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Classification of underwater objects using acoustic techniques

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Abstract: Underwater object classification is an attractive approach using acoustic remote sensing techniques due to its high coverage capabilities and limited costs as compared to manual method. In this approach Multi beam method is used for detection of underwater objects like sand, stone, silt etc. This under water object classification is performed by using model based approach which is achieved by implementing mathematical model of reservoir in Matlab using Finite Volume Method. An acoustic signal of particular frequency of Multi beam echo sounder is transmitted through this reservoir model. And thus from received signal strength various features are extracted, like backscatter strength, energy, power, surface roughness, skewness etc. It shows that these features are varying with changing seabed type, hence can be used to detect under water objects by using Multibeam echosounder of particular frequency. The scope of this project is found in underwater depth measurement using ultra sound to estimate the capacity, area elevation and sedimentation of a reservoir.

Keywords: Mathematical modelling, finite volume method, multibeam echosounder, acoustic signal.

1. Introduction

For many applications one is not only interested in depth, but also in the bottom sediment composition. The composition of the sediment is among others important in developing sediment transport models for predicting change of river and sea depths. Now a days there are different kinds of techniques available for this purpose like a single-beam echo-sounder (SBES), a multibeam echo-sounder (MBES), side scan sonar (SSS) or seismic systems. So in this paper a method is proposed to perform the sediment classification using multi beam methods as it scans more area as compared to other methods.

This object classification can be performed using two methods, the Empirical and the Model based approach. Hence instead of performing object classification on actual reservoir using empirical method, the model based approach is used where mathematical modelling of reservoir is created using Finite volume method and simulated in Matlab. Then an acoustic signal of 300 KHz is passed through the model and then the principle of Multi beam method is applied to detect and classify the objects like sand, stones etc.

2. Literature Survey

Riverbed sediment classification or measurements of seafloor bathymetry can be carried out through the use of the multi-beam echo-sounder system (MBES). In general, sediment classification methods using MBES can be divided into phenomenological (or empirical) and model-based (or physical) methods. In the phenomenological methods, features that are indicative for sediment type (e.g., backscatter strength or features derived from the bathymetric measurements) are used for classification. These methods discriminate the sediments as belonging to different acoustic classes, each with its own acoustic features. These acoustic classes represent the different sediment types that are present in the survey area. However, independent information, e.g., from grab samples taken in the area, is usually needed to assign sediment type, such as mud, sand or gravel, or sediment parameters, such as mean grain size, to the acoustic classes.

On the contrary, the model-based methods determine the sediment type by maximizing the match between modelled and measured signals or signal features, where sediment type or parameters indicative for sediment type, are input into the model. In principle, no independent information is required for model-based methods, since they provide the sediment type, or properties indicative for sediment type, instead of acoustic classes. In some of the model based methods, backscatter strength is matched versus grazing angle as measured by the MBES to model predictions, thereby providing sediment properties. Models exist that predict these backscatter curves as a function of sediment properties and frequency. By searching for those sediment properties that result in an optimal agreement between modelled and measured backscatter curve, the sediments can be classified. In this case, the classification results consist of real sediment properties instead of acoustic classes. So in this project such type of model is created using numerical solution to solve shallow water equation to perform underwater object classification.

3. Methodology

The implementation of the proposed system is shown below.

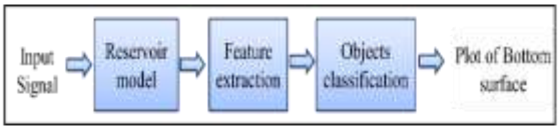

Fig. Block diagram of proposed work

3.1 Creating mathematical model of reservoir

The very first block of the proposed work is creating the model of reservoir. To create this mathematical model of reservoir Finite Volume Method (FVM) is found to be a good option where the following shallow water equation is solved.

$$\frac{\partial}{\partial t}\int_{\Omega} U d\Omega + \oint_{\partial\Omega} (Fdx - Gdy) = \int_{\Omega} S d\Omega \qquad (1)$$

The FVM falls into the family of Godunov-type algorithms and is a technique for solving a system of hyperbolic equations. This method is considered very accurate as it conserves mass at every time step. It operates by updating the solution within some control volume and includes all the inter-cell mass and momentum flux contributions in a single step.

Here FVM is used as the variation of the Godunov algorithm. Instead of breaking the model into discrete cells, we break the model into discrete volumes. The main advantages of this method are that it can handle Non-Cartesian geometries which are required for most natural circumstances. It does not need to generate and remove cells around wetting and drying boundaries. It can handle subcritical and supercritical boundaries with only minor adjustments.

3.2 Propagation of acoustic signal through Reservoir model

Acoustic signals are nothing but the sound waves which are defined as periodic variation in pressure, particle displacement and particle velocity in elastic medium. Water is elastic medium for underwater acoustics and water may be either fresh or saline. Sound waves are produced by mechanical vibrations and the energy from the vibrating source is normally transmitted as longitudinal waves because the molecule transmitting the wave move back and forth in the direction of wave propagation, producing alternate regions of compression and rarefaction. Thus acoustic wave equation is given as follow,

$$P(x,t) = Po\ Cos\ (w\left(t - \frac{x}{c}\right)) \qquad (2)$$

Where Po is constant amplitude and a phase depending on single Cartesian space co-ordinate x and c is sound velocity in the reservoir which is relatively small, lies between about 1450 m/s and 1540 m/s. The sound velocity can be calculated by empirical formulae if the temperature (*T*), salinity (*S*) and depth (*z*) are known. The sound velocity is given by,

$$c = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.01T)(S - 35) + 0.016z \qquad (3)$$

An acoustic wave sent out by an echo-sounder in the water will propagate through the water column until it collides with the boundaries of the medium. These boundaries will send back echoes of the transmitted signal. Two phenomena describe the interaction of sound with the seafloor, reflection and scattering. Reflection occurs for a perfectly flat seafloor, which is in not the case in reality. For low frequencies, reflection often suffices for the modelling of the interaction. The incident wave is reflected in a direction symmetrical to its angle of arrival. This induces a loss of amplitude, which is dependent on the angle of arrival, the densities of the mediums and the sound speeds in the respective mediums. In addition to reflection, roughness at the interface of water and seafloor and in homogeneities in the water column or sediments give rise to scattering. The scattering of acoustic energy back towards the sonar is called backscattering. Sonar systems like the side-scan sonar and the multibeam echo-sounder use these backscattered echoes. So below are the losses caused by sound propagation in reservoir are described

3.2.1 Transmission Loss of Sound

1) Spreading loss

Spreading loss is a measure of signal weakening due to the geometrical spreading of a wave propagating outward from the source. Two geometries are of importance in underwater acoustics, spherical spreading, i.e. a point source in an unbounded homogeneous medium and cylindrical spreading, i.e. a point source in a medium that has upper and lower boundaries. If medium is assumed to be lossless then intensity for spherical spreading inversely proportional to the surface of the sphere of radius *r*, i.e.

$$I\ \alpha\ {}^{1}/_{(4\pi r^2)} \qquad (4)$$

For Cylindrical spreading inversely proportional to the surface of the cylinder of radius *r* and depth *d*, i.e

$$I\ \alpha\ {}^{1}/_{(2\pi rd)} \qquad (5)$$

2) Sound Attenuation in Water

The acoustic energy of a sound wave propagating in the ocean is partly absorbed, i.e. the energy is transformed into heat and lost due to sound scattering by in homogeneities. Thus sound attenuation in water is given by

$$a_w = 8686\left(\frac{SAf_T f^2}{f_T^2+f^2} + \frac{Bf^2}{f_T}\right)(1 - 6.54 * 10^{-4}P) \qquad (6)$$

Where A=2.34x10^{-6}, B=3.38x10^{-6}, S=Salinity [ppt], f= in KHz

3) Sound Attenuation in Sediment

The sound attenuation in the sediment mainly varies with the bottom type. So it can be used to determine sediment type. It can be approximately determined by the empirical formula as

$$a_s = \frac{1}{8.686}K\left(\frac{f}{1kHz}\right)^n \qquad (7)$$

Where *K* and *n* denote two bottom type dependent parameters which are given in table below

Parameter	Sediment type				
	Clay	Silt	Sand	Gravel	Stone
K	0.17	0.45	0.48	0.53	
n	0.96	1.02	0.98	0.96	

Table1. Values of K and n for different sediment type

3.2.1 Forward reflection loss

A rough sea surface or seafloor causes attenuation of the acoustic field propagating in the ocean waveguide. The attenuation increases with increasing frequency. The field is scattered away from the specular direction

The forward reflection loss due to a rough boundary is often simply modelled by incorporating an additional loss factor into the calculation of the specular reflection coefficient. A formula often used to describe reflectivity from a boundary is

$$\tilde{R}(\varphi) = R(\varphi)e^{-p^2/2} \qquad (8)$$

Where

$$p(\varphi) = 2k\sigma\cos\varphi$$

Where $k = \frac{2\pi}{\lambda}\ with\ \ \lambda = \frac{c}{f}$ the wavenumber, σ the RMS (root mean square) roughness and φ the angle of incidence.

The following table provides the values of mean grain size and the RMS roughness for various sediment types.

3.2.3 Sound Scattering

The reservoir contains, within itself and on its boundaries, in homogeneities of many different kinds. These inhomogeneities reradiate a portion of the acoustic energy incident upon them. This reradiation of sound is called scattering. The total sum of all scattering contributions is called reverberation. The reverberation basically produced by scatterers is called volume reverberation, surface reverberation or bottom reverberation.

1) Surface Backscattering

Because of surface roughness and the occurrence of sediments inside reservoirs, the bottom surface is a significant scatterer of sound. Experiments indicate that the backscattering strength of the sea surface varies with the

a. Grazing angle (θ= π/ 2 – φ with φ= angle of incidence)
b. Sound frequency and
c. Wind speed induced roughness,

2) Bottom Backscattering

The bottom like the sea surface acts as a reflector and scatterer of sound due to its roughness. The specular direction has been considered as part of the sound propagation via the forward reflection loss. Experimental investigations have shown that the backscattering strength of the bottom varies with the
a. Grazing angle (θ= π/ 2 – φ with φ= angle of incidence),
b. Sound frequency and
c. Bottom type induced roughness

Furthermore, it could be observed that a Lambert's law relationship between the backscattering strength and the grazing angle fits to many experimental data satisfactorily accurate for angles below 60°.

Consequently, the backscattering strength can be described by Lambert's law and an empirically specified scattering coefficient, i.e. The total backscatter strength is expressed as a combination of the interface roughness scattering and volume scattering, it is given as

$$BS(\theta) = 10\ log10\big(\sigma r(\theta) + \sigma v(\theta)\big) \qquad (9)$$

With $\sigma r(\theta)$ and $\sigma v(\theta)$ are the backscattering cross sections due to the interface roughness and volume scattering, respectively.

Table 2. Value of **σ** for different sediment type

Sediment type	Mean Grain Size [φ = -log2(a)]	RMS Roughness σ [cm]
Sandy gravel	-1	2.5
Very coarse sand	-0.5	2.25
Coarse sand	0.5	1.85
Medium sand	1.5	1.45
Fine sand	2.5	1.15
Very fine sand	3.5	0.85
Coarse silt	4.5	0.7
Medium silt	5.5	0.65
Fine silt	6.5	0.6
Very fine silt	7.5	0.55
Silty clay	8	0.5
Clay	9	0.5

3.3 Feature extraction from Received Signal

Once the acoustic signal is passed through reservoir model the behaviour of received signal is observed and following features are extracted from it.

1) Power - The acoustic power P is received by a surface ∑ is the intensity corrected for the surface considered. It is given as

$$P = I \times \Sigma \;\; = {Po^2\Sigma}/{2\rho c} \quad \text{(In Watts)} \qquad (10)$$

2) Total Energy: It is given as

$$E = \int_0^{T_0} I(t)\, dt \qquad (11)$$

Where To is the truncated return pulse duration and I(t) is the water-depth corrected intensity as a function of time. In practice one has to be satisfied with discrete evaluation of the integral. The total energy is an important parameter as it directly relates to the hardness and roughness of the seabed.

3) *Skewness*: As a third-order moment, the skewness is

$$T = \frac{8}{T^3} E \int_0^{T_0} I(t)\,(t - t_0)^3 dt \qquad (12)$$

As a measure of the asymmetry, the skewness is typically positive for all seafloor echoes. This indicates that the echo shape is right-skewed, meaning that the mass of the shape is concentrated on the left hand side.

4) *Flatness:*

The fourth-order moment, the flatness or kurtosis, is

$$T = 16/ET^4 \int_0^{T_0} I(t)\,(t - t_0)^4 dt \qquad (13)$$

This is a measure of the "peakedness" of the signal. A signal with high kurtosis (less flatness) tends to have a distinct peak near the mean and to have heavy tail(s). But an echo with low kurtosis has a flat top near the mean rather than a sharp peak, with short tail(s).

5) Time Spread

It is a second-order moment, and given as

$$T = 4/E \int_0^{T_0} I(t)\,(t - t_0)^2 dt \qquad (14)$$

Where t_0 is the echo centre of mass and is given as

$$t_0 = \frac{1}{E\int_0^{T_0} I(t)dt} \qquad (15)$$

Then using the feature vector of these extracted features classification of underwater objects is done by scanning the bottom surface of reservoir.

5. Results and discussions

Mathematical model of reservoir is created using Finite Volume method and then it is simulated in Matlab. Output of the simulation is as shown below.

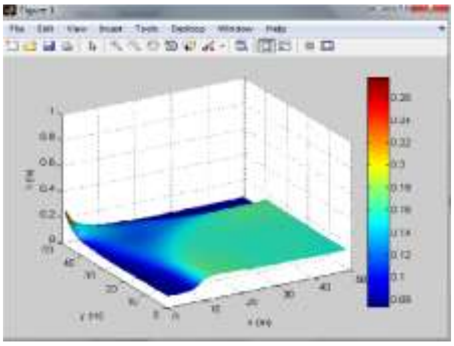

Figure 1-1 Plot obtained from Simulation of Reservoir

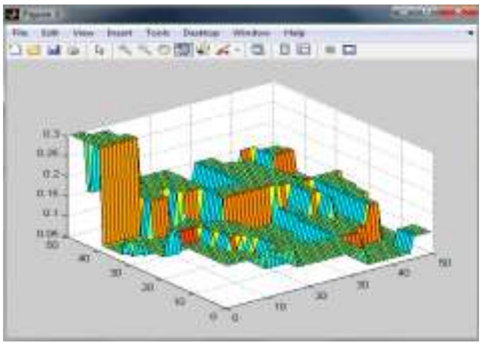

Figure 1-2 Plot of bottom surface of Reservoir

After creating model of reservoir in Matlab, an acoustic signal is transmitted through reservoir model with following inputs

- Frequency (F) - 300KHz
- Salinity (S) - 0.1ppm
- Temperature (T) – 25^{o} C
- Depth (Z) – 10 m

Then acoustic signal is passed through this model to classify underwater objects. Then classification is made from the features obtained from received signal characteristics like energy, time spread, standard deviation, skewness and flatness of the received signal. Features obtained from received signal are shown in table 3.

Features	Clay	Silt	Sand	Gravel	Stones
Power	6.02E +03	5.98E +03	5.65E+0 3	5.60E+0 3	5.01E+0 3
Energy	1.5E+ 13	1.49E +13	1.41E+1 3	1.3E+13	1.39E+1 3
Skewness	20.18 935	20.33 476	24.8497 9	29.8789 5	31.5299 6
Standard deviation	17336 .55	17281 .06	16797.8 3	16125.6 7	16715.8 1
Flatness	4658. 324	4658. 964	4747.11 1	5132.35 4	4663.72 3
Mean	- 9.126 08	- 8.955 29	- 3.54066	14.8789 4	34.8683 7

Table 3. Features obtained from received signal

Finally the plot of bottom surface is plotted depending on the results obtained from the classification.

6. Conclusion

Underwater object classification can be performed using MBES in two ways, the Empirical and the Model based approach. The empirical is the most commonly used method. This method uses bottom samples to calibrate the output of the echosounder, which then can be used to classify a bigger area in the vicinity of the samples. The drawback is that this approach is slow and expensive.

The model based approach in principle eliminates the need for bottom samples. Here a theoretical model is used to predict what the signal would look like for environmental conditions in the area to be surveyed. The model produces predictions for a range of seabed types that then can be correlated to the actual received signal. The best match is expected to provide the actual seabed type.

Hence Model based approach is used to create reservoir and object classification is done by extracting features from received signal. These features are found to vary depending on sediment type.

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