Development of Attenuation Model for Saturated Water and Sedimentary Deposits for Underwater Acoustic Signal Communication

Sweta S Panchal, Jayesh P Pabari, Sandip R Panchal

Abstract: In this paper, the model for absorption co-efficient for underwater tank is proposed for medium of raw water concentrated with sodium chloride. With course of time, sediments gets deposited at the bottom of tank. The attenuation model for underwater tank deposited with sediments is also developed. The attenuation models for pure water and sodium chloride are developed separately. The overall model for raw water saturated sodium chloride suitable for bounded shallow underwater medium like tanks. The resultant absorption co-efficient for pure water saturated with sodium chloride can be obtained by summation of the respective models and their percentage concentration. Similarly attenuation model for underwater tank having sedimentary deposits is also developed for various types of sedimentary deposits. For particular operating frequency of communicating devices placed in underwater tank, the absorption of underwater acoustic signal increases. The model reflects the change in attenuation loss as the length of sedimentary deposit increases. The underwater acoustic signal strength gets affected while its transmission in such mediums which can affect received signal strength. Also the length of sedimentary deposits can be related using attenuation model. These models helps to identify the increases concentration of sodium chloride and increases sedimentary deposits by analyzing the received signal strength.

Keywords : Attenuation co-efficient, Sediments, Transmission loss, Underwater Acoustic communication.

I. INTRODUCTION

The applications of wireless sensor network (WSN) have expanded dramatically to a wide range over a last decade, which include the monitoring, identification, tracking and many more. An underwater acoustic sensor network may be useful for investigation of such applications in a liquid media and address the specific scientific issues. The radio waves are not preferred as at low frequency as these waves are not capable to travel long distance. The radio waves have high attenuation, low signal-to-noise ratio and extremely large size antennas. The optical waves do not have such issues, but the optical waves face the problem of scattering of signal. The range of optical waves is few meters. The acoustic signal is useful for few kilometers and serves as the best option for underwater acoustic communication [1].

The attenuation co-efficient for the acoustic signal, propagate through aqueous solution of sodium chloride, with concentration of 2 to 3 moles per liter. For underwater acoustic frequency range and concentration of sodium chloride of 2 to 3 moles per liter is considered as propagating medium. At frequencies above 200 kHz, pure water has excessive contribution towards the maximum absorption. Also other minerals present in water has significant effect on absorption loss while underwater propagation. Raw water in underwater tank contains various chemical salts like sodium chloride, magnesium sulphate, boric acid, potassium chloride etc. in it. The pre dominant effect due to sodium chloride as chemical comsposition present in the water has been considered. Sodium chloride is under consideration as the presence affects badly health and vegetation in long course of duration [1].

With due course of time, the bottom of underwater tank gets accumulated with various deposits. The underwater acoustic signal faces multiple reflections while propagation from various parts of tank. One such reflection it faces is bottom reflection. The underwater acoustic signal has absorption loss during its traversal to bottom of tank and reflects from surface of deposits [13]. As the length of deposits increases from the bottom of tank, the attenuation co-efficient changes at particular operating frequency of underwater acoustic sensor. The model for attenuation is simulated in medium of sodium chloride saturated pure water at various frequencies and 10 ℃ and 20 ℃ temperature. Also the attenuation co-efficient for sedimentary deposits in underwater tank for bottom reflected acoustic signal is modeled.

II. SIGNAL ATTENUATION

The acoustic wave propagation suffers from loss of intensity and absorption of acoustic energy by propagation medium. The propagation loss is a main parameter that constraints the amplitude of the received signal. The path loss is due to the lost sound intensity from the transmitter.

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Spreading loss is due to the expanding area that the sound signal encounters as it geometrically spreads out from the source and it is given in [2].

$$P_{spread} = K * 10 \log(R) \ dB \qquad (1)$$

where R is the range in meters and K is the spreading factor. For unbounded transmission medium, the spreading is spherical, so the spreading factor has to be considered as $K = 2$; whereas for bounded transmission medium,

the spreading is to be considered as cylindrical $K = 1$ as given in [2]. The absorption loss represents energy loss in the form of heat due to viscous friction and ionic relaxation that occur as acoustic wave propagates outwards.

$$P_{absorb} = 10 \log(\propto_{overall}) * R \ dB \qquad (2)$$

where R in range in meters and $\propto_{overall}$ is absorption co-efficient for proposed model. The total path loss P_{total} (3)[2] is combined contribution of both the spreading and absorption losses which is given by

$$P_{total} = P_{spread} + P_{absorb} \ dB \qquad (3)$$

For the absolute value of path losses [2],

$$L = 10^{-[P_{total}/10]} \qquad (4)$$

The path loss is dependent on various components of transmitted signal like depth of acoustic medium, temperature, hydrostatic pressure and frequency. With increase in depth till 100 meters and change in temperature from $0°C$ to $20°C$, the hydrostatic pressure remains constant. For change in temperature till 20 ℃, the attenuation depends directly on square of frequency. The absorption co-efficient is a parameter that depends on temperature, atmospheric pressure, frequency and depth of the bounded shallow water. The shallow under water also faces absorption losses same as deep underwater acoustic channel [3].

III. ABSORPTION LOSS FOR SATURATED WATER WITH SODIUM CHLORIDE

The absorption of sound in pure water is considered to be due to pure water plus excess absorption due to small amounts of various salts in the water. The absorption is limiting factor for acoustic propagation. The amount of propagation losses depends on the propagation medium, concentration of various salts and the frequency. In shallow water basically the absorption is due to pure water viscosity and its effect increases with frequency. Propagation of an acoustic wave from a sound source spreads the transmitted acoustic energy over larger surface. Water is a dissipative propagation medium and it absorbs part of transmitted wave energy, which is dissipated through viscosity of chemical reaction [4-5]. Molecular relaxation consists in dissociation of ionic compounds in water. Absorption losses due to signal propagating in pure water with ionic saturation of sodium chloride up to 3 moles/liter can be evaluated using attenuation model. The acoustic absorption in sodium chloride saturated in pure water occurs at wide frequency range of 20 KHz to 1 MHz [5]. For the low concentration of sodium chloride from 0.01 to 0.5 moles/liter , the sound absorption is found to be independent of concentration. With increase in concentration of sodium chloride, the attenuation increases. The significant increase in attenuation at acoustic frequencies for the concentration of sodium chloride more

than 2 moles/liter . The model for attenuation due to propagation of underwater acoustic signal in pure water is demonstrated. The model for attenuation is also developed for sodium chloride in following section. The mechanisms responsible for attenuation in water are viscous loss, loss due to heat conduction, temperature, depth of acoustic medium and frequency of operation. Due to various losses and effect of quantity of sodium chloride above 2 moles/ liter , the noticeable effect on attenuation of acoustic waves can be demonstrated. The model for attenuation has been developed pure water saturated with sodium chloride for underwater tank, a bounded medium. The molar concentration of sodium chloride is 4.66% which is 3 moles/liter in raw water having concentration 55.26 moles/liter. Thus the proportion of raw water is 95.34% with 4.66% of proportion of sodium chloride.

A. Model for Attenuation in raw-water

The absorption takes place in raw water due to various minerals present in the water. The acoustic wave travels through propagating medium water. As water is dissipative medium consisting of various minerals, the acoustic waves suffer from attenuation. The concentrated water consists of very small proportion of various minerals like potassium chloride, sodium chloride etc. The concentration of sodium chloride is nearly 4.66% [5] for 3 moles/liter. Generally contribution of all other components are very small compared to raw water and sodium chloride, so it dominates for attenuation of acoustic waves.

The propagation model can be developed for attenuation in pure water as per Eq. (5) [6]. The attenuation is affected by variation in frequency; the attenuation is very high at high frequency i.e. above $100 \ kHz$ of frequency. The attenuation in pure water at various frequency and temperature $10°C$ to $20°C$ and depth of $1 \ meters$ to $100 \ meters$. The majority of content is raw water i.e. approximately 95.34%. The remaining content is of mineral like sodium chloride. The attenuation due to raw water is given by following equation, where α_{water} is attenuation in $dB/meter$, z is depth in $meter$, T is temperature in $°C$, A is hydrostatic pressure, P is atmospheric pressure can be assumed to be constant 1 bar for temperature till $20°C$ from the Eq. (5) [6-7] with depth variable from $1 \ meter$ to $100 \ meter$.

$$\propto_{water} = A * P * f^2 \qquad (5)$$

where,

$$P = 1 - 3.83 * 10^{-5}z + 4.9 * 10^{-10}z^2 \qquad (6)$$

$$A = 4.937 * 10^{-4} - 2.59 * 10^{-5}T + 9.11 * 10^{-7}T^2 - 1.5 * 10^{-8}T^3 \qquad T < 20℃ \qquad (7)$$

$$A = 3.964 * 10^{-4} - 1.146 * 10^{-5}T + 1.45 * 10^{-7}T^2 - 6.5 * 10^{-10}T^3 \qquad T > 20℃ \qquad (8)$$

The shallow water can assumed to have depth of $100 \ meter$ and underwater tank can have temperature ranging from $0°C$ to $20°C$. For the shallow water with maximum depth of $100 \ meter$ and temperature upto $20°C$, the hydrostatic pressure according to Eq. (6) is $0.99 \ bar$ constant.

The concentration of raw water with small amount of impurity that is nearly 95.34% pure water and 4.66% sodium chloride considered as chemical composition present apart from raw water and the attenuation model gives the absorption losses for underwater acoustic signal transmission. Thus the attenuation due to pure water of 95.34% can be calculated using Eq. (5).

B. Model for Attenuation with Sodium Chloride

The raw water consists of various ions with varying concentration. Various ions have diverse effect on vegetation, health and physical properties of saturated pure water. Also these ions affect the physical parameters for underwater transmission. From various ions with different proportion, the effect of sodium chloride is considered, as sodium chloride severely affects the health, vegetation and physical properties of water. When use such water, the losses incurred changes which ultimately effects the faithful communication. The model is proposed for raw water saturated with sodium chloride, the concentration of sodium chloride is approximately 4.66% which 3 moles/liter. The concentration of remaining raw water follows with proportion of 95.34%. The propagation model is derived for attenuation due to raw water and other impurities, basically considering due to sodium chloride. The attenuation due to sodium chloride at various frequencies is carried out by given propagation model as shown in Eq. (9) [8].

$$\alpha_{Nacl} = (0.0225 * f^2/2\rho v^3)\big[(4\eta/3 + \eta^v) +$$
$$\tau 1Cp - 1Cv \qquad (9)$$

where, α is attenuation in dB/meter, f is frequency in Hz, ρ is density g/m^3, v velocity in m/s, η^v is volume viscosity, τ is thermal conductivity, C_p and C_v are specific heat constants at constant pressure and constant temperature [8].

The values of various parameters are derived and used to obtain attenuation occurring due to sodium chloride [9]. The conductivity for $NaCl$ concentration $2\ to\ 3\ moles/liter$, temperature $20℃$ and pressure of $1\ bar$. Shear viscosity $\eta = 1048\ \mu\ Pa\ s$; thermal conductivity $\tau = 0.5773$ [10]. The attenuation due to sodium chloride is as shown in Eq. (10).

$$\alpha_{Nacl} = 0.28\ f^2\ dB/m \qquad (10)$$

The attenuation due to sodium chloride with concentration of $3\ moles/liter$ is frequency dependent as shown in Eq. (10). For shallow underwater in tank with maximum depth of $100\ meters$, the attenuation increases with increase in frequency and makes the attenuation co-efficient proportional to the square of frequency.

C. Proposed Model and Results

The proposed model helps to give indication regarding necessity developed for cleaning underwater tank. The attenuation model developed shows the increase in attenuation loss of underwater acoustic signal, when transmitted through underwater acoustic medium with 95.34% of raw water and 4.66% of sodium chloride. The mentioned underwater medium has constituents as 95.34% of pure water saturated with 3 moles/liter of sodium chloride, which constitute 4.66%. The transmission of underwater acoustic signal leads to signal attenuation, if the concentration of sodium chloride increases beyond 3

moles/liter. The proposed model for mentioned scenario for attenuation loss is dependent on frequency is as shown in Eq. (11).

$$\alpha_{overall} = 0.9534\alpha_{water} + 0.0466\alpha_{NaCl}\ dB/meter \qquad (11)$$
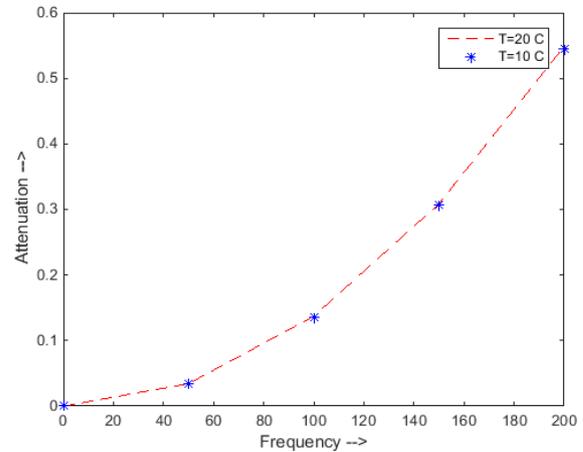

Fig. 1.Attenuation Vs Frequency

The attenuation co-efficient is applicable to the shallow water tanks depth of 100 m, temperature up to 20˚C and hydrostatic pressure 1 bar is frequency dependent. The simulation results are obtained using MATLAB as shown in figure 1. The results in Fig. (1) shows that for frequency up to 200 kHz and temperature 10˚C and 20 ˚C. The losses related to the signal transmission increases, when the concentration of sodium chloride increases. For low concentration of sodium chloride nearly 0.5 moles/liter, the attenuation loss for the acoustic frequency range is negligibly small. But as the concentration increases losses incurred increases. The acoustic signal has absorption as one of its characteristic which may deteriorate the received signal, as attenuation co-efficient leads to transmission losses.

D. Transmission Loss

The transmission loss that occurs at the time when sound travels from transmitter to receiver, is called as spreading loss. Spreading loss is given as shown in Eq. (1). Spreading loss depends on range of transmission. Transmission losses lead to decrease in intensity of sound along path from transmitter to receiver in acoustic network [11]. Transmission loss depends on attenuation of acoustic signal along the path and range of transmission. The transmission loss is expressed in dB as shown in Eq. (12).

$$TL = 20\log R + \propto_{overall} * 10^{-3} \qquad (12)$$

Where, R in range of transmission between transmitter and receiver, $\propto_{overall}$ is overall attenuation in dB/m [12]. The atmospheric pressure for shallow is considered as 1 bar at constant temperature of $10℃$ and $20℃$ and range of transmission between transmitter and receiver is 10 meters and 20 meters in Fig. (2). The model for transmission loss in Eq. (12) verifies for the attenuation in underwater acoustics in water saturated with sodium chloride.
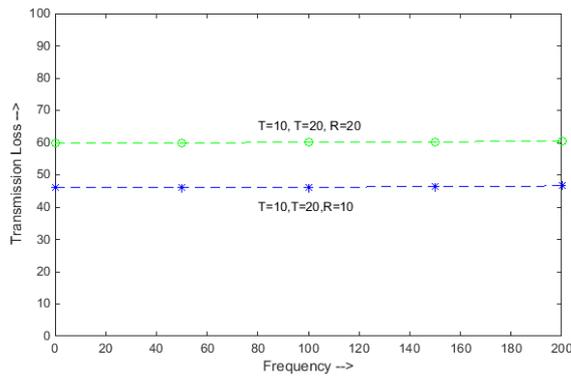
Fig. 2.Transmission Loss Vs Frequency

The transmission loss increases with increase in range between communicating device. The transmission loss also changes with change in frequency of operating devices. For ultrasonic frequencies, the transmission loss is very high. Also, the model is valid for temperature till 20℃. More the temperature, the transmission loss is also more.

IV. ATTENUATION MODEL FOR SEDIMENTS

The underwater acoustic signal travelling through underwater tank, take multiple path to reach receiver. This multipath propagation of acoustic signal occurs because of reflections from various parts of communication medium like water surface, tank bottom and walls of tank. The bottom reflection leads to attenuation of acoustic signal due to property of bottom of tank. With due course, the sediments get deposited at the bottom of tank. The acoustic signal gets reflected from the various deposits of sediments. Various types of sediments deposited at the bottom of tank, the layer of sediments increases. As the depth of sediments increases, the absorption of the acoustic signal increases through underwater. Various types of sediments like fine silt, sand and coarse sand are considered as sediments [12]. The attenuation co-efficient for bottom reflected underwater acoustic signal is also dependent on density of water and type of sediment [13]. The attenuation model developed for underwater bottom reflected acoustic signal is simulated using MATLAB for acoustic frequency range till 200 kHz [13].

$$\alpha_{sed} = 0.11 \, lk(f)^n \frac{\rho_w}{\rho_s} \qquad (13)$$

where k is attenuation co-efficient in dB/m/kHz for associated frequency and n is exponent of frequency, also l is the length of sediment deposited at the bottom of tank. α_{sed} is expressed in dB and l is length in meters. The value of k and n are provided in following table-I [14].

Table- I: Sediments and its corresponding values

Sediment Type	K	N
Very fine silt	0.17	0.96
Fine sand	0.45	1.02
Coarse sand	0.53	0.96

The attenuation model for sedimentary deposits is simulated using MATLAB. For various types of sediments, the attenuation is different for particular operating frequency of sensors used.
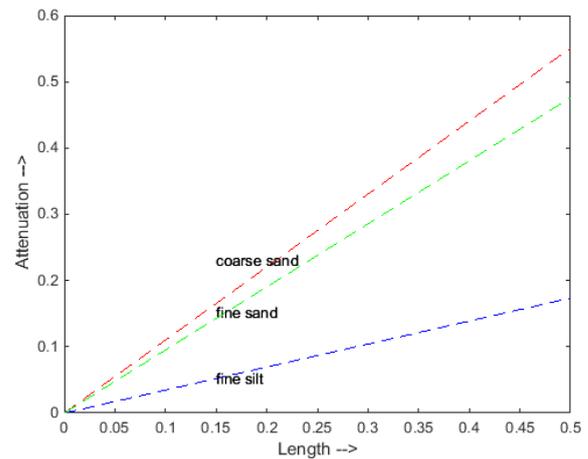

Fig. 3.Attenuation due to sediments Vs Length

The attenuation model is simulated of the sedimentary deposits for length up to 0.5m for the underwater acoustic sensor network employing transmitting and receiving device with operating frequency 30 kHz. With accumulation of sediments, the attenuation loss increases for particular operating frequency of communicating device. Attenuation is more for coarse sand compared to fine silt and fine sand.

V. CONCLUSION

In this paper with the development of attenuation model for raw water saturated with sodium chloride, for the temperature till 20 ˚C, depth of water tank till 100 meters and concentration of sodium chloride till 3 moles/liter, the attenuation loss of underwater acoustic signal is less. As the temperature and depth of tank increases, the attenuation due to raw water concentration increases which makes raise in overall attenuation. For Underwater acoustic signal band, the attenuation co-efficient has small increase with increase in frequency. For ultrasonic frequencies, the absorption due to raw water and sodium chloride is drastically increasing. For small concentration of sodium chloride about 0-0.5 moles/liter, the attenuation co-efficient is negligibly small. But for high concentration of sodium chloride about 5 moles/liter, the attenuation loss is very high. Thus the acoustic signal reception degrades with increasing concentration of sodium chloride. As the distance between communicating device increases, the transmission loss also increases. This helps to know the increasing amount of sodium chloride in tank which in turn is required to be taken care. With the help of attenuation model for sediments, the length of sediments is directly related to attenuation. The sedimentary deposits increases at the bottom of tank which leads to increase in absorption loss. The received acoustic signal strength helps to identify the increasing sedimentary deposits.

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