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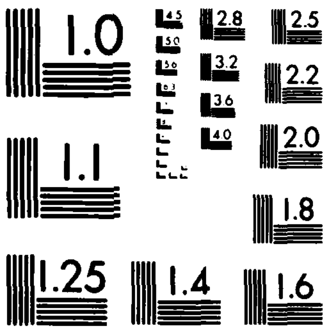

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TECHNICAL MEMORANDUM

WSRL-0360-TM

THE MEASUREMENT OF THE DEPTH OF A SONAR ARRAY

G.M. COLLINS and A.P. CLARKE

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COPY No. 22

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TECHNICAL MEMORANDUM

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THE MEASUREMENT OF THE DEPTH OF A SONAR ARRAY

G.M. Collins and A.P. Clarke

SUMMARY

The measurement of the depth of a sonar array using a modified counting technique for the demodulation and decoding of frequency modulated instrumentation signals is presented. A data dependent overflowing counter feeds demodulated data into a Programmable Read Only Memory based lookup table. Controlled, repeated counter overflows maximise the information content of the data. The system resolution is thus considerably increased with no effect on accuracy or component count. Frequency discriminating circuits are superfluous with this technique.

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1. INTRODUCTION

One of the tasks of the Weapons Systems Research Laboratory is the investigation of the design, development and performance of passive sonar systems. These systems will be employed in the long range detection, identification and surveillance of vessels operating in the waters surrounding Australia.

The shape and attitude of a horizontally towed sonar array will change in accordance with ocean currents, swells etc. The processing of acoustic signals received from such arrays will be considerably enhanced if the array shape can be well defined. Depth sensors distributed along the acoustic section of the array can define the array shape in the vertical plane.

Sonar array depth sensors frequently contain quartz crystal pressure transducers. At the data processing station, pressure sensitive signals from the array transducers are accepted and converted into depth measurements. In this case, the depth information is numerically displayed and is also made available in analog voltage form for subsequent recording and analysis.

The design and implementation of the pressure to depth conversion hardware are discussed in this report. Use of an analysis given in the Appendix demonstrates the level of accuracy attainable.

2. THE PRESSURE TRANSDUCERS

The sinusoidal signal from the array pressure transducers consists of a frequency modulated tone whose modulation index is dependent on water pressure. The frequency of the tone varies non-linearly from approximately 40 kHz at a water depth of 0 m to approximately 39.5 kHz at a depth of 100 m. The transducer transfer function is of the form:

$$P = AX - BX^2$$

where P represents pressure, A and B are transducer calibration coefficients, and X represents the modulated frequency information.

The pressure transducer is calibrated by the transducer manufacturer prior to its despatch. Recalibration and calibration checking facilities are also available from the manufacturer.

3. THE DEPTH CONVERSION HARDWARE

A block diagram of the hardware which converts pressure sensitive signals into depth measurements is given in figure 1.

Fundamentally, the hardware consists of two sections - the frequency counter and the depth conversion circuitry. The frequency counter is based on an enhanced form of the counting technique known as "multiple period averaging"(ref.1). With this technique, a reference frequency is counted for a period which is determined by the frequency of the signal from the source being measured. The counting period incorporates many cycles of the input signal frequency. This will reduce the effects of incoming noise, jitter etc.

A Programmable Read Only Memory (PROM) array accepts data from the frequency counter and, operating as a lookup table, generates equivalent depth information. The principle on which the lookup table is based is given in Section 7.

A more detailed description of the pressure to depth conversion hardware follows:

(a) The low amplitude signal from the pressure transducer is sent to the level translator via the acoustic array and its associated tow cable. Within the translator, the signal is amplified and band limited by a 27 kHz to 60 kHz bandpass filter. Filtering reduces the level of the out of band noise present with the signal. The filtered analog signal is then converted into logic compatible levels by a phase locked loop. As a consequence of the use of the phase locked loop, the signal to noise ratio of the transducer signal is considerably enhanced.

(b) A programmable counter accepts n cycles of the incoming signal from the level translator, where n is a preset constant. A design example given in Section 6 demonstrates how the value of n is determined.

(c) The main gate is enabled while the above cycle counter is active. This allows a previously zeroed binary up counter to be incremented at the rate of the gated reference frequency ie 1 MHz. Because of the low modulation index of the transducer signal, the binary counter is allowed to overflow many times. This increases the modulation index of the data contained in the counter and effectively increases the system resolution to better than 1 part in 100 000. Sections 5 and 6 contain more information on the overflowing counter principle.

The increased resolution means the transducer frequency is accurately measured to better than 0.5 Hz.

(d) After n transducer signal cycles have been counted, the main gate is disabled by the input signal cycle counter. This will halt the 1 MHz clock to the binary counter and leave the counter with contents which are derivatives of the transducer frequency. A pipelining latch stores this data, thus allowing the frequency counter to commence a new data acquisition cycle.

The latched data must be converted into appropriate units to obtain depth information. This conversion is accomplished by a PROM array configured as shown in figure 2.

The two PROM's contain a lookup table which, when used in conjunction with the frequency counter, performs the following tasks:

(1) linearises the data,

(2) calculates absolute pressure from the measured frequency of the transducer signal,

(3) calculates water pressure by subtracting atmospheric pressure from the absolute pressure,

(4) converts water pressure information into depth measurements,

(5) rounds off the depth measurements to the nearest 0.1 m,

(6) formats the resultant depth data into a three decade Binary Coded Decimal (BCD) code.

Data from the PROM array is fed in parallel to a three digit numeric display and a BCD encoded digital to analog converter. The converter output can be recorded on analog magnetic tape for subsequent analysis and correlation with the acoustic data.

4. PERFORMANCE

Some display unit details are given below:

(a) water depth range = 0 to 99.9 m.

(b) numeric display resolution = 0.1 m.

(c) accuracy ≥ 0.1 m.

(d) sample rate - approximately 4 Hz.

(e) anti aliasing filter - not necessary because of the high sample rate of the unit.

5. DISCUSSION

Successful operation of the frequency counting component of the hardware is dependent on controlled, repeated overflows of the 11 bit binary counter. The number of overflows permissible is inversely proportional to the modulation index of the incoming signal.

Overflows increase the modulation index of the data contained in the 11 bit counter. In this way, the information content of the counter data is increased. This means that, in this particular application, the resolution of the data held in the counter is increased from 1 part in 2048 to better than 1 part in 100 000.

The overflowing counter can only operate correctly over a narrow range of input signal frequencies. Therefore the sampling period of the unit must be controlled to prevent out of range operation of the counter. This is accomplished by programming the input signal cycle counter to accept a known number of cycles. The deleterious effects of noise, jitter etc. present with the incoming signal will decrease as the number of input cycles accepted by the counter is increased.

6. COUNTER DESIGN EXAMPLE

A practical, iterative design example may best illustrate the concepts previously discussed.

The relationship between pressure applied to the transducer and the resultant output signal period is represented by the equation:

$$P = A(1-To/T) - B(1-To/T)^2$$

where A, B and To are calibration coefficients and T is the period of the transducer output signal for a pressure P.

Assume the display unit is required to interface to a transducer which has the following characteristics:

(a) Transducer output signal period at a water depth of [illegible]

(b) Transducer output signal period at a water depth of 100 m = 25.1836 µs.

Also assume that the non linearities in the transducer transfer function are relatively minor. Thus, for the sake of the preliminary design, the transfer function can be viewed as being linear.

The change in transducer output period over the entire depth range

$$= 25.1836 - 24.8388\ \mu s = 0.3448\ \mu s$$

All of the depth information is contained within this change in period - the period itself only acts as a carrier for that information. Thus, for optimum data resolution, the change in transducer period must be spread over a maximum of $2^{11} - 1 = 2047$ states within the 11 bit binary counter.

When the main gate is enabled by the transducer signal cycle counter, the previously zeroed binary counter is incremented at a 1 MHz rate. This means the binary counter has an effective "time window" equal to:
number of possible counter states x counter clock period

$$= 2047 \text{ states} \times 1\ \mu s$$

$$= 2047\ \mu s$$

It is this "time window" into which the changes in transducer period must fit. Therefore:

$$n \leq \frac{\text{11 bit binary counter "time window"}}{\text{maximum change in transducer signal period}}$$

$$\leq \frac{2047\ \mu s}{0.3448\ \mu s}$$

$$\text{ie} \quad n \leq 5936.8$$

where n is the number of transducer signal periods during which the main gate is enabled.

Because of the particular input signal cycle counter design used, n must include a half cycle. Therefore let n equal 5936.5, noting however that the value of n is a tentative figure which may change as the design progresses.

The number of 11 bit binary counter overflows that occur during acquisition of the transducer data can now be determined ie:

The minimum time during which the main gate will be enabled
= number of transducer cycles counted during acquisition of the data x minimum transducer signal period = n cycles x 24.8388 µs/cycle.

transducer signal period = n cycles x 24.8388 µs/cycle.

The number of 11 bit counter overflows that occur is proportional to this time ie: minimum gate enable time = N x counter size x counter clock period.

$$\text{ie} \quad n \text{ cycles} \times 24.8388\ \mu s/\text{cycle} = N \times 2048 \times 1\ \mu s$$

where N represents the number of 11 bit counter overflows.

Therefore,

$$N < 71.99$$

It is preferred that N be an integer, therefore let N = 71.

Having tentatively determined the number of 11 bit counter overflows that occur during acquisition of the data, it is now possible to define the final system configuration:

For the 11 bit counter, the minimum count prior to underflow

$$= 71 \text{ overflows} \times 2048 \text{ counts/overflow}$$

$$= 145\ 408 \text{ counts of the 1 MHz clock.}$$

The maximum count prior to overflow
= minimum count prior to underflow + 2047 counts = 147 455 counts.

The number of transducer output signal cycles that must be counted can now be determined:

$$n \text{ minimum} \geq \frac{\text{minimum count period}}{\text{minimum transducer signal period}}$$

$$\geq \frac{145\ 408 \text{ counts} \times 1\ \mu s/\text{count}}{24.8388\ \mu s}$$

$$\geq 5854.07$$

and similarly,

$$n \text{ maximum} \leq \frac{\text{maximum count period}}{\text{maximum transducer signal period}}$$

$$\leq \frac{147\,455 \text{ counts} \times 1\ \mu s/\text{count}}{25.1836\ \mu s}$$

$$\leq 5855.2$$

Therefore n must lie in the range:

$$5854.07 \leq n \leq 5855.2$$

Since n must include a half cycle, let n = 5854.5.

The design boundaries have now been established. Computer modelling of the frequency counter is used to verify correct circuit operation over the entire depth range.

A performance summary of the frequency counting hardware is given below:

(a) number of transducer output signal cycles counted during acquisition of the data = 5854.5,

(b) number of 11 bit counter overflows occurring during data acquisition = 71,

(c) worst case data acquisition time = 5854.5 x 25.1836 μs = 147 ms.

(d) counter resolution > 1 part in 145 408.

It is interesting to note that an 18 bit counter would be required to achieve the same resolution using conventional techniques. The number of bits required is quite significant - especially when contemplating implementation of the PROM based lookup table. Every one bit increase in the size of the frequency counting circuit requires a lookup table which is double the former size.

7. PRESSURE TO DEPTH CONVERSION PRINCIPLE

After the transducer data has been acquired (ie after n cycles have been detected by the input signal cycle counter), the main gate is disabled. This will inhibit further clocking of the 11 bit binary counter by the 1 MHz reference frequency. The counter will thus remain static with its contents being directly related to the pressure which was applied to the transducer.

It is possible to determine the transducer signal period since: signal period = [(N overflows x 2^{11} counts/overflow) + current contents of 11 bit counter] x period of reference frequency/n signal cycles.

The absolute pressure applied to the transducer can then be derived from the previously defined transducer transfer function.

Depth information can be determined by subtracting atmospheric pressure from the transducer absolute measurement and combining the result with the appropriate pressure to depth conversion factor.

In practice, the above conversion sequence does not occur. Other than the contents of the 11 bit binary counter, every component of the conversion procedure is a known constant. This circumstance allows the counter contents to directly address a PROM based lookup table which has been pre-programmed to accommodate all factors.

The approach virtually eliminates the majority of the hardware/software costs normally associated with the measurement of pressure and subsequent depth conversion.

8. DESIGN FEATURES

The important features of this design approach are listed below:

(a) Heterodyning or frequency discriminating components that isolate the pressure dependent signal from its carrier frequency are unnecessary.

(b) Minimal hardware is required. Because of the signal processing requirements of the unit, a low to medium performance microcomputer/microprocessor based design would still require frequency counting hardware. Besides the counters, the only other components in the basic system are a pair of PROM's.

The circuit size is also minimised by allowing a low resolution counter to overflow repeatedly in a controlled manner. This technique is legitimate if the operational circumstances are well defined.

(c) The system throughout is high - the address access time of the PROM's (a few hundred nano-seconds) is the main propagation delay present after accumulation of the data by the counter.

(d) Calibration of the display unit is unnecessary. Because of its digital implementation, the unit will operate predictably within the design constraints.

(e) The technique is versatile - many FM encoded signals can be accommodated using this approach.

(f) The circuit operating concepts are simple. This facilitates maintenance and equipment modifications.

(g) Cheap, readily available components are used throughout the unit.

9. INPUT SIGNAL/NOISE RATIO CONSIDERATIONS

The accuracy with which the transducer signal period can be measured is somewhat dependent on the level of the noise present with the incoming signal. When the equipment noise threshold has been reached, a further decrease in the input signal/noise ratio will cause inaccurate performance of the display unit.

Based on probability theory, an approximate analysis of the effect of varying the transducer signal/noise ratio is given in the Appendix. The results of the analysis are summarised in Table 1.

TABLE 1. VARIATION IN $\sigma(f)$ FOR 27 kHz < f < 60 kHz FOR 5854.5 CYCLES OF NOISY INPUT DATA AT SIGNAL/NOISE POWER RATIOS RANGING FROM 20 TO 80 dB, WHERE σ REPRESENTS ONE STANDARD DEVIATION

Transducer signal/noise ratio (dB)	$\sigma(f)$....Hz		
	f = 27 kHz	f = 35 kHz	f = 40 kHz
20	6.08	7.88	9.00
40	0.608	0.788	0.900
60	0.0608	0.0788	0.0900
80	0.00608	0.00788	0.00900

A change in transducer depth of 0.1 m corresponds to a change in transducer frequency of approximately 0.5 Hz. Thus over the transducer signal frequency range, a perturbation of < one standard deviation at 0.5 Hz requires an approximate transducer signal/noise ratio of >50 dB. To obtain this level of performance, various techniques are incorporated in the system ie:

(a) use of a balanced, twisted pair signal transmission line between the transducer and the display unit.

(b) impedance matching of the transmission line to the transducer and the display unit

(c) use of a phase locked loop in the level translator circuitry.

10. CONCLUSIONS

An unusual approach to the demodulation and decoding of FM instrumentation signals has been demonstrated for a particular design problem. The technique is novel and, for a moderate signal/noise ratio, features high accuracy and resolution combined with a very low component count.

11 ACKNOWLEDGEMENT

The authors wish to acknowledge the contribution by Mr W. Marwood of the Weapons Systems Research Laboratory in providing software support.

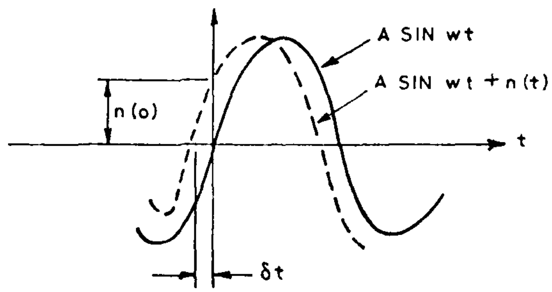
REFERENCE

No.	Author	Title
1		"The Fundamentals of Electronic Frequency Counters". Hewlett Packard Application Note 17[illegible]

APPENDIX I

THE ERROR DUE TO NOISE IN MEASURING THE FREQUENCY OF A NOISY SINE WAVE

Noise will introduce an error in measuring the duration (and hence frequency) of a fixed number of cycles of a narrow band signal. The noise will, if narrow band, displace the position of the zeroes as shown in the following figure:



For expediency, consider the noise is limited to the depth sensor range as described in the body of the report. This range is adequate for describing the signal and noise statistics as narrow band.

If $\delta t << 2\pi/w$ a Taylor's series expansion can be written for $n(-\delta t)$ ie:

$$n(-\delta t) = n(0) - dn/dt\ \delta t + \frac{d^2n/dt^2(\delta t)}{2!} - \ldots\ldots$$

A zero of the corrupted signal occurs where

$$A \sin w(-\delta t) + n(-\delta t) = 0$$

Hence $-A \sin w(\delta t) + n(0) - dn(0)/dt,\ \delta t + \ldots\ldots = 0$

If $wt\delta$ is small (a necessary assumption for the Taylor's series expansion to be valid):

$$\sin w(\delta t) \cong w(\delta t)$$

and hence

$$\delta t \cong \frac{n(0)}{Aw + dn(0)/dt}$$

If the noise is normally distributed then the distribution of $dn(t)/dt$ follows easily.

However, n(t) and dn(t)/dt are correlated and this poses some difficulty in defining the distribution of δt.

Since the noise is band limited the derivative is unlikely to exceed Aw and hence for signal to noise ratios greater than one:

$$\delta t \;\widehat{=}\; \frac{-n(0)}{Aw}$$

Hence

$$\sigma(\delta t) \;\widehat{=}\; \frac{\sigma(n(t))}{Aw}$$

$$\widehat{=}\; \frac{1}{(2\pi f).\frac{A}{\sqrt{2}\sigma(n(t))}.\sqrt{2}}$$

$$= \frac{1}{2\pi\ \sqrt{2} fS}$$

where S = signal to noise voltage ratio.

To measure the duration of n cycles two zeroes are involved. If the distributions at each pair of zeroes are independent, the standard deviation of the time interval to be estimated is:

$$\sigma(t) = \sigma(\delta t)\ \sqrt{2}$$

$$= \frac{1}{2\pi fS}$$

Thus for n cycles:

$$\sigma(t) = \frac{1}{2\pi fS\ \sqrt{n}}$$

and, as f = 1/t

$$\sigma^2(f) \;\widehat{=}\; \frac{\sigma^2(t)}{t^4}$$

$$\widehat{=}\; f^4\ \sigma^2(t)$$

$$\text{ie}\quad \sigma(f) \;\widehat{=}\; \frac{f}{2\pi S\ \sqrt{n}}$$

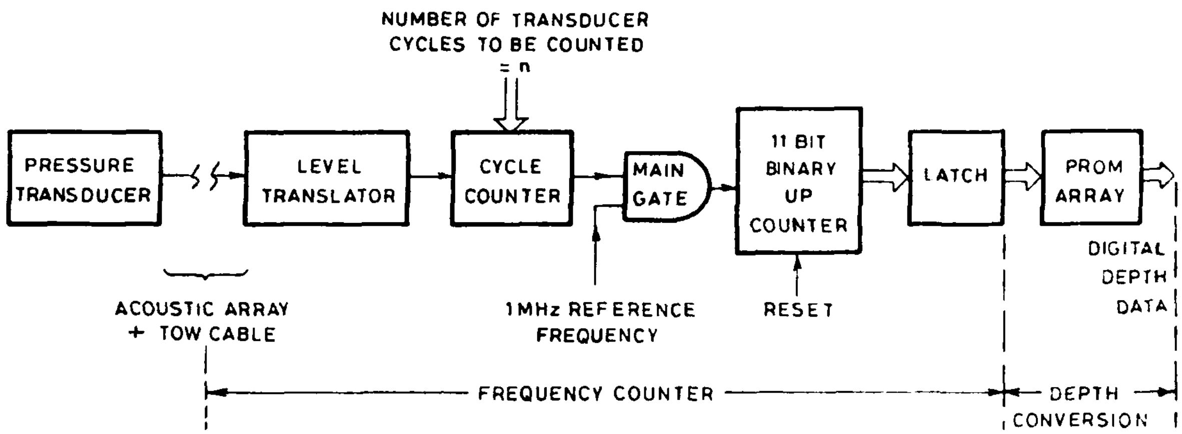


Figure 1. Pressure to depth conversion hardware

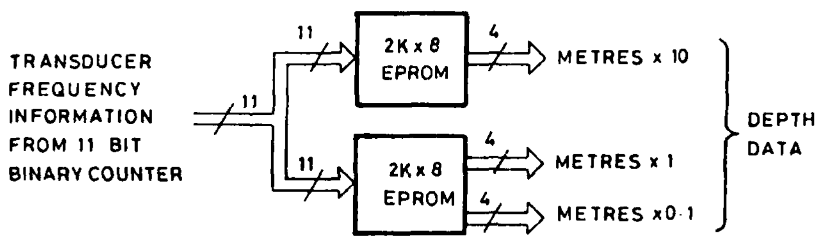


Figure 2. Depth conversion circuitry

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DOCUMENT CONTROL DATA SHEET

Security classification of this page: UNCLASSIFIED

1 DOCUMENT NUMBERS		2 SECURITY CLASSIFICATION	
AR Number:	AR-003-785	a. Complete Document:	Unclassified
Series Number:	WSRL-0360-TM	b. Title in Isolation:	Unclassified
Other Numbers:		c. Summary in Isolation:	Unclassified

3 TITLE

THE MEASUREMENT OF THE DEPTH OF A SONAR ARRAY

4 PERSONAL AUTHOR(S):

G.M. Collins and
A.P. Clarke

5 DOCUMENT DATE:

May 1984

6 6.1 TOTAL NUMBER OF PAGES: 12

6.2 NUMBER OF REFERENCES: 1

7 7.1 CORPORATE AUTHOR(S):

Weapons Systems Research Laboratory

7.2 DOCUMENT SERIES AND NUMBER

Weapons Systems Research Laboratory
0360-TM

8 REFERENCE NUMBERS

a. Task:

b. Sponsoring Agency:

9 COST CODE:

10 IMPRINT (Publishing organisation)

Defence Research Centre Salisbury

11 COMPUTER PROGRAM(S)
(Title(s) and language(s))

12 RELEASE LIMITATIONS (of the document):

Approved for Public Release

Security classification of this page: UNCLASSIFIED

Security classification of this page: UNCLASSIFIED

13 ANNOUNCEMENT LIMITATIONS (of the information on these pages):

No limitation

14 DESCRIPTORS:

a. EJC Thesaurus Terms

Sonar arrays
Depth finding
Pressure sensors

b. Non-Thesaurus Terms

15 COSATI CODES:

17010

16 SUMMARY OR ABSTRACT:
(if this is security classified, the announcement of this report will be similarly classified)

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