Significance of a low noise preamplifier and filter stage for under water imaging applications

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Abstract

High frequencies of the order of hundreds of kHz to MHz are employed for underwater imaging applications. Signal to noise ratios encountered for the front end receiver sections are seen to be very much reduced for these applications. Hence a low noise preamplifier and filter stage is very essential prior to the conventional antialiasing and digitization functionalities of the front end receivers. In this paper, an attempt is made to design and develop a low noise pre amplifier and filter to achieve a better SNR for the system. The pre amplifier stage designed is interfaced with hydrophones directly for gain and impedance matching purposes. The noise reduction is further achieved by means of a filter following the preamplifier stage which rejects the out of the band noise to an optimum level. Thorough study and analysis is carried out in this paper for the selection of low noise opamps, associated passive components and configuration of the preamplifier sections. Acoustic measurements are carried out for a sensor array of 150 kHz for evaluating the preamplifier and filter performance in the real scenario.

Keywords: Voltage noise; Current noise; Bandpass filter; Op-amp configuration

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1. Introduction

Imaging sonar operating in the very high frequency ranges has to be compact and portable as the application demands in certain cases. Hence the receiver section of imaging sonar is designed with a signal conditioner unit which comprises the following blocks namely preamplifier, filter, compact analog front end module (AFE) and a controller section.

Output from the sensor drives to a preamplifier and filter, which provides the complete analog signal conditioning functions required between a sonar hydrophone and an analog to digital converter (ADC) including a) conversion of impedance of the hydrophone to a lower value to match with the impedance of the measuring instrument used and b) amplification of the relatively weak output signal from the hydrophone. The critical features of the preamplifier include low input noise, high input impedance, high dynamic range and first stage gain.

The preamplifier output, which is a combination of signal and noise, goes to a filter, which filters out the noise outside the sonar frequency band and thus improves the Signal to Noise Ratio (SNR). The block diagram of a front end receiver for underwater imaging system is shown in Fig 1.

![Fig 1: Block diagram of front end receiver of an underwater imaging sonar](image)

The filtered output is fed to Analog Front-End (AFE) solution, which is specifically designed for high frequency systems where high performance and compact size are required. It mainly integrates a low noise amplifier (LNA), voltage controlled attenuator (VCAT), programmable gain amplifier (PGA), low pass filter (LPF) and an analog to digital converter (ADC).

The controller section provides the logic controls for AFE and configures the data for interfacing with efficient telemetry schemes. The output from the controller is sent to the remote signal-processing unit using defined telemetry system.

This paper is dedicated to the design, development and testing of preamplifier and filter circuits preceding AFE and controller section.

2. Criticality of first stage preamplifier and filter section

Medical applications interfaces analog front end modules (AFE) comprising of antialiasing filters and ADCs directly with sensors for ultrasonic imaging purposes. The signal to noise ratios encountered by these applications are much better when compared to that of underwater applications mainly due to limited ranges of operation in the orders of centimeters of length. For underwater applications, as range increases signals get attenuated to a high degree due to the propagation losses depending on the conditions in which it is operated such as the ocean or turbid water environment. Also the sensitivity and capacitance of these very high frequency sensors are found to be reduced when compared with their low frequency counterparts. The reduced sensitivity further places restrictions on the availability of the minimum signal received by the systems in presence of ambient noise. Hence the signal encountered here should be enhanced to a sufficient level which can be taken by the conventional receiver systems to prevent the degradation...
in SNR\(^1\). Hence extreme care is taken for the design of the first stage preamplifier and filter section of the front end receivers\(^2\).

### 3. Design of preamplifier and filter section

The critical external factor determining the choice of low noise preamplifier is the sensor capacitance and sensitivity at the frequency band of operation. This paper deals with the design of preamplifier and filter circuit designed for sensors operating in the frequency range of 150 kHz. Sec 3.1. briefs the results of characterization studies from the sensor development section for the sensors array with the frequency of operation of 150 kHz. These are the critical inputs taken into consideration for the design of the preamplifier and filter circuit.

#### 3.1 Sensors

The sensor receives the underwater signals and converts it to the electrical signals to be interfaced with front end receiver. The active material for the sensors in these frequencies is 1-3 piezo-composites which has a number of 1-D connected piezoelectric ceramic rods (Usually PZT- Lead Zirconate Titanate) in 3D connected polymer matrix. Since the dimensions are of the order of few millimeters at high frequencies (of the order of few wave lengths), accurate machining and processing is essential. On the performance side, power handling capacity, voltage sensitivity and capacitance are limited because of reduced sizes of piezoelectric material.

The design of the preamplifier was carried out based on the following parameters from the sensor sections in Table 1 and Fig 2.

Table 1: Sensor characteristics
3.2 Selection of low noise op-amps

The op-amps used to design preamplifier circuit are chosen based on mainly the noise at the operating frequency such as voltage noise density and current noise density. Following the optimization of component selection based on noise density values, the properties such as slew rate and gain band width product is taken into account. Finally suitable configuration is chosen for preamplifier circuit optimizing the dynamic range required and noise performance of the system.

Literature survey for selection of low noise opamps are carried out for the design of first stage preamplifier section. Op-amps selected for analysis with varying parameter values are given in Table 2.

To analyze the effect of noise due to selected opamps, a circuit modeled for noise calculation is shown in Fig 3.

![Graph showing receiving sensitivity of 150 kHz sensor element](image-url)
The noise due to each of the resistors is calculated separately and the voltage and current noise density effects of the selected op amp on the output noise is calculated. The gain of the op-amp circuit is set as 28 through the feedback and input resistor for theoretical analysis. The output noise for different op-amps are calculated considering the source impedance (800 ohms approx.) from sensor array operating at 150 kHz. The total voltage noise at the output of the op amp model is theoretically calculated. Noise analysis with various low noise op-amps and the comparison of theoretical results are shown in Fig 4.

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>opamps</th>
<th>slew rate (V/us)</th>
<th>GBW (MHz)</th>
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<tbody>
<tr>
<td>1</td>
<td>AD8620</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>OPA2227</td>
<td>22</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>AD743</td>
<td>2.8</td>
<td>4.5</td>
</tr>
<tr>
<td>4</td>
<td>AD797</td>
<td>20</td>
<td>110</td>
</tr>
<tr>
<td>5</td>
<td>AD8429</td>
<td>22</td>
<td>15</td>
</tr>
<tr>
<td>6</td>
<td>OPA827</td>
<td>28</td>
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<td>OPA687</td>
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</tr>
<tr>
<td>9</td>
<td>LMH6624</td>
<td>350</td>
<td>1500</td>
</tr>
<tr>
<td>10</td>
<td>LT1028</td>
<td>11</td>
<td>50</td>
</tr>
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</table>

Fig 3: Comparison of noise output of op-amps
Low noise op-amp OPA827 is selected for interfacing with the sensor array of 150 kHz taking into account the parameters such as slew rate and gain bandwidth product in addition to the noise parameters from Fig 4.

3.3 Optimization of preamplifier configuration

Preamplifier circuits are designed and analyzed in voltage and charge amplifier configurations for sensor interface. Two configurations of voltage amplifiers namely inverting and non-inverting configurations were analyzed. Both non-inverting voltage amplifier and charge amplifier configurations are found to be comfortable and convenient for sensor interface in respect of gain and impedance matching properties. The source impedance of the sensor is found to be on the upper side for high frequency operation ranges. Hence to design a matching inverting voltage preamplifier circuit for these sensors, the input impedance of the op-amp has to be made sufficiently higher. This can lead to additional noise for the system.

The noise variations expected for the circuit designed with inverting and non-inverting voltage amplifier configurations is simulated and the result is shown in Fig 5. It is inferred from the figure that the non-inverting configuration is preferred over the inverting configuration for the same set of selected components.

![Fig 5: Noise comparison of op-amp configurations](image-url)
3.4 Preamplifier circuit for interfacing 150 kHz sensor array.

For a typical underwater imaging application of mines, the minimum level expected at the preamplifier stage for this frequency of operation is in the range of less than microvolts. Hence to accommodate the low signal into the dynamic range of AFE, two stage preamplifier sections designed with a total gain of 38-40 dB is implemented. The gain is distributed as 28-30 dB in the first stage and 10-12 dB in the second stage. The first stage preamplifier section is designed based on the analysis of sections 3.1, 3.2 and 3.3. The second stage is a non-inverting op-amp stage which is not as critical as the first stage as the former is the major contributor to the noise of the system.

3.5 Filter circuit for interfacing 150 kHz sensor array.

The output of the preamplifier is given to a filter to remove the out of band noise. Here the filters are realized in two stages and is designed to have a bandwidth of 100 kHz with center frequency of 150 kHz to interface the preamplifier circuits. A fourth order Butterworth Sallen key configuration is chosen for the filter. The gain of the filter circuit is set as unity since sufficient gain is given in the preceding stages. The stop band attenuation of the filter is limited by the current order since the signal is sufficiently sampled in the AFE which takes care of the noise in the band width before processing.

4. Testing and evaluation

Experiments were conducted at acoustic measurement facility for evaluating the performance of sensor with preamplifier and filter. The measurements were carried out with a cable of 10m length for preamplifier in charge amplifier configuration and with a cable of 1m in voltage amplifier configurations. The target is placed at a distance of 3m. Experimental set up of the preamplifier and filter circuit with a single sensor element is shown in Fig 6 and the echo received is given in Fig 7.

Measurements for the preamplifier and filter circuits with sensor interface are carried out for comparing the preamplifier stage in three op-amp configurations. The performance of the circuit is compared with the direct sensor output. The gain set in the circuit and impedance matching of the hydrophone with preamplifier designed for the circuit was achieved in testing as validated from the receiving sensitivity plot shown in Fig 8.

Fig 6: Experimental set up of the preamplifier and filter circuit with a single sensor element
Fig 8: Receiving sensitivity plot with and without preamplifier
Conclusions

A low noise pre amplifier for sensor interface is mandatory prior to the conventional analog front end modules of receivers for high frequency underwater imaging applications due to the low SNR encountered here. Selection of op-amps for preamplifier stage can be chosen based on very low current density values for sensors with low capacitance values and very low voltage density for sensors with high capacitance values. The configuration of the op-amps depends on the value of source impedance interfaced by the preamplifier section, dynamic range of the system and the distance of the sensor from the preamplifier section. Inverting amplifier configuration for the can be resorted to, provided the sensor interfaced with is of moderate output impedance. On inverting configuration for the preamplifier can be utilized if the sensor is placed very near to the sensor. Otherwise, the loss due to cable has to be taken into account which is not advisable for compact applications. Configuration of the preamplifier section in charge amplifier configuration nullifies the effect of cable capacitance interfaced with the sensor. Hence even though the voltage amplifiers work with underwater imaging sensors, charge amplifier is expected to provide optimum performance for most of the frequency ranges and for moderate cable lengths when sufficient gain is set using the suitable feedback capacitor for the preamplifier stage.

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