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A PDP-8 FORTRAN Program for Reduction of Acoustic Impedance Data

J. L. LASTINGER AND G. A. SABIN

Methods and Systems Branch
Underwater Sound Reference Division

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NAVAL RESEARCH LABORATORY
Underwater Sound Reference Division
P. O. Box 8337, Orlando, Florida 32806

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ABSTRACT

A FORTRAN program has been developed to compute the propagation constants of a sample of material from measured values of the complex reflection coefficient, the sample density, and the sample thickness. Because the equations relating the reflection coefficient to the propagation constants are transcendental and cannot be solved algebraically for the attenuation and sound speed, the technique is to assume a pair of values and use the method of successive approximations. The program and its present limitations are discussed, and sample computations are presented.

PROBLEM STATUS

This is an interim report on the problem.

PROBLEM AUTHORIZATION

NRL Problem S02-30

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A PDP-8 FORTRAN PROGRAM FOR REDUCTION OF ACOUSTIC IMPEDANCE DATA

INTRODUCTION

The propagation constants of a bulk material can be obtained by measuring the complex reflection coefficient at the front boundary of a sample when the value of the terminal impedance at the rear boundary is known. In practice, the measurements are made using an acoustic transmission line or rigid-walled tube within which a sound source is mounted at one end and the sample at the other.

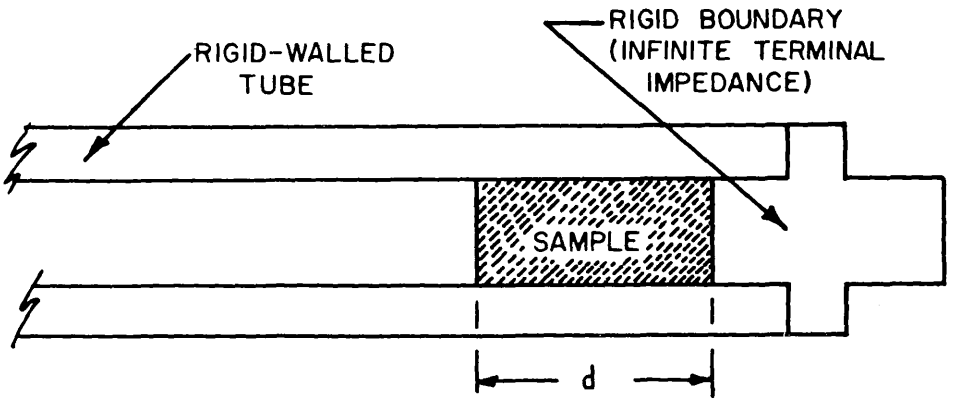

Fig. 1. Diagram, acoustic impedance tube.

Such a measuring system, shown in Fig. 1, is in use at the USRD in the frequency range 3 to 8 kHz at hydrostatic pressures to 10,000 psi. Because the sample is mounted on a specially designed steel plug, the terminal impedance presented to the sample is infinite. A description of the system and its operation, including theory and practice, has been published [1]. At first, the only available method for computing the propagation constants from the measured values of the reflection coefficient was with a calculator or slide rule and charts [2]. When a small digital computer became available, this time-consuming and laborious method was discontinued, and a FORTRAN program was written to make full use of the new computing capability. The evolution of that program is the subject of this report.

DERIVATION OF THE PROGRAM

The complex reflection coefficient r at a plane fluid-solid interface is given by

$$r = \frac{Z_{in} - Z_T}{Z_{in} + Z_T}, \tag{1}$$

where Z_{in} is the specific acoustic impedance at the boundary and $Z_T = \rho_T c_T$ is the characteristic impedance of the fluid medium--in this case, water. For a thickness d of a sample of characteristic impedance Z, terminated in an infinite impedance and normalized with respect to Z_T,

$$\frac{Z_{in}}{Z_T} = \frac{Z}{Z_T} \coth \gamma d = \frac{j\rho\omega}{Z_T(\alpha + jk)} \coth \gamma d, \qquad (2)$$

where ρ is the sample density and $\gamma = \alpha + jk = \alpha + j(\omega/c)$ is the complex propagation constant of the sample. Here, α is attenuation in nepers per unit length, ω is the angular frequency $(2\pi f)$, and c is the speed of sound in water.

The equation for Z_{in} is transcendental and cannot be solved algebraically for α and c. Therefore, the approach is to assume values for α and c, compute r, and then check the computed r against the measured r to see if the assumed values are close enough. If they are not, then different values of α and c are tried until the measured and the calculated r agree within predetermined limits. The mathematical statements in the program (those between Nos. 19 and 23, exclusive, as shown in the Appendix) account for the computations needed to go from the assumed values of α and c to the computed r. An early version of the program consisting of these mathematical statements, together with an introductory part (input statements and guiding statements), required the operator to compare visually the computed r and the measured r and then to assume new values for α and c. This routine worked much better than manual computation and the charts, but it was realized that full use of the computer's capability was not being made.

FORTRAN PROGRAM AND FLOW DIAGRAM

It seemed reasonable to assume that the entire decision-making process could be programmed so that the computer simply would type out the final values for α and c corresponding to the measured value of r. The flow diagram of Fig. 2 shows how this was accomplished. The tags for the input quantities in the equations are:

Tag	Quantity
DIST	Length of sample (d in Fig. 1) in cm.
DENS	Ratio of sample density to water density at operating pressure and temperature.
ALFA	Sound attenuation in sample (dB/m)(assumed value). Note: α = ALFA/8.686, because α is in nepers/m and ALFA is in dB/m.
C	Sound speed in sample (m/sec)(assumed value).

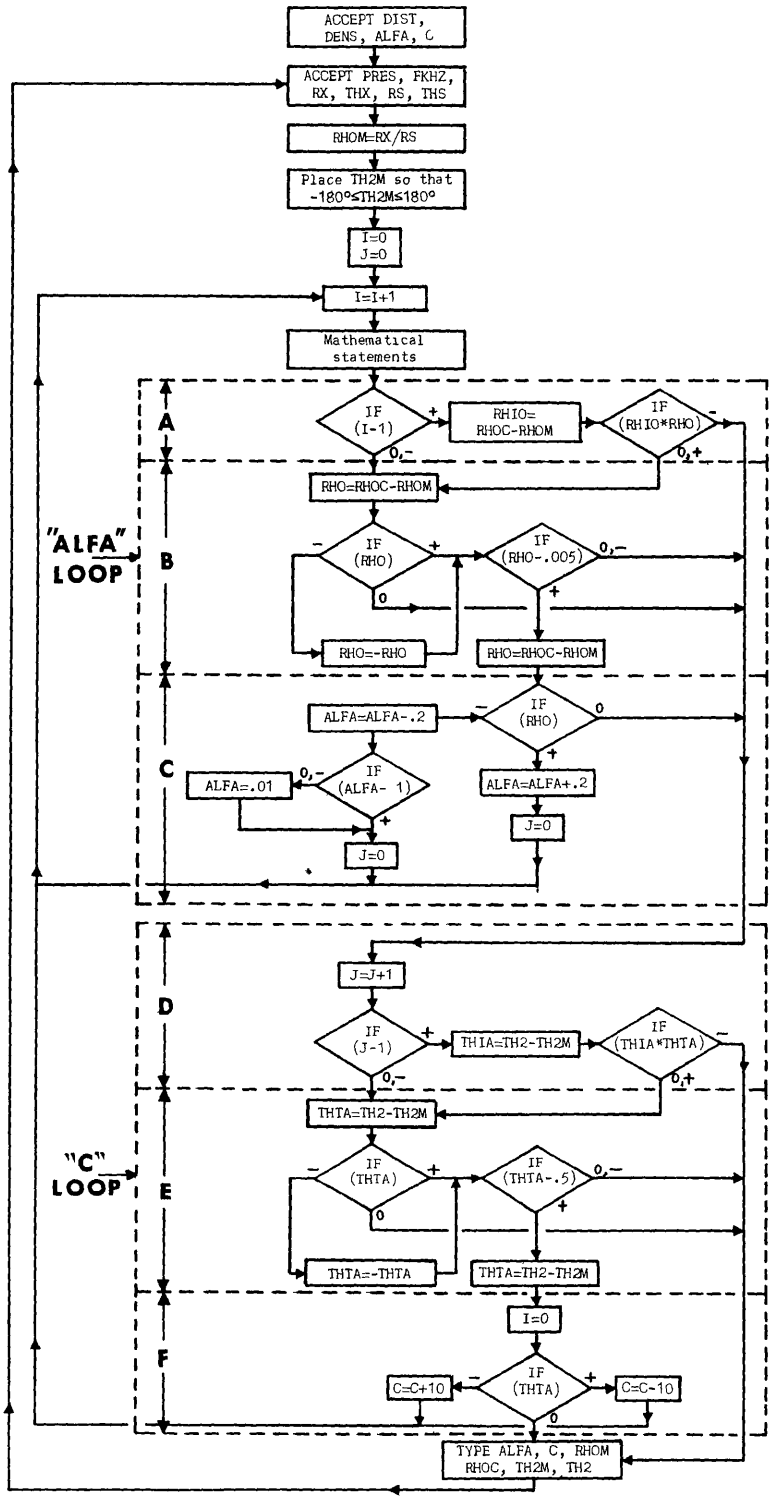

Fig. 2. Flow diagram, FORTRAN acoustic impedance program.

Tag	Quantity
PRES	Hydrostatic pressure (kpsi).
FKHZ	Frequency (kHz).
RX	Measured relative magnitude of reflection, with sample in tube.
THX	Measured relative phase angle (degrees) of reflection, with sample in tube.
RS	Measured relative magnitude of reflection, without sample.
THS	Measured relative phase angle (degrees) of reflection, without sample.

The portion of the program preceding the mathematical statements accepts the measured data and the assumed values of ALFA and C as input to the program. The mathematical statements compute the magnitude (tagged as RHOC) and phase (tagged as TH2) of the reflection coefficient. The portion following the mathematical statements performs two functions. First, it checks the computed value of RHOC against the measured value (tagged as RHOM) and decides if it is too small, too large, or within acceptable limits. This portion of the program is referred to as the "ALFA" loop. Second, if RHOC is acceptable, the program proceeds to check the phase angle (computed vs measured) in a similar way. This part of the program is called the "C" loop. If, however, the error in computed $|r|$ is not acceptable, then the assumed value of ALFA is incremented (the increment can be positive or negative, depending upon the sign of the error), and a new computation for $|r|$ is made. The check on computed $|r|$ is again made and the procedure outlined is repeated until the calculated and the measured values of $|r|$ agree within the prescribed limits. When a check is made on the computed phase angle of r and the angle is not within the specified limits, the assumed value of C is incremented and the mathematical statements are recomputed. This will automatically send the program back through the ALFA loop to check $|r|$ again, etc. (It should be realized that there is some interdependence between ALFA and the angle of r, as well as between C and $|r|$.) Type-out occurs when both the magnitude and the phase of the computed r match those of the measured r within the prescribed limits.

The eight statements beginning with the one preceding No. 80 insure that the value of TH2M = THS - THX is an angle less than 180° but greater than -180°. The correction for the additional path length 2d of the reference reflection (that is, the reflection from the standard reflector) is accounted for by the statement TH2 = THDG + TKTD, located 2 statements below No. 8. After the statement (No. 9) that converts kHz to Hz, two counting tags, I and J, appear, whose purpose is to count the number of passes through the ALFA and C loops, respectively. The reason is that the program must distinguish between the first pass and subsequent passes

through either loop. When it exits from either loop, the appropriate tag is reset to zero.

The ALFA loop (Fig. 2) can be represented as having 3 functions: (1) assess the error or difference between measured and calculated $|r|$; (2) increment the assumed ALFA; and (3) check for a change in sign of RHO, in the event that function (1) did not detect the solution (which can happen if, for instance, the increment of ALFA is large enough so that the error is never less than 0.005). Function (1) is performed by portion B of the ALFA loop; function (2), by portion C; and function (3), by portion A of the ALFA loop. Portion C also has a subloop that keeps ALFA from becoming zero. (Zero is a point of mathematical discontinuity in the fifth statement after No. 19.)

The C loop is analogous to the ALFA loop, and similar functions are represented by the corresponding parts of the two. That is, the error check is made by part E of the C loop, the increment by part F, and the check for change of sign in the error, by part D of the C loop.

COMPUTATIONS

Sample input and output data are shown in Fig. 3. A print-out of the measured and the final calculated values of r is requested so that a visual cross-check of the final agreement can be made. This step was added during the program development period as a test for the over-all operation of the program, and it seems worth retaining for the same reason.

Typically, computer print-out of the answers occurs within 10 to 15 seconds; occasionally, however, the computer will not arrive at the answer within a reasonable period of time (2 to 3 minutes) and continues computing. When this occurs, frequently it is possible to start over and obtain the solution by assuming different initial values for ALFA and C. This problem has not been solved completely; the difficulty seems to occur most frequently with data from samples whose densities are considerably greater (say, by a factor of 3, or more) than that of water.

CONCLUSION

This program is an immense aid in reducing data obtained from the USRD acoustic impedance pulse tube. The decisions involved in the process of successive approximations are all made within the program, and type-out occurs whenever both the magnitude and the phase of the measured and the calculated r are within the prescribed limits of error. The program has been found useful for over 95% of the measured data. The failure to converge in exceptional cases has been, and still is, a subject of investigation for which no completely satisfactory remedy has yet been found.

```
SYSZDA
INPUT:LENGTH(CM),DENSITY(GMS/CC),ALPHA(DB/M),C(M/SEC)
      PRESSURE(PSIG/1000),FREQ.(KHZ),RX,THX,RS,THS

OUTPUT:ALPHA,C
       RHOM,RHOC,TH2M,TH2

12.6 1.16 5 3000
.1 3 96 289 118 17

+0.419999E+1     +0.215000E+4
+0.813559E+0     +0.814435E+0     +0.880000E+2     +0.877163E+2

.1 3.5 123 7 161 96

+0.519998E+1     +0.214000E+4
+0.763975E+0     +0.761988E+0     +0.890000E+2     +0.885513E+2

.1 4 148 95 192 184

+0.499998E+1     +0.217000E+4
+0.770833E+0     +0.768448E+0     +0.890000E+2     +0.897219E+2

.1 4.5 19 179 187 246 270

+0.679997E+1     +0.216000E+4
+0.727642E+0     +0.727465E+0     +0.830000E+2     +0.826963E+2

.1 5 214 282 300 1

+0.879996E+1     +0.216000E+4
+0.713333E+0     +0.718311E+0     +0.790000E+2     +0.790583E+2

.1 6 178 111 269 202

+0.177998E+2     +0.221000E+4
+0.661710E+0     +0.658881E+0     +0.910000E+2     +0.910585E+2

.1 7 167 225 261 300

+0.269996E+2     +0.202000E+4
+0.639847E+0     +0.639308E+0     +0.105000E+3     +0.105160E+3

.1 8 238 1 327 137

+0.175994E+2     +0.200000E+4
+0.727829E+0     +0.726132E+0     +0.136000E+3     +0.136503E+3
```

Fig. 3. Sample input and output data, FORTRAN acoustic impedance program.

The program also has been run successfully on a TIME-SHARING terminal by introducing the minor changes necessary to make it compatible with TIME-SHARING FORTRAN.

References

[1] G. A. Sabin, "Acoustic-Impedance Measurements at High Hydrostatic Pressures," J. Acoust. Soc. Am. 40, 1345-1353 (1966).

[2] G. A. Sabin, "Analysis of Acoustic Impedance Data," Navy Underwater Sound Reference Laboratory Research Report No. 81 (1966)(AD-632 075).

Appendix

FORTRAN PROGRAM

```
C; SYSTEM Z ALPHA (DB/M) & C (M/SEC) 5TH ED REV. 2 JAN 1968
C; CONSTANT INCREMENT METHOD
   TYPE 1
1;FORMAT("INPUT:LENGTH(CM),DENSITY(GMS/CC),ALPHA(DB/M),C(M/SEC)",/)
   TYPE 2
2;FORMAT("       PRESSURE(PSIG/1000),FREQ.(KHZ),RX,THX,RS,THS",/,/)
   TYPE 4
4;FORMAT("OUTPUT:ALPHA,C",/)
   TYPE 7
7;FORMAT("        RHOM,RHOC,TH2M,TH2",/,/)
   ACCEPT 5,DIST,DENS,ALFA,C
3; ACCEPT 5, PRES,FKHZ,RX,THX,RS,THS
5; FORMAT (E)
   RHOM=RX/RS
   IF (THS-180.)80,80,90
80;IF(THX-THS-180.)100,100,110
90;IF(THX-THS+180.)120,100,100
100;TH2M=THS-THX
    GO TO 9
110;TH2M=THS-THX+360.
    GO TO 9
120;TH2M=THS-THX-360.
9; FREQ=FKHZ*1000.
   I=0
   J=0
19;I=I+1
  TAFD=.230259E-2*ALFA*DIST
  TWKD=.125664*FREQ*DIST/C
  CHAD=EXPF(TAFD)+EXPF(-TAFD)
  FMAG=SQTF((CHAD+2.*COSF(TWKD))/(CHAD-2.*COSF(TWKD)))
  A=TWKD/TAFD
  ZMAG=DENS*C*FMAG*SQTF(A*A/(A*A+1.))/(1460.+10.*PRES)
  SOSH=2.*SINF(TWKD)/(EXPF(TAFD)-EXPF(-TAFD))
  ZANG=ATNF(1./A)-ATNF(SOSH)
  RHOC=SQTF((ZMAG*ZMAG+1.-2.*ZMAG*COSF(ZANG))/(ZMAG*ZMAG+'
  1.+2.*ZMAG*COSF(ZANG)))
  TH=ATNF(2.*ZMAG*SINF(ZANG)/(ZMAG*ZMAG-1.))
  IF(ZMAG-1.)6,8,8
6;TH=3.14159+TH
8;THDG=TH*57.2958
  TKTD=7.2*FREQ*DIST/(1460.+10.*PRES)
  TH2=THDG+TKTD
20;IF(TH2-180.)23,23,22
22;TH2=TH2-360.
  GO TO 20
23;IF(I-1)25,25,29
29;RHIO=RHOC-RHOM
  IF(RHIO*RHO)39,25,25
25;RHO=RHOC-RHOM
   IF(RHO)30,39,31
30;RHO=-RHO
31;IF(RHO-.005)39,39,32
32;RHO=RHOC-RHOM
   IF(RHO)11,39,10
10;ALFA=ALFA+.2
   J=0
   GO TO 19
11;ALFA=ALFA-.2
   IF(ALFA-.1) 60,60,61
60;ALFA=.01
61;J=0
   GO TO 19
39;J=J+1
   IF(J-1)85,85,40
40;THIA=TH2-TH2M
   IF(THIA*THTA)24,85,85
85;THTA=TH2-TH2M
   IF(THTA)41,24,42
41;THTA=-THTA
42;IF(THTA-.5)24,24,43
43;THTA=TH2-TH2M
   I=0
   IF(THTA)17,24,16
16;C=C-10.
   GO TO 19
17;C=C+10.
   GO TO 19
24;TYPE 14,ALFA,C,RHOM,RHOC,TH2M,TH2
14;FORMAT(/,E,E,/,E,E,E,E,/,/)
  GO TO 3
  END
```

```
SYMPRT

DIST   7574
DENS   7571
ALFA   7566
C      7563
PRES   7560
FKHZ   7555
RX     7552
THX    7547
RS     7544
THS    7541
RHOM   7536
TH2M   7522
FREQ   7511
I      7505
J      7503
TAFD   7476
TWKD   7470
CHAD   7462
FMAG   7457
A      7446
ZMAG   7443
SOSH   7427
ZANG   7421
RHOC   7413
TH     7374
THDG   7355
TKTD   7347
TH2    7333
RHIO   7321
RHO    7316
THIA   7270
THTA   7265
  6632   7253
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13. ABSTRACT

A FORTRAN program has been developed to compute the propagation constants of a sample of material from measured values of the complex reflection coefficient, the sample density, and the sample thickness. Because the equations relating the reflection coefficient to the propagation constants are transcendental and cannot be solved algebraically for the attenuation and sound speed, the technique is to assume a pair of values and use the method of successive approximations. The program and its present limitations are discussed, and sample computations are presented.

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