# Active Noise & Vibration Controls in Submarines

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## Abstract

The sound and vibration generated at the propeller and the machinery spaces are propagated through the hull and water. The vibration produced by the machinery, the propeller shaft, and the propeller itself will be reradiated by the hull and reach up to the forward location. The vibration reradiated by the hull structure will be narrow band tonal, with various fundamental frequencies & harmonics related to propeller / machinery operation. The radiated noise in the water body around the platform has both broad band and narrow band characteristics which includes all signatures related to self-noise or radiated-noise. The passive noise cancellation techniques have limitations in cancelling the self noise in a submarine platform.

In this paper, design and experimental validation of two types of noise controls, viz. Active Noise Control and Active Vibration Control, are addressed. The adaptive noise cancellation (ANC) techniques are the options and this paper discusses in detail an ANC system with required sensors, viz. hydrophones, accelerometers and projectors. The cancellation algorithm for both broadband and narrowband is given in detail using Least Mean Square (LMS) algorithm. A recursive LMS (RLMS) algorithm is described. The active noise control system contains an acoustic projector that cancels the unwanted sound by generating an anti sound (anti-noise) of equal amplitude and opposite phase. The original, unwanted sound and the anti-noise acoustically combine, resulting in the cancellation of both sounds. The measurement result of single frequency cancellation based on simulation is also presented.

## I. INTRODUCTION

This paper presents an overview of the self-noise of the submarine, adaptive noise cancellation (ANC) techniques of broadband & narrowband noise and extends the ANC techniques for Active Noise Control and Active Vibration Control. A practical implementation technique is proposed.

An overview of self-noise and radiated-noise of the submarine is presented in Section II and noise radiation from submarine pressure hull is discussed in Section III. The adaptive noise control basics are briefly presented in Section IV. An overview of broad band and narrow band noise is discussed in Section V. The adaptive noise cancellation techniques are discussed in Section VI. Section VII and VIII discusses broad band and narrow band adaptive cancellation algorithms. The measurement and results for a single tone narrow band frequency is shown in Section IX. The adaptive vibration control is discussed in Section X. Section XI concludes the paper.

## II. SELF-NOISE AND RADIATED-NOISE OF THE SUBMARINE

Self-noise is generated and measured onboard the submarine whereas radiated noise is measured at a location few distance away. The Fig. 1 [1] shows various noise sources and interrelationships. Self - noise refers to those noise sources between the dashed lines. The relative importance of the various noise sources is different even though the causes of both noises are same. Self-noise is one of many different kinds of undesired sound in own sonar and originates in a variety of ways. The radiated-noise is the source level which is to be detected by the target sonar. The principal sources of radiated acoustic noise of ships and submarines are [2] propulsion system (engine, reduction gears, drive shaft, bearing, and so on), propeller, auxiliary machinery (non-propulsion related mechanical and electrical system, such as air conditioning, electrical generators and pumps) and hydrodynamic effects (radiated flow noise and flow-induced excitation of plates or other structure features). The propulsion system contains large rotating shafts, bearings, gears and reciprocating engines, turbines, or electric drive motors.

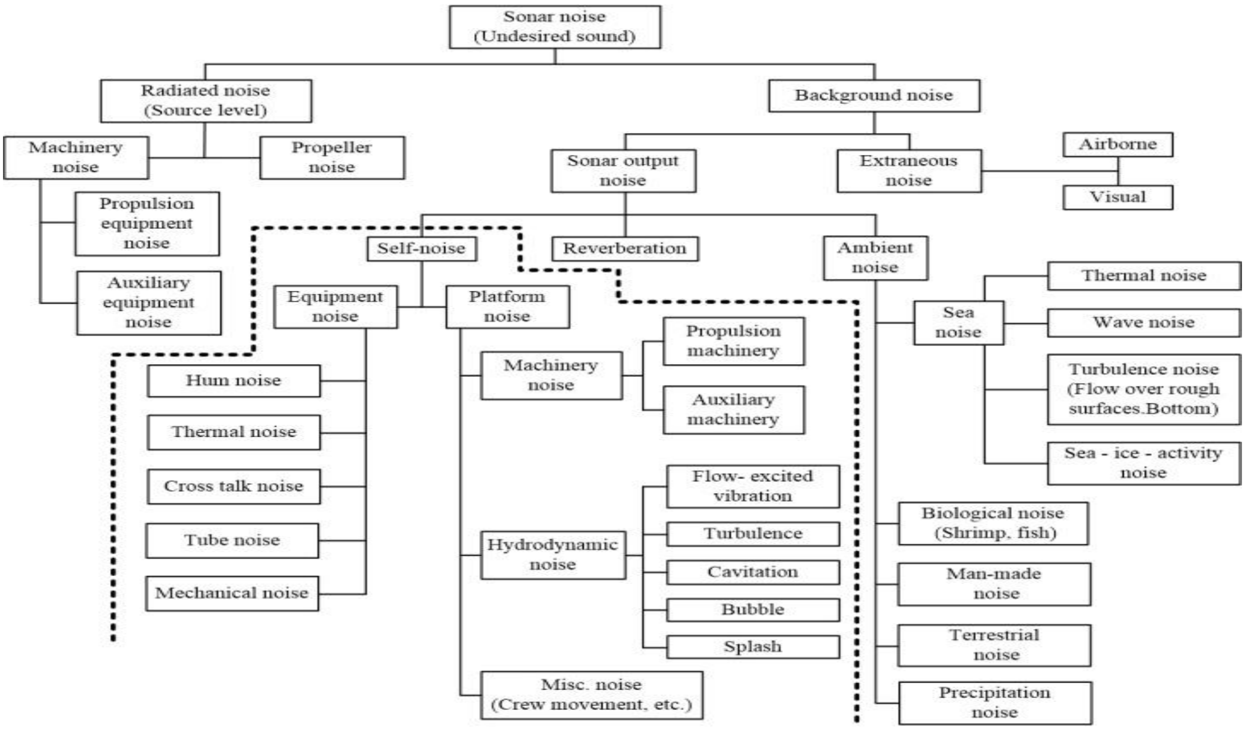



Fig. 1. INTERRELATIONSHIPS OF VARIOUS NOISE SOURCES

The forces involved typically increase as the square of the velocity, so that tonal associated with the propulsion system vary in intensity with the vessel speed. The auxiliary machines like electrical generators, pumps, blowers, and similar devices operate more or less continuously, and generally rotate at constant speed. Signals generated due to dynamic unbalance in rotating components are also narrow band tonal and generally operate at constant speed.

The Linear frictional forces present in the propulsion system result in a broadband component of the signature and are also speed dependent. The machinery noise, propeller noise and hydrodynamic noise are the major classes of self-noise and radiated-noise.

The sound and vibration generated at the propeller and the machinery spaces are propagated through the hull and water. The vibration produced by the machinery, the propeller shaft, and the propeller itself will be reradiated by the hull and reach up to the forward location. The vibration reradiated by the hull structure will be narrow band tonal, with various fundamental frequencies & harmonics related to propeller / machinery operation. The radiated noise in the water body around the platform has both broad band and narrow band characteristics which includes all signatures related to self-noise or radiated-noise.

## III. NOISE RADIATION FROM SUBMARINE PRESSURE HULL, AN OVER VIEW. (Ref Fig 2 & 3)

Sound & vibration are connected in the sense that any sound is associated with a mechanical vibration at some stage. The sound wave is the wave form caused by a vibration and which in turn causes an identical vibration to be set up in any material affected by the sound wave. When sound is transmitted the wave parameters are velocity (speed), wave length and frequency.

Forcing the hull at a machinery mounting point produces a highly localised stress field that contains all angular orders and axial wave numbers and which will excite all the natural modes of propagation of the fluid ( water ) loaded hull. The nature of the radiated field within the fluid will depend upon whether these modes are subsonic or super sonic with respect to the speed of sound in water. Supersonic modes will radiate to large distances whereas sub sonic modes generate only a near field pressure.

The strength of coupling between the hull and water for each mode of propagation is dependent upon the principal component of hull displacement; only the radial component of displacement couples to the fluid. The displacement components of shear and longitudinal waves within the hull are mainly transverse, although there is weak Poisson coupling to the radial component. Therefore, these waves produce little far field pressure even though they are supersonic.

Bending or flexural waves produce large radial displacements that generate large pressure amplitudes at the hull, water interface. At low frequencies bending waves are sub-sonic and the associated fluid pressure is confined to the near field, close to the submarine hull; the radiated field comes principally from the point at which the hull is being excited. The point behaves as an Omni-directional source and for radial forcing will be an efficient radiator of sound. However, bending waves are dispersive and at higher frequencies may become super-sonic. When this occurs, sound radiation from the hull as a whole will increase and the source region will no longer be confined to regions close to the point of forcing. The field thus produced is highly directional, being mainly confined to propagation directions such that the phase speed of sound wave, as measured along the axis of the submarine hull, matches that of the bending wave. For example, an axially propagating bending wave produces a cone of radiation from the hull.

The effects of noise on the array due to hydrodynamic flow are also significant. These sources of self-noise have two undesirable effects which are common to both the mechanical and hydrodynamic components. Firstly they constitute an ensemble of noise sources which could be detected by the enemy. Secondly the pressure field created on the array due to this noise results in deterioration in its detection capabilities. The ability of Sonar to perform its task is therefore severely compromised.

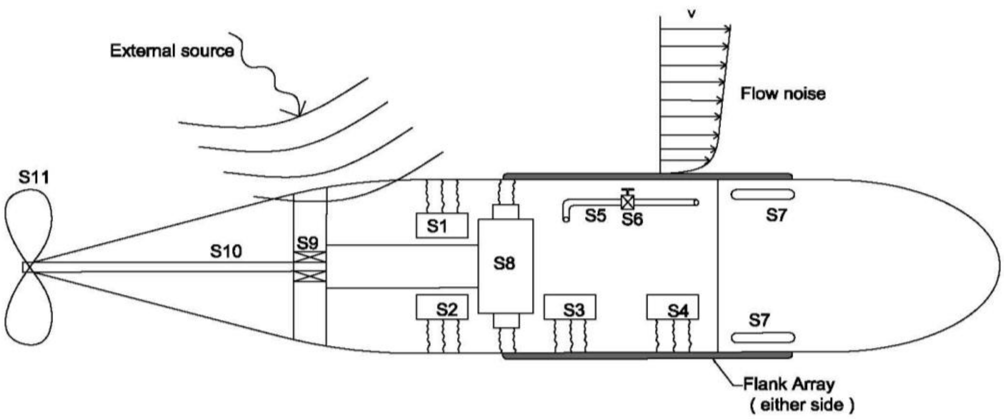



Fig. 2. SOURCE OF NOISE & VIBRATION

S1, S2, S3, S4 – Machineries
(eg: motor, pump, generator )
S5 – Piping’s
S6 – Valves
S7 – Ballast tank
S8 – Propulsion machineries
S9 – Propulsion shaft bearings
S10–Propulsion shaft
S11–Propeller

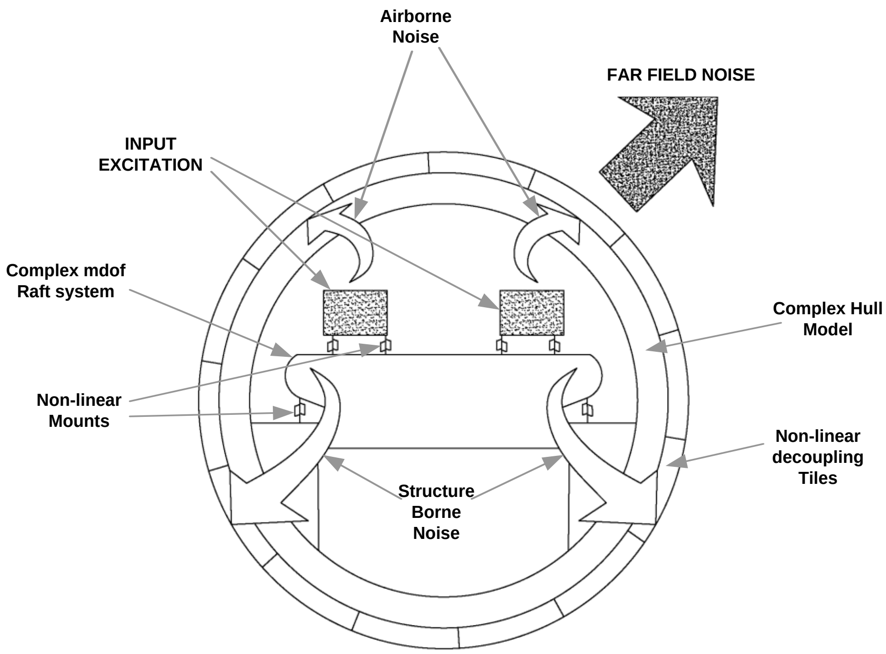



Fig. 3. A TYPICAL NOISE AND VIBRATION PROBLEM

The techniques for reduction of these noises are to be seriously addressed in the submarines considering the tactical role of submarines. This paper addresses the application of active noise control techniques to reduce the self and radiated noise of the platform. The adaptive noise control at optimum hull positions in water is attempted which can be extended further and get superior noise cancellation or reduction. The active vibration control technique is also addressed so as to limit the noise at the source which is the platform structure which can be directly used in flank arrays of the sonar.

## IV. ADAPTIVE NOISE CONTROL

The two types of noises as described above, broadband noise whose energy is distributed across the frequency band and narrowband noise which concentrates most of its energy at specific periodic frequencies. The noise can be controlled by active and passive ways. The passive techniques include special mounting of the machinery such as raft mounting schemes, shock mounts as silencers etc. and attenuate the undesired noise. Reactive silencers are commonly used as mufflers on internal combustion engines, while resistive silencers are used mostly for duct-borne fan noise. These passive silencers are valued for their high attenuation over a broad frequency range. However, they are relatively large, costly, and ineffective at low frequencies, making the passive approach to noise reduction with limitations. It is required to control the noise and many steps are followed as part of submarine construction.

The active noise control of the radiated noise is not attempted in a big way in the submarine platforms due to its practical complexity and optimal implementation. The noise will be radiated from the hull, but not from a single point but from all parts of hull structure. Although the amplitude of the energy will be more in the vicinity of the concerned hull area the large hull structure makes the active cancellation process bit difficult to achieve. However this paper proposes a scheme for active noise control of radiated noise.

The active noise control system contains an acoustic projector that cancels the unwanted sound by generating an anti sound (anti-noise) of equal amplitude and opposite phase. The original, unwanted sound and the anti-noise acoustically combine, resulting in the cancellation of both sounds. Fig. 4 shows the waveforms of the unwanted noise (the primary noise), the cancelling noise (the anti-noise), and the residual noise that results when they superimpose. The effectiveness of cancellation of the primary noise depends on the accuracy of the amplitude and phase of the generated anti-noise.

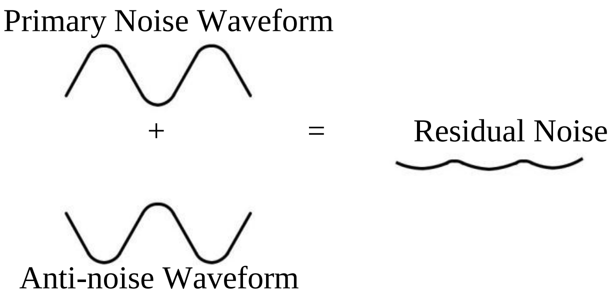


Fig. 4. PHYSICAL CONCEPT OF ACTIVE NOISE CANCELLATION

## V. BROADBAND AND NARROWBAND NOISE

The origin of self noise / radiated noise with its broadband and narrow band characteristic is briefly covered in the introduction. The prominent contribution to these is the machinery noise and propeller noise. As the speed is increased propeller noise becomes the main contributor. The narrowband tonal frequency components and its harmonics are generated from propeller, electrical generators and auxiliary machinery. Considering various types of submarines, its shaft, no. of propeller blades and speed, the tonal frequencies caused by the rotation of propellers will be in the band 0.1-10Hz. The electric generator of the submarine produces 50Hz or 60Hz tonal. Various tonal frequencies will also be generated by the non propulsion-related electric and mechanical auxiliary machinery.

The broadband component is mainly due to the frictional forces present in the propulsion system and the propeller noise due to cavitation produced by the rotating blades. During the propeller rotation, low pressure region will be created on and around the propeller blades. As the pressure drops below a critical value, the water column ruptures and bubbles will be formed which grow in size and collapse rapidly, thus generating broad-band radiated acoustic noise signal.

The ambient-noise spectra are also present in the water body around the submarine. The total noise prevailing will be the combination of self-noise / radiated noise and ambient noise.

## VI. ADAPTIVE NOISE CANCELLATION (ANC)

The adaptive noise cancellation therefore has to take into account of both broadband and narrow band noises. The noise control system comprises of broadband, narrowband noise sources, noise input sensors, adaptive noise control filter and the anti-noise generator or the projectors. Here the broadband and narrow band acoustic signature can be measured by an Omni directional wide band hydrophone. The platform vibrations generated by the rotating/reciprocating machinery consist of fundamental frequencies and its harmonics. This can be measured by an underwater accelerometer mounted to the hull. The noise input is passed through the adaptive filter and the output is transmitted through the acoustic projector. The Fig.5 is a block diagram representation of the Adaptive noise Cancellation (ANC) system

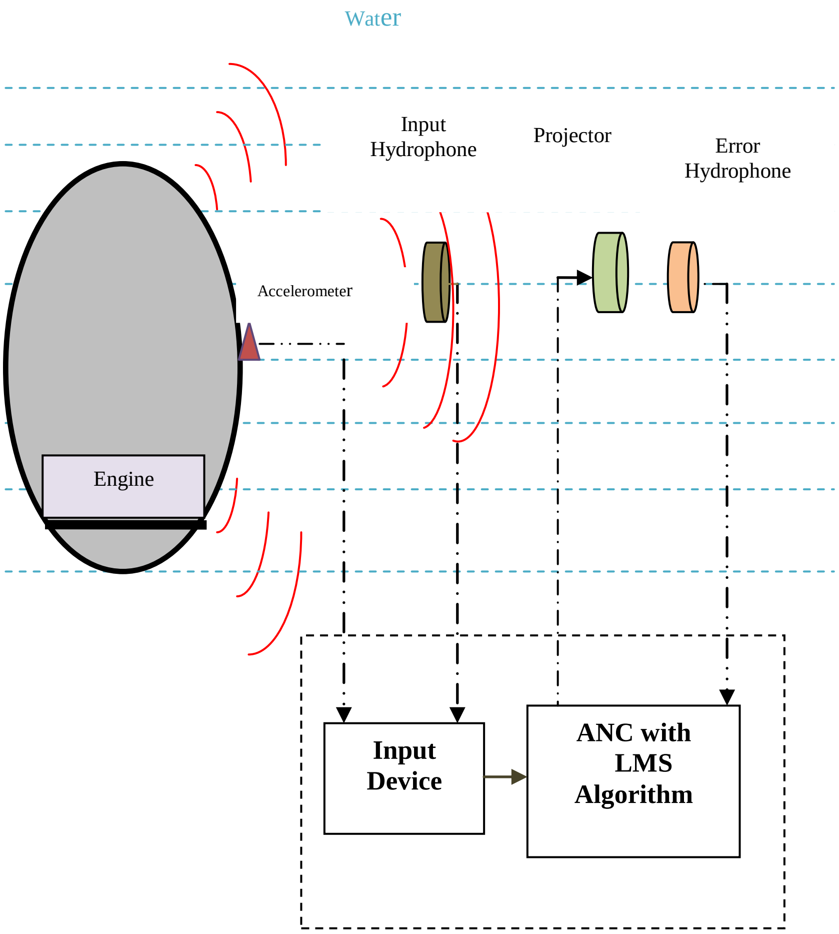



Fig. 5. ANC SYSTEM

## VII. BROAD BAND ANC

Broadband noise cancellation requires knowledge of the noise source (the primary noise) in order to generate the anti-noise signal. The measurement of the primary noise will be carried out by a hydrophone and is used as a reference input to the noise canceller. The hydrophone measures the entire acoustic signature both narrowband and broadband frequencies.

Primary noise that correlates with the reference broad band input signal is cancelled when phase and magnitude are correctly modeled in the ANC controller. The adaptive filters can be realized as Transversal Finite Impulse Response (FIR) and Recursive Infinite Impulse Response (IIR). The most common algorithm applied to adaptive filters is the transversal filter using the least mean squared (LMS) algorithm [4]. The block diagram of the LMS algorithm is given in the Fig. 6

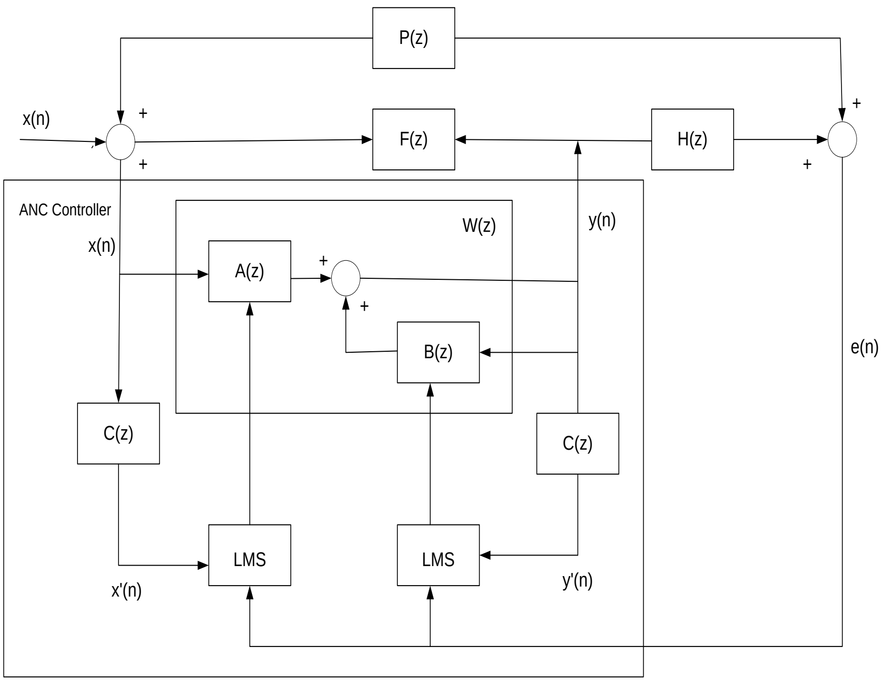



Fig. 6. BLOCK DIAGRAM OF THE LMS ANC

The adaptive filter W(z) has to estimate the response of an unknown primary acoustic path P(z) between the reference input hydrophone and the error hydrophone. The anti-noise signal y(n) can be modified by the secondary-path function H(z) in the acoustic channel from y(n) to e(n). It also radiates upstream to the input hydrophone which affects the reference input. The adaptive filters A(z) and B(z) are estimates of feedback path F(z) from the adaptive filter output y(n) of the reference hydrophone to the output of the reference hydrophone. These filters remove the acoustic feedback from the sensor input. It improves the stability of the system. The C(z) is the secondary path estimate which filters the input to the error correlator. The models C(z), A(z) and B(z) can be estimated simultaneously by an offline modeling technique using an internal white noise generator or optimum filter.

The acoustic feedback introduces a feedback loop or poles in the response of the model and will result in instability in the control system. An adaptive IIR filter [3][5] can remove poles introduced by the adaptive filter by its poles by dynamically tracking the changes in the feedback paths during cancellation operation. The IIR structure has the ability to model the transfer functions directly with poles and zeros. A computationally simple recursive LMS (RLMS) algorithm is covered in [8].

The output signal of IIR filter, y(n) computed by:

$$y(n) = a^T(n)x(n) + b^T(n)y(n-1)$$
$$= \sum_{i=0}^{N-1} a_i(n)\, x(n-i) + \sum_{j=1}^{M} b_j(n)\, y(n-j) \qquad (1)$$

where:

$a(n) = [a0(n)\ a1(n) \ldots\ aN-1(n)]^T$ is the weight vector of A(z) at time n
$b(n) = [b1(n)\ b2(n) \ldots bM(n)]^T$ is the weight vector of B(z) at time n

$y(n-1) = [y(n-1)\ y(n-2) \ldots\ y(n-M)]^T$ is the signal vector containing output feedback with one delay,
N = order of A(z), M = order of B(z)
$a(n+1) = a(n) - \mu e(n)x'(n)$
$b(n+1) = b(n) - \mu e(n)y'(n-1)$

$c(n+1) = c(n) + \mu e(n)y'(n-1)$

where:
$y'(n-1) = [y'(n-1)\ y'(n-2) \ldots\ldots\ldots\ldots\ y'(n-M)]^T$

$$x'(n) = \sum_{i=0}^{M-1} c_i x(n-i) \quad (2)$$

$x'(n)$ is the filtered $x(n)$ from $C(z)$.

and

$$y'(n) = \sum_{j=1}^{M} c_j\, y(n-j) \quad (3)$$

$y'(n)$ is the filtered $y(n)$ from $C(z)$[7].

## VIII. NARROW BAND ANC

For narrowband noise cancellation reduction of periodic noise caused by rotational machinery is to be carried out. An underwater accelerometer mounted to the hull structure measures only the structure borne vibration noise signal which will be the primary frequency of the noise generator. Because all of the repetitive noise occurs at harmonics of the machine's basic rotational frequency, the narrow band ANC control system can model these known noise frequencies and generate the anti-noise signal.

The reference signal used in the narrowband ANC system is a sine wave with the same frequency as the narrowband noise to be canceled. When a sine wave is employed as the reference input, the LMS algorithm becomes an adaptive narrow notch filter to remove the primary spectral components within a narrow band centered about the reference frequency. The application of the adaptive notch filter to active periodic noise control was referred in [6]. A block diagram of this narrowband ANC system with two adaptive weights is shown in Fig. 7. The accelerometer output is used to determine the fundamental frequency at which the repetitive noise is being generated. For example, an electric motor running at 1800 RPM completes 30 revolutions per second with a fundamental frequency of 30 Hz. A four-cylinder engine running at 1800 RPM also completes 30 revolutions per second.

A sine wave generator provides a sinusoidal reference signal at the desired frequency. Employing a Hilbert transform as the 90° phase shifter, the sine wave is split into two orthogonal components, x0(n) and x1(n), which can be used as reference inputs for the adaptive filter. These two signals are separately weighted and then summed to produce the canceling signal y(n):

$$y(n) = w_0(n)\, x_0(n) + w_1(n)\, x_1(n) \quad (4)$$

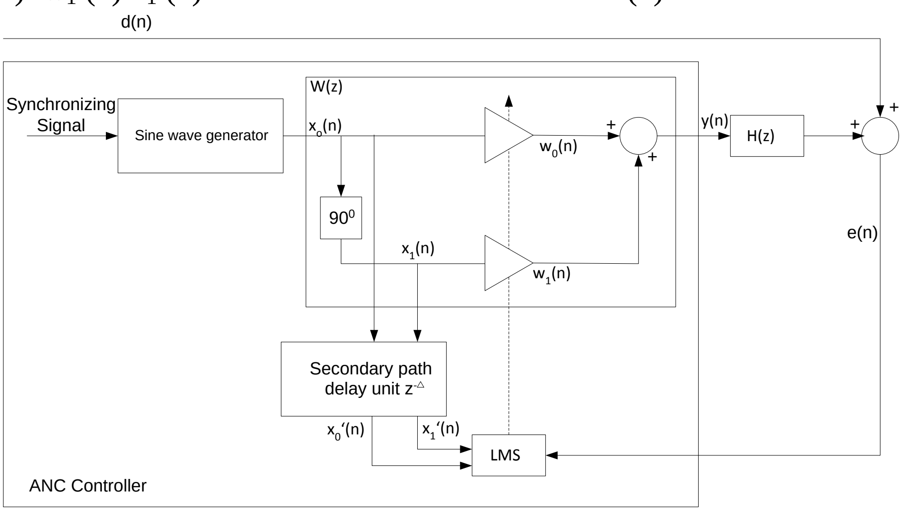



Fig. 7. SINGLE TONE ANC SYSTEM WITH ADAPTIVE NOISE FILTER

where $x_0$ (n) =A cos(k$\omega_0$n) and $x_1$ (n) =A sin(k$\omega_0$n), $\omega_0$ is the fundamental frequency, k is the harmonic index, A is the amplitude of the reference signal and n is the time index.

The magnitude and the phase of this reference signal are adjusted in the controller, which feeds one or more projectors serving as the control source to cancel the corresponding noise components. The LMS algorithm updates the filter weights to minimize the residual error e(n):

$$w_0(n+1) = w_0(n) - ue(n)\, x_0(n) \qquad (5)$$

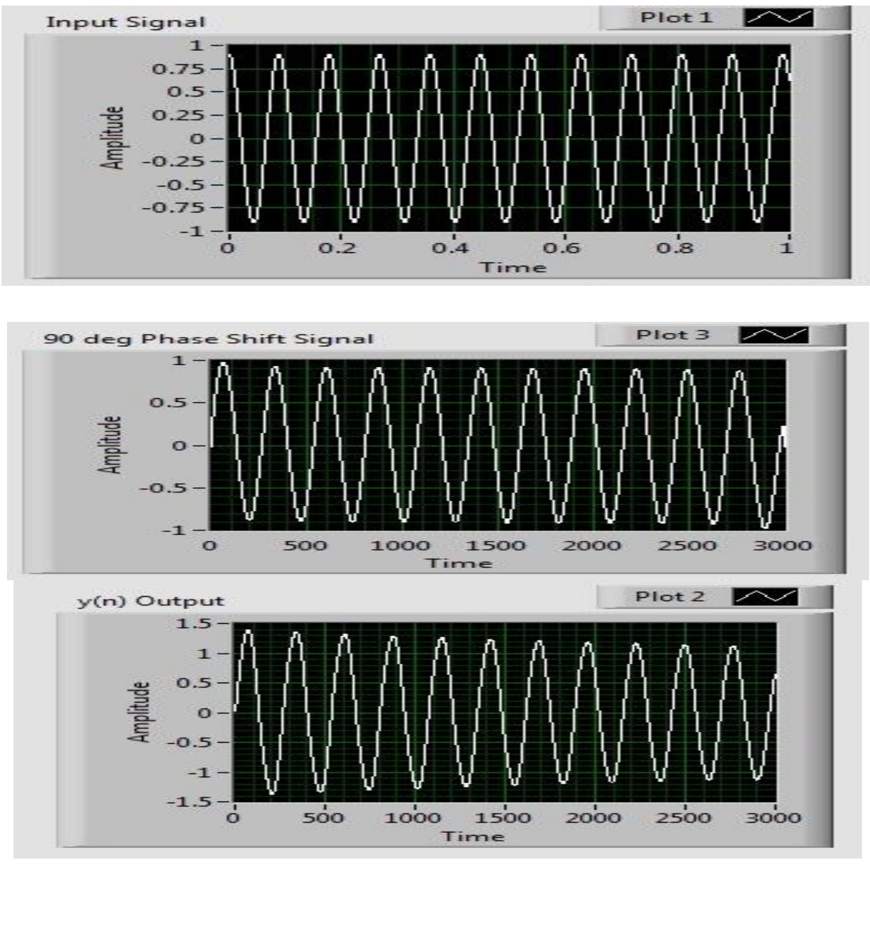
and

$$w_1\,(n+1) = w_1(n) - ue(n)\, x1(n) \qquad (6)$$

In practical applications, the periodic noise usually contains tones at the fundamental frequency and several harmonic frequencies. This type of noise can be attenuated by a filter with multiple notches. In general, realization of multiple notches requires a filter with higher order, which also can be realized by a parallel or cascade connection of multiple second-order sections. A detailed method is covered in [6]. The application of this technique to active periodic noise control is to generate the reference input as a sum of M sinusoids, i.e) x (n) =$A_m$*cos(k$\omega_m$n) where $A_m$ and $\omega_m$ are the amplitude and the frequency of the mth sinusoid, respectively. When a sum of sinusoids is applied to an adaptive filter, the filter converges to a time-varying, tunable notch filter with a notch located at each of the reference frequencies. The accelerometer output will include every sinusoidal interference with harmonics the ANC system creates a notch over the fundamental and its harmonics.

## IX. MEASUREMENTS AND RESULTS FOR A SINGLE TONE NARROWBAND FREQUENCY

A signal tonal of frequency is injected into and its corresponding results are shown in Figure. 8



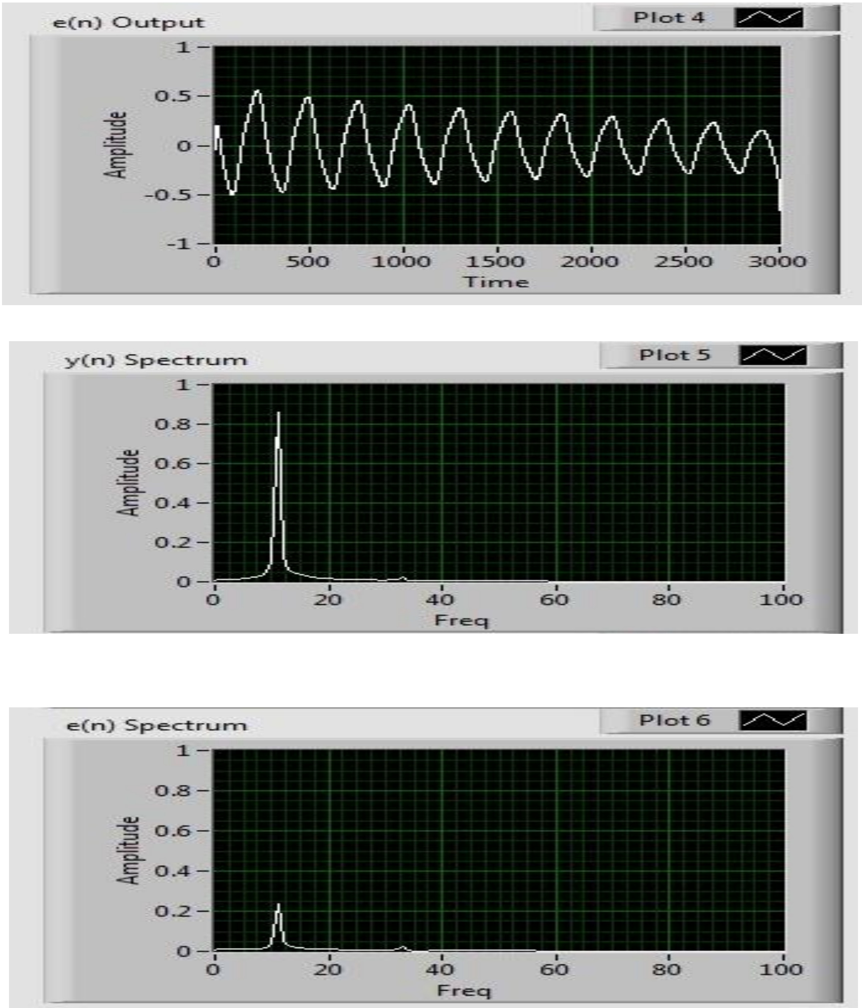



Fig. 8. SIMULATION AND OBSERVATION

## X. ADAPTIVE VIBRATION CONTROL[10-16]

As can be seen, the noise problems described above resulted due to radiation from structure borne Vibration. Outboard case is attempted which considers the noise cancellation on the systems fitted on to the hull. One of the typical example is flank array sonar sensor panels where the sensors picks up the vibration noise and manifests as correlated static noise in the sensor output affecting significantly the detection performance. An experimental study has been carried out demonstrating vibration damping of a metal plate by means of PZT stacks acting as actuators. The test setup is shown in Fig. 9 and experimental setup is shown in Fig. 10. A metal plate as shown as vibrating body is mounted on a turn table fitted with a shaker. The PZT transducer actuator stack is mounted on to the vibrating body. The vibration frequency is measured by an accelerometer mounted on to the vibrating body. Also another transducer stack is mounted to the vibrating body which is the error sensor sensing the resultant vibration of the vibrating body. The output from Accelerometers will be monitored with and without energising the PZT stacks

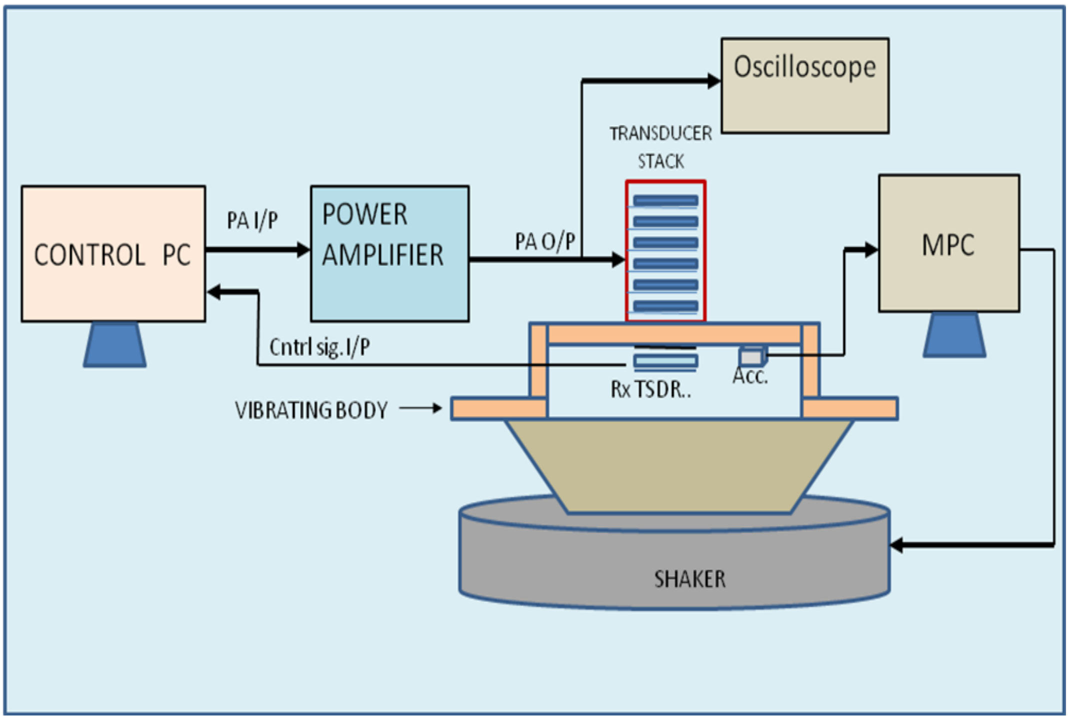



Fig. 9. TEST SETUP FOR ACTIVE VIBRATION CANCELLATION

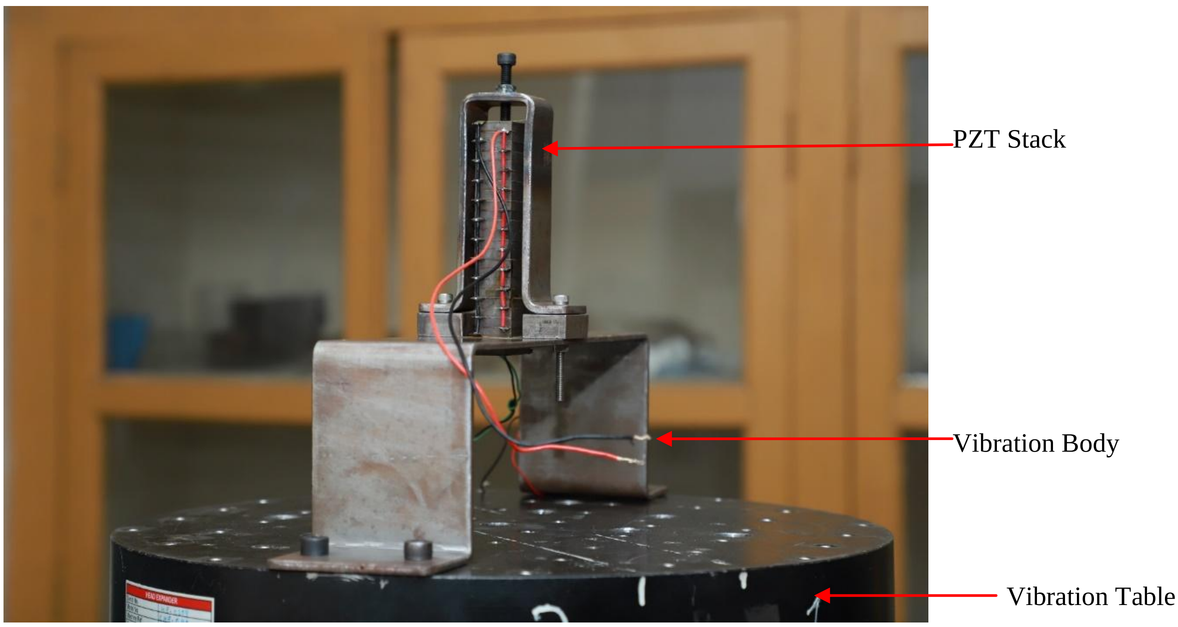



Fig. 10. VIBRATION TABLE WITH SHAKER, VIBRATION BODY AND PZT STACK

In this approach noise reduction is attempted by controlling the vibration of the structure, which is the mounting structure on the hull. The adaptive noise control algorithm is run on the control unit which receives input from the transducer error sensor. The shaker is excited with a known vibration frequency. The noise cancellation feed back algorithm running on the control unit, using the sensor input generates an amplified signal through the power amplifier and drives the PZT actuator. The adaptive algorithm converges by driving the actuator with opposite phase and hence resulting in cancelling vibration. This can be monitored at the accelerometer output and the sensor output. See Fig. 11.

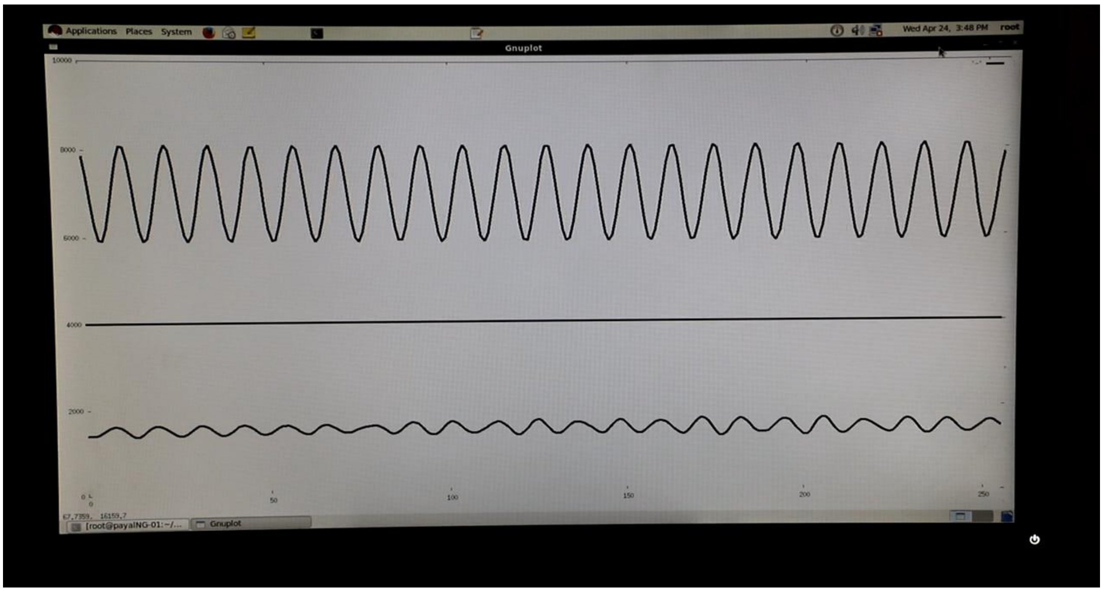


Fig. 11. OUTPUT OF VIBRATION CANCELLATION

Active Vibration Cancellation is thus realised by detecting and processing vibration disturbances through suitable adaptive noise controller, so that when super imposed on the disturbances, cancellation occurs. The actuators are to be incorporated or interfaced on mounting points of the frame integrated with the sensor.

Detailed laboratory experiments are to be carried out to ascertain its suitability for flank array, which is exposed to sea water and thereby hydrostatic pressure.

## XI. CONCLUSIONS

The self noise comprises of broadband and narrowband spectrum. An adaptive noise controller combining both broadband and narrowband (multiple frequencies with harmonics) can be realized to minimize and cancel the total self-noise. In the submarine application a distributed ANC sensor system is to be planned to achieve a practical system. Detailed study has to be carried out to understand the propeller, other machinery noise spectrum, and broadband noise spectrum, arrive the input sources, locations which will be distributed in the water to arrive the multiple set of required sensors and projectors. Active vibration control can be addressed both inboard and outboard and reduce the vibration generated noise.

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