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SIGNAL PROCESSING CONSIDERATIONS IN THE DESIGN OF A SONAR SYSTEM FOR DIVERS

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1. INTRODUCTION

With the advent of digital integrated circuits and other miniature components the design and construction of very small and inexpensive sonar systems has become possible. Compactness is a vital requirement if such a system is to be used by a diver, but in addition it must be capable of delivering sufficient power to the transmitting transducer to achieve the range required. In commercial applications the power may possibly be fed along an umbilical cable from a diving chamber, but in non-commercial applications the power must be derived from batteries. These are usually the most bulky components in a self contained sonar system.

Most conceivable applications of diver-held sonar systems do not involve great ranges. For navigation, search and survey purposes, the maximum operational range may be no more than two or three hundred metres, primarily because the diver's own range is limited by his life support system. In surveying a wreck site or an area of biological or geological interest, a sonar system with a range of a hundred metres would be quite suitable. All these applications involve the use of transponders, which when interrogated by an acoustic pulse will reply with another pulse or a coded series of pulses, at the same frequency or a different frequency.

The primary aim of this paper is to deduce the electrical power required to drive a transmitting transducer in order to achieve the necessary range to detect a mid-water target of known target strength. Our approach uses the active sonar equation for a specified transducer geometry, transducer efficiency, pulse length, sound absorption in water, and detection threshold for deterministic signals. Clearly, if a sonar system is designed to detect a mid-water target at a certain range, then it will be capable of detecting a transponder at twice that range if the transponder has the same detection threshold as the sonar receiver and replies at the same transmitting power.

The carrier frequency we have chosen is 300 kHz because it allows a small transducer array with a narrow beamwidth to be made. For our array of ten elements arranged in two rows of five and measuring 49 mm x 48 mm the -3 dB beamwidth is about 5^{o}.

2. BANDWIDTH REQUIREMENT

If an acoustic pulse sent out by a sonar transmitter encounters two mid-water targets at ranges r_1 and r_2 along the transmission axis, two echoes will be returned to the sonar receiver. If the receiver has a large bandwidth compared to that of the transmitted pulse then the echoes will be undistorted by the receiver and separated in time provided $r_2 - r_1 > \ell$, where ℓ is the length of the acoustic pulse in the water. Here, the length $\ell = ct$, where c is the velocity of sound and t is the pulse duration.

Thus the range resolution required determines the maximum duration of the transmitted pulse. It also determines the receiver bandwidth. If the bandwidth is too large the receiver may detect too much extraneous noise; if it is too small the received pulse will be distorted and lengthened, thereby reducing the range resolution.

A good rule of thumb is that the system should have a bandwidth of 1.2/t. For example, in the system being developed at Loughborough ranges can be displayed to the nearest metre, which requires a resolution of 0.5 m, corresponding to a pulse duration of ℓ/c and a bandwidth of 1.2 c/ℓ. If the velocity of sound is 1500 ms^{-1}, then t = 333 μs and the receiver bandwidth is 3.6 kHz.

It must be emphasised that the duration of the acoustic pulse propagated through the water is always longer than that of the electrical pulse driving the transmitting transducer because of the transducer's vibration characteristics[1]. Briefly, the duration of the acoustic pulse depends on the Q of the transducer or transducer array. For an air-backed array made of elements of PZT-4 the Q (resonant frequency / -3 dB bandwidth) is approximately 36. If the array is driven by a sinusoidal electrical pulse with a "square" envelope it takes a time of approximately Q cycles to "ring up" to its steady state excitation. After the end of the electrical pulse it takes the same time to "ring down" again. Thus, the acoustic pulse in the water will be approximately Q cycles longer than the applied electrical pulse. If the array subsequently detects the echoes returning from targets, the waveform of the received pulse will be further distorted elongated as shown in Figure 1.

For a resonant frequency of 300 kHz each cycle lasts 3.33 μs, so that Q cycles represents a duration of 36 x 3.33 = 120 μs. From this it may be deduced that in order to propagate a 333 μs acoustic pulse, a 213 μs electrical driving pulse must be generated to obtain our required bandwidth of 3.6 kHz.

In practice, a slightly larger bandwidth of 5 kHz is still acceptable for two reasons. Firstly, this bandwidth can be achieved using commercially available ceramic filters; secondly, the slightly inferior noise immunity is of no consequence at a centre frequency of 300 kHz. For the analysis in the next section a "worst case" bandwidth of 10 kHz is assumed. This corresponds to an acoustic pulse duration of $(1.2/10^{-2} + 120)$ = 240 μs, say 250 μs approximately.

3. POWER REQUIREMENT

The electrical power that must be supplied to our sonar array to achieve a certain range can be deduced from the active sonar equation[2]. In its practical application our diver-held sonar system will display the ranges of up to sixteen targets, therefore it is its capability of discriminating echo signals from noise that is important and we should use the sonar equation in terms of detection threshold. When a target is just detectable, the signal-to-noise ratio is the same as the detection threshold which is defined as

$$DT = SL - 2TL + TS - NL + DI_R \qquad (1)$$

where DT is Detection Threshold, SL is Source Level, TS is Target Strength, NL is Noise Level and DI_R is receiver Directivity Index.

Source Level, which is a measure of the intensity of radiated sound, may be defined for a directional array as[2]

$$SL = 170.8 + 10 \log P_a + DI_T \qquad (2)$$

where DI_T is the transmitter Directivity Index and P_a is the radiated acoustic power, which is related to the electrical driving power P_e by the electromechanical conversion efficiency η, given by

$$\eta = P_a / P_e \qquad (3)$$

Substituting (2) and (3) into (1) and rearranging we have the following expression in terms of electrical power:

$$10 \log P_e = -DI_T + 2TL - TS + DT - 170.8 + NL - DI_R - 10 \log \eta \qquad (4)$$

Having arrived at a suitable expression we need to consider more closely what each parameter represents, then to evaluate it. We will assume the range to be achieved is 200 m.

(i) Directivity Index, DI_T depends on the geometry of the array. For a rectangular array with sides of length L_1 and L_2, and for a wavelength of sound λ

$$DI_T = 10 \log(4\pi L_1 L_2/\lambda^2) \qquad (5)$$

Our array is very nearly a square, measuring 49 mm by 48 mm, and at its resonant frequency of 300 kHz the wavelength is 5 mm, therefore $DI_T \approx 30$ dB.

Since the same array is used both for transmitting and receiving, the receiving Directivity Index DI_R is the same, i.e.

$$DI_T = DI_R = 30 \text{ dB} \qquad (6)$$

(ii) Transmission Loss, TL is a function of both geometrical spreading (assumed here to be spherical) and absorption. For the active sonar case, the transmission loss for the "round trip" from array to target and back again is given by

$$2TL = 40 \log_{10} r + 2\alpha r \qquad (7)$$

where r is the range in metres and α is the absorption coefficient in dBm^{-1}. At a frequency of 300 kHz we will assume the absorption coefficient to be $\alpha = 0.1\ dBm^{-1}$, therefore for our required range of 200 m

$$2TL = 132 \text{ dB} \qquad (8)$$

(iii) Target Strength, TS In these calculations we will use a Target Strength of -15 dB, which is appropriate for an "unsuited swimmer". When the system is being used to search for a diver TS would be higher, perhaps better than -10 dB, because compressed air tanks, a wet suit or dry suit, and the diver's bubbles of exhaled air, behave as very good acoustic reflectors.

(iv) Detection Threshold DT can be calculated using a formula for deterministic signals (which is appropriate here):

$$DT = 10 \log(S/N_o) = 10 \log(d/2t) \qquad (9)$$

where S is the signal power in the receiver bandwidth,
N_o is the noise power in a 1 Hz band,
d is the detection index on the receiver-operating characteristics (reproduced from reference (2) in Figure 2), and
t is the pulse length in seconds.

It is not our intention to discuss receiver-operating-characteristics in detail, merely to use them. They are plots of p(D) against p(FA), where p(D) is defined as the probability that a signal, if present, will be detected, and p(FA) is the probability that noise will be detected as a signal. Figure 2 shows a logarithmic representation of the receiver-operating-characteristics where d, in simple terms, is a parameter representing different noise thresholds.

Intuitively, we will choose $p(D) = 0.9$, since we want a fairly reliable system.

The pulse repetition frequency of the sonar transmitter is 4, ie 240 pulses per minute. If we set an arbitrary limit of one "false alarm" per minute then $p(FA) = 1/240 = 0.004$.

Referring to Figure 2 it can be seen that for $p(D) = 90\%$ and $p(FA) = 0.4\%$, $d = 16$. In this specific case we have a small (bandwidth-pulse length) product of 2.5 and must accordingly[3] add a correction factor of 5.5 dB to (9), giving

$$DT = 10 \log(16/2 \times 250 \times 10^{-6}) + 5.5$$
$$DT = 50.5 \text{ dB} \qquad (10)$$

(v) Noise Level, NL At 300 kHz the primary noise source is thermal noise. It could be argued that noise from rain, rough seas and certain marine creatures might contribute to the background spectrum but we will confine the argument to fairly ideal diving conditions. For simplicity we will use a relationship[4] for the thermal noise spectrum. The parameter NL in (4) is for a non-directional receiving array, and is given by

$$NL = -15 + 20 \log f \qquad (11)$$

where f is the carrier frequency in kHz. Evaluating this for 300 kHz, we have

$$NL = 34.5 \text{ dB re } 1\mu\text{Pa} \qquad (12)$$

Since our array is very directional, (11) must be modified to

$$NL = -15 + 20 \log f - DI_R - 10 \log \eta \qquad (13)$$

and for a DI_R of 30 and efficiency of 0.8, the noise level becomes

$$NL = 5.5 \text{ dB re } 1 \mu\text{Pa} \qquad (14)$$

This is, of course, the result of evaluating the last three terms in (4).

From these results we can evaluate (4) to give the electrical power required to achieve a range of 200 m.

$$10 \log P_e = -30 + 132 + 15 + 50.5 - 170.8 + 34.5 - 30 + 1$$
$$= 2.2$$
$$P_e = 1.66 \text{ W} \qquad (15)$$

In practice, we consider it would be appropriate to design for up to 2 W electrical power. Figure 3 shows the dependency of range in metres on acoustic power for a 60 dB variation of power and for absorption coefficients ranging from 0.05 dB m^{-1} to 0.1 dB m^{-1}.

4. CONCLUSIONS

The special requirements of a sonar system for divers have been considered with view to calculating the electrical power required to achieve a transmission range of 200 m at a frequency of 300 kHz. We have shows that this objective may be realised with a power of less than 2 W. With a transducer array having an impedance of about 100 Ω, this power can be obtained by applying a peak-to-peak voltage of less than 40 V across the array.

5. REFERENCES

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(3) Nuttall A H and Magaraci A F, "Signal to Noise Ratios Required for Short Term Narrowband Detection of Gaussian Processes," U.S. Navy Underwater Syst. Center Tech. Rep. 4417, 1972.

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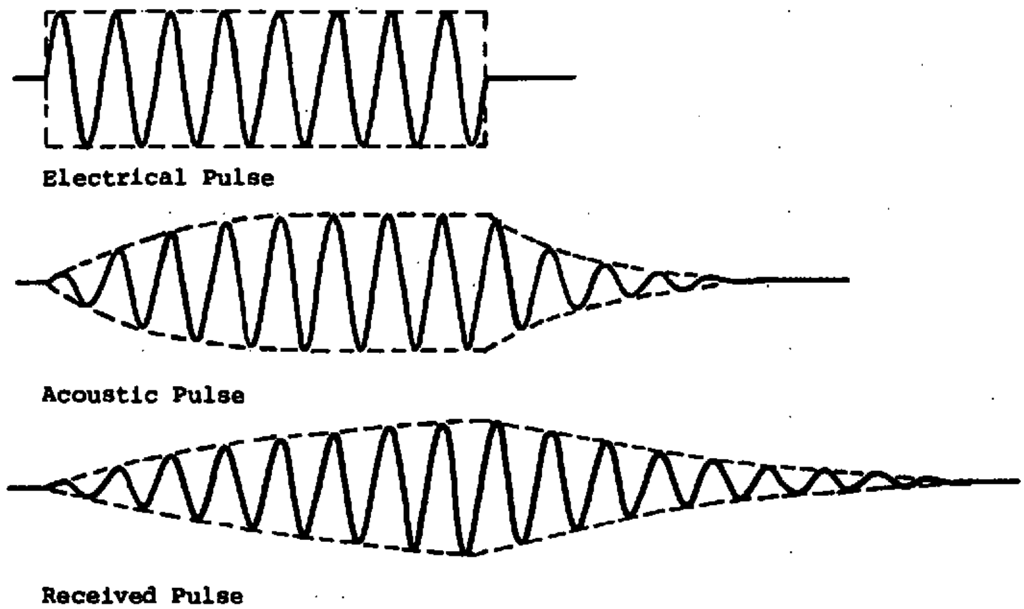

Figure 1 Pulse Waveforms

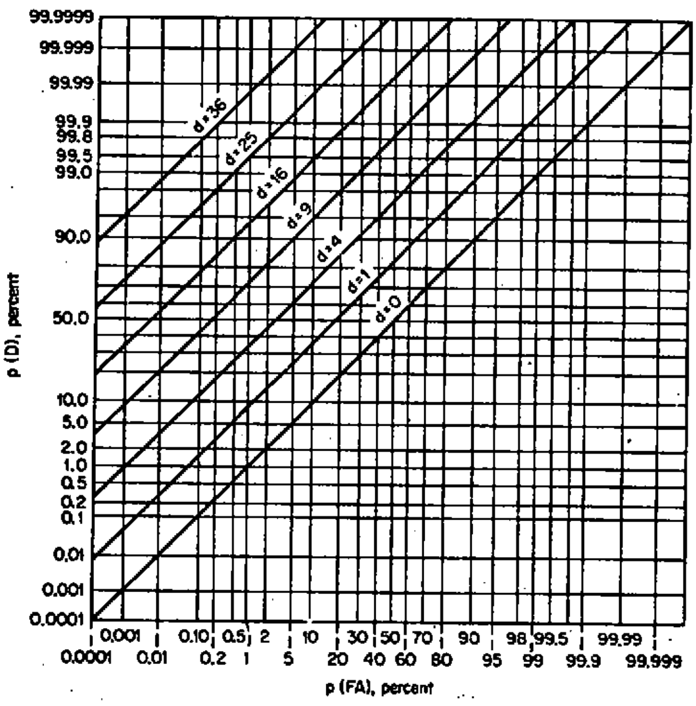

Figure 2   Receiver-operating-characteristics

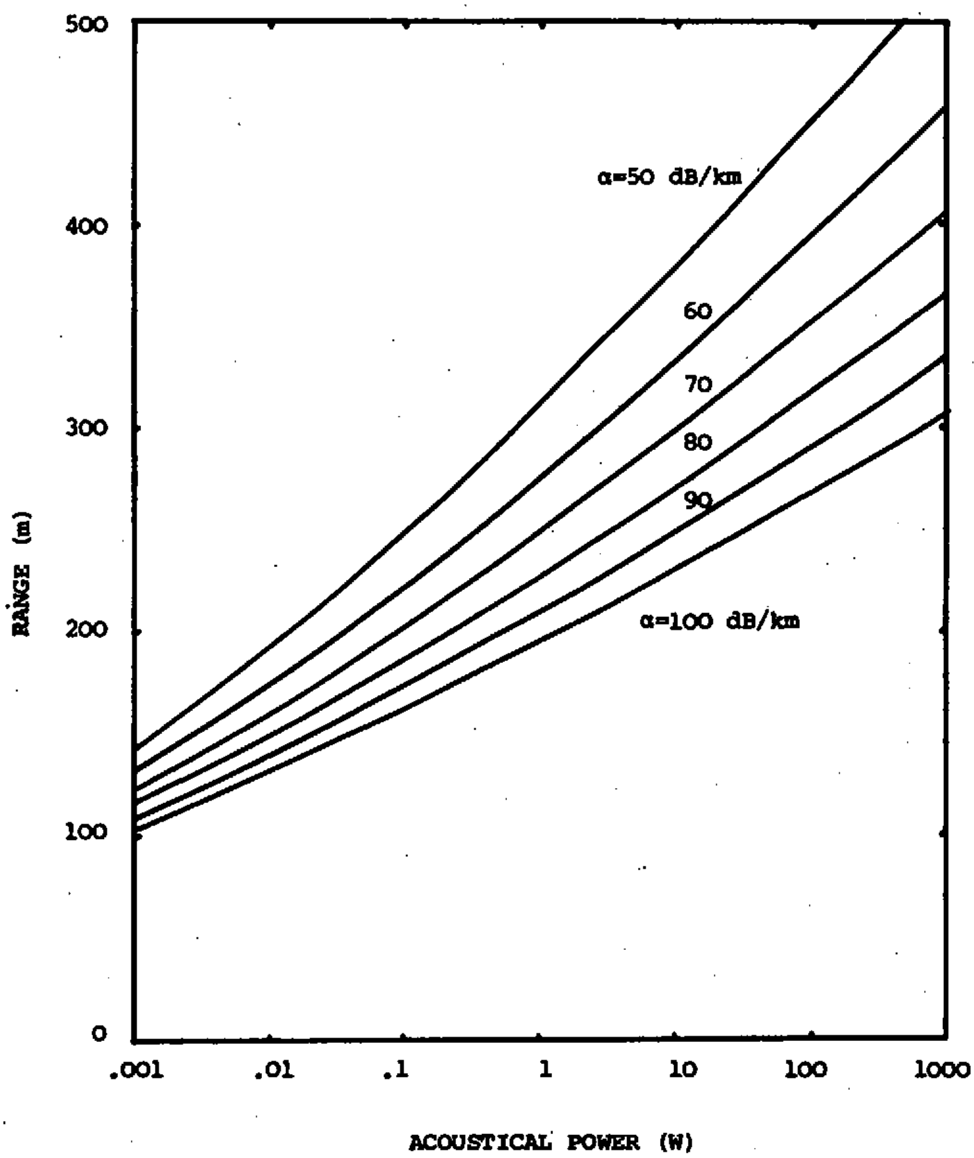

Figure 3 Acoustical Power versus Range for various Absorption Coefficients