered range. This, again, is a purely empirical relationship. Furthermore, as expected from other experimental results (see, e.g. Kramer, Peterson, and Walter 1968), the bubble period as a function of depth (fig. 3b) is in accordance with equation (2). The relation between R and D (fig. 3c) can be approximated by the empirical relation

$$R \propto D^{-1} \tag{5}$$

in the considered depth range.

Pressure P. The signature-dependence of P was measured by varying P in steps of 0.5 MPa from 10 to 13 MPa. In addition, $P = 13.7$ MPa (which was used as a standard value of P) was included.

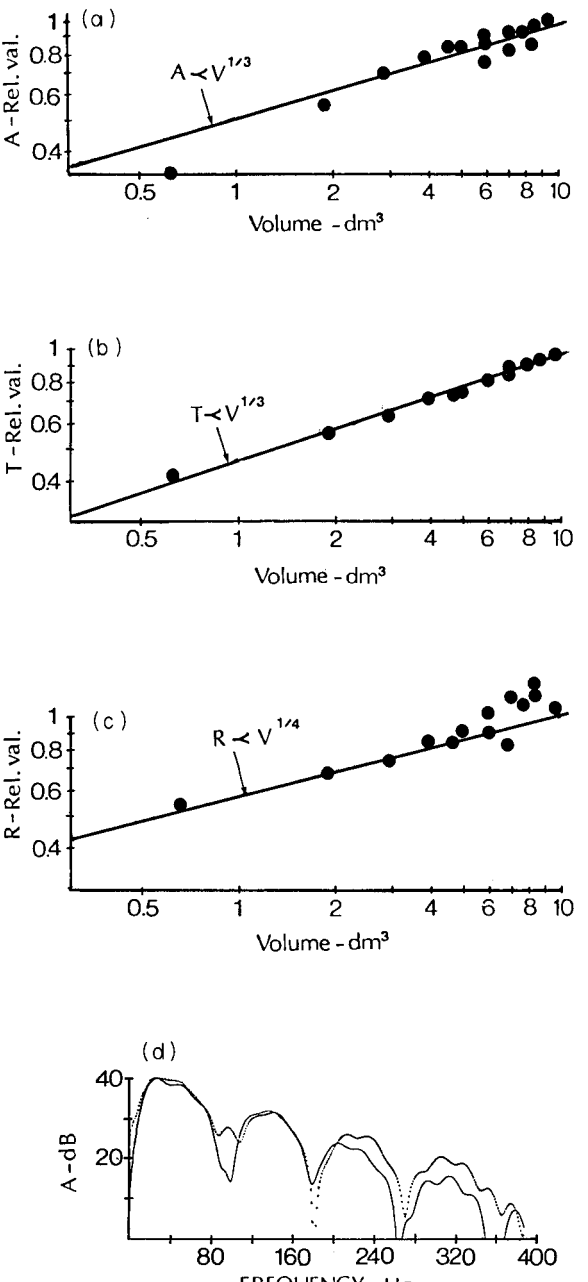


Fig. 2. Variation in chamber volume V. (a) Primary amplitude A; (b) bubble period T; and (c) primary/bubble amplitude ratio R. The values of A, T, and R are normalized relative to $V = 10$ l. (d) Normalized (relative to their maximum value) amplitude spectra of the primary pulse. The solid and dashed curves represent volumes of 9.5 and 0.65 l, respectively.

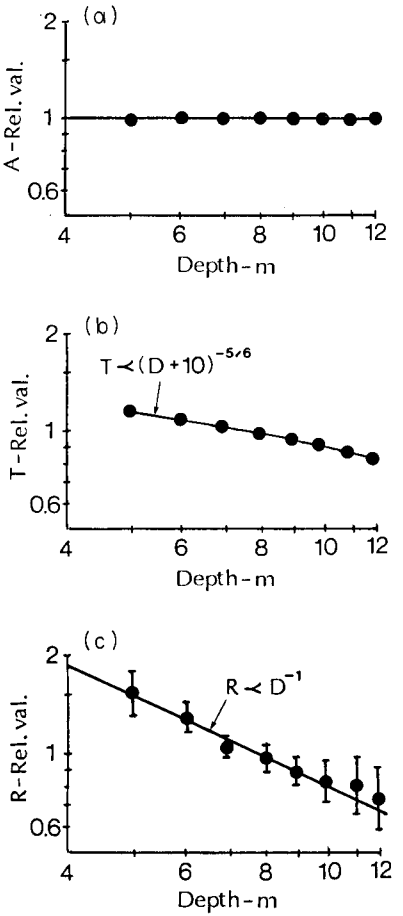


Fig. 3. Variation in airgun depth D. (a) Primary amplitude A, corrected for spherical divergence; (b) bubble period T; and (c) primary/bubble ratio R. The values of A, T, and R are normalized relative to $D = 7.5$ m. Each data point in the figures represents the average value of 10 test series, each consisting of 5–10 shots. The standard deviations of the average values are indicated by vertical bars, or are within the size of the symbols.

A total of nine test series were carried out using a 1500 C airgun with chamber volumes ranging from 0.65 to 9.5 l, both with and without waveshape kits. The results presented in fig. 4(a–c) are the average values with standard deviations of A, T, and R as functions of P.

The results in fig. 4(a) show

$$A \propto P^{3/4} \tag{6}$$

while equation (3a) predicts $A \propto P$. Ziolkowski (personal communication) has deduced theoretically that amplitude must scale with chamber pressure as in equation

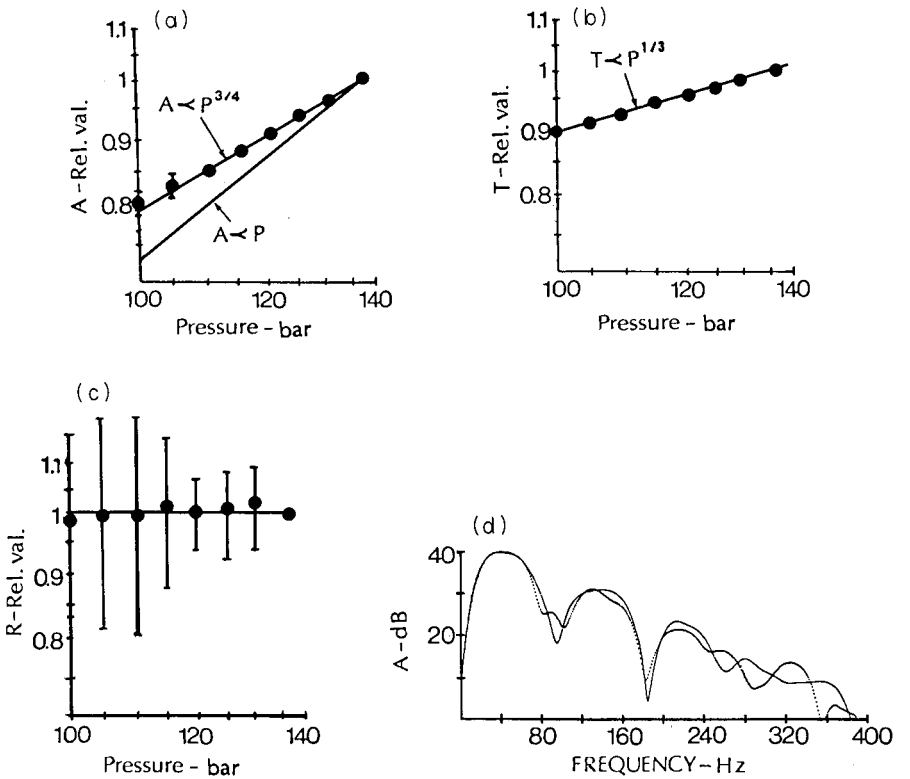


Fig. 4. Variation in pressure P. (a) Primary amplitude A; (b) bubble period T; and (c) primary/bubble amplitude ratio R. The values of A, T, and R are normalized relative to $P = 13.7$ MPa. For number of test series, etc., see fig. 3. (d) Normalized (relative to their maximum value) amplitude spectra representing pressures of 13.7 MPa (solid curve) and 10 MPa (dashed curve), with a chamber volume of 5.9 l.

(6) for the law of conservation of energy to be obeyed. We therefore suggest that equation (6) is the correct expression of amplitude variations with pressure in the considered range. The result in equation (6) is not in agreement with the experimental result (equation 3b) found by Johnston (1980). However, equations (3b) and (6) have been derived for different pressure ranges and are not directly comparable.

The results in fig. 4(b) clearly demonstrate that the theoretical (equation 2) and experimental results are consistent, i.e. $T \propto P^{1/3}$.

The variation in primary-to-bubble amplitude ratio R with pressure is shown in fig. 4(c), indicating that R is nearly independent of variations in pressure in the range 10–13.7 MPa. We have not been able to find any systematic variations connected with either chamber volume or the use of waveshape kits which could explain the relatively large standard deviations in the measurements.

The spectra in fig. 4(d) show that variations in P have only a minor influence on the spectral content of the signature up to 200 Hz.

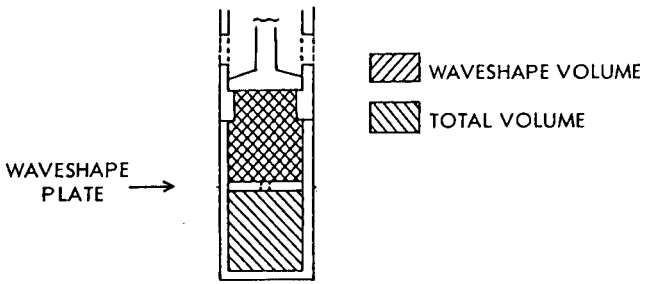


Figure 5. Definitions of total chamber volume V_T and waveshape volume V_W.

Waveshape volume V_W. Waveshape volume is defined as the chamber volume above the waveshape plate, while V_T is the total chamber volume (see fig. 5).

V_T and V_W were varied in the range 3.5–9.5 l and 1–8 l, respectively. In this part of the experiment a PAR 1900 C airgun was also included.

In fig. 6(a–c) we have plotted A_W/A_T, T_W/T_T and R_W/R_T as functions of V_W/V_T, where, e.g. A_W is the primary amplitude measured with waveshape volume V_W and total volume V_T and A_T is the primary amplitude with total volume V_T without waveshape kit. The figures outline how the signature varies with different waveshape volumes when the total volume is kept constant.

The amplitude–volume relation (fig. 6a)

$$\frac{A_W}{A_T} = \left(\frac{V_W}{V_T}\right)^{1/4} \tag{7}$$

is a rough approximation of the relatively scattered data. From equation (1) and fig. 2(a) we have

$$\frac{A}{A_T} = \left(\frac{V}{V_T}\right)^{1/3}. \tag{8}$$

By setting $A = A_W$ we get from equations (7) and (8)

$$\left(\frac{V_W}{V_T}\right)^{1/4} = \left(\frac{V}{V_T}\right)^{1/3}$$

and, since $V_W, V \leq V_T$, we get

$$V \geq V_W,$$

which implies, as far as amplitude is concerned, that the "effective" volume of an airgun with waveshape kit is slightly larger than the waveshape volume. This can also be seen directly from fig. 6(a) by comparing the data with the line drawn according to equation (8). This indicates that the compressed air *below* the waveshape plate gives some contribution to the primary energy.

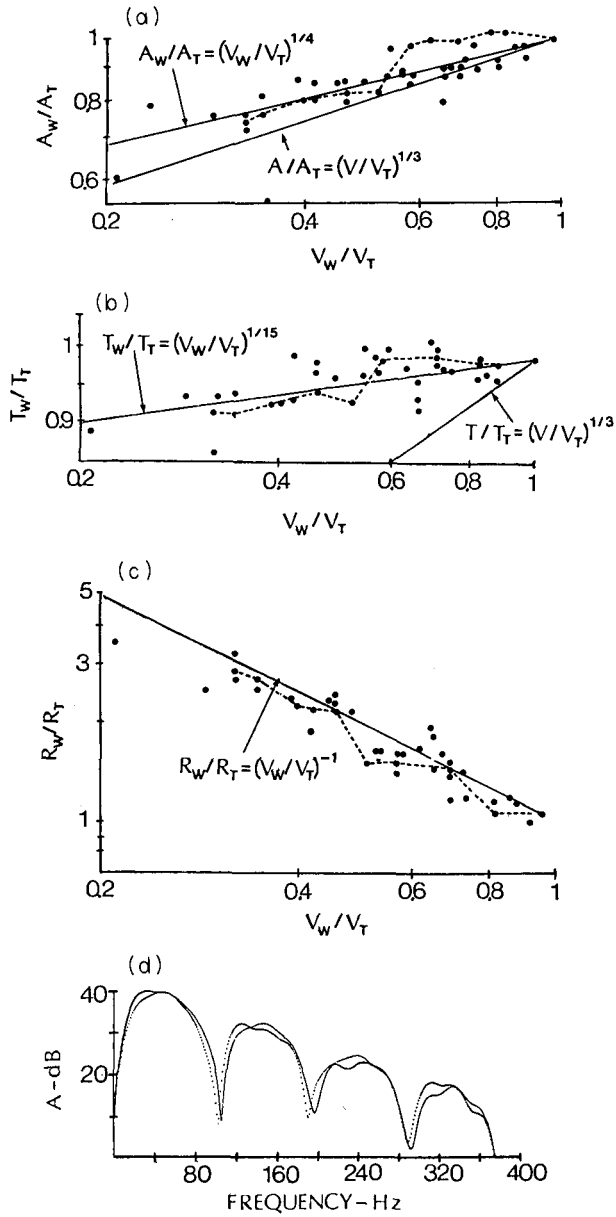


Fig. 6. Variation in waveshape volume V_w. (a) Primary amplitude A; (b) bubble period T; and (c) primary/bubble amplitude ratio R. The meaning of the subscripts "W" and "T" are explained in the text. Each point represents the average value of eight shots; the spreading in the data is an indication of the standard deviation in the measurements. The broken curve is the result from one test series with $V_T = 8.5$ l. (d) Normalized (relative to their maximum value) amplitude spectra representing waveshape volumes of 7.8 l (solid curve) and 2.8 l (dashed curve). The total chamber volume was 8.5 l in both cases.

Even though the scatter in the data is relatively large, the relation

$$\frac{T_W}{T_T} = \left(\frac{V_W}{V_T}\right)^{1/15} \tag{9}$$

is an approximation of the results in fig. 6(b). From fig. 2(b) we have

$$\frac{T}{T_T} = \left(\frac{V}{V_T}\right)^{1/3}. \tag{10}$$

This relation is shown in fig. 6(b). Equations (9) and (10) imply that the bubble period is almost exclusively dependent on the total chamber volume, and is only slightly affected by waveshape plates in different positions within the chamber.

From fig. 6(c) we have

$$\frac{R_W}{R_T} = \left(\frac{V_W}{V_T}\right)^{-1}, \tag{11}$$

expressing that the increase in the primary-to-bubble amplitude ratio obtained by using waveshape kits is inversely proportional to the waveshape volume. Furthermore, variation of waveshape volume does not significantly influence the spectral content of the signatures (fig. 6d).

Summary and Conclusions

By combining equations (4)–(11) we have

$$A = C_5 V_T^{1/3} P^{3/4} \left(\frac{V_W}{V_T}\right)^{1/4}, \tag{12}$$

$$T = C_6 V_T^{1/3} P^{1/3} (D + D_0)^{-5/6} \left(\frac{V_W}{V_T}\right)^{1/15}, \qquad (D_0 = 10 \text{ m}) \tag{13}$$

and

$$R = C_7 V_T^{1/4} D^{-1} \left(\frac{V_W}{V_T}\right)^{-1}. \tag{14}$$

In addition, the primary amplitude A is independent of airgun depth D.

The constants C_5, C_6, and C_7 depend on airgun design. Of these relations, equation (14) is probably the most uncertain, since the ghost influence is not accounted for in the measurements of primary-to-bubble amplitude ratio.

Of special interest is the result

$$A \propto P^{3/4},$$

which also can be deduced theoretically.

We also stress that, when using a waveshape kit, the primary amplitude is dependent on both the waveshape volume *and* the total chamber volume, while the bubble period seems to be almost exclusively dependent on the total volume.

The comparison of normalized amplitude spectra demonstrates that the spectral content (up to 200 Hz) of the primary pulse in airgun signatures is almost independent of variations in pressure and chamber volumes.

Finally, we would like to stress that equations (12)–(14) have been derived mainly by using one type of airgun (PAR 1500 C) and by varying the chamber volume, depth and pressure in the ranges 0.65–9.5 l, 5–12 m, and 10–13.7 MPa, respectively.

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