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Fault Detection and Prognostic Health Monitoring of Towed Array Sonars

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ABSTRACT

Sonars are used to detect underwater targets and are important tools in maintaining naval superiority. Towed array sonars can operate at very low frequencies thus giving larger ranges and are capable of variable depths of operation. Towed array sonars offer long range surveillance capability and is the sensor of choice for sustained surveillance operations. Reliable operation and maintenance of towed array sonars need effective methods of health monitoring and reliability prediction. Fault detection methods for towed arrays include sensor health monitoring and analyzing their effects on beam former gain. This paper introduces certain metrics that are easily measurable in-situ and which offer insights into the health of the sonar system. These new metrics give direct measureable impact for different failure modes and offer insights into the current health of an operational towed array sonar. Hence, they can be used to build on line prognostic predictions for estimating the remaining useful life of the sonar. Simulation results are shown to demonstrate the effectiveness of the proposed metrics and detailed trial data results from different towed array trials are presented to validate them in operational scenarios.

Keywords: Towed array sonars; Failure modes and identification; On-line health monitoring

1. INTRODUCTION

Towed array sonars are extensively used in anti-submarine warfare for detecting enemy submarines. A towed array sonar consists of an array of hydrophones which are packaged along with the necessary sensing electronics in a long and flexible tube which is towed behind the ship using a tow cable. The processing system on-board the ship uses the data acquired from the hydrophone array to achieve target detection and localization. Over the years several improvements have happened in the towed array domain[1]. As the submarines have grown quieter with advanced technologies in propulsion and acoustic cladding the relevance of towed arrays has only increased as the primary mode of anti-submarine operations[3].

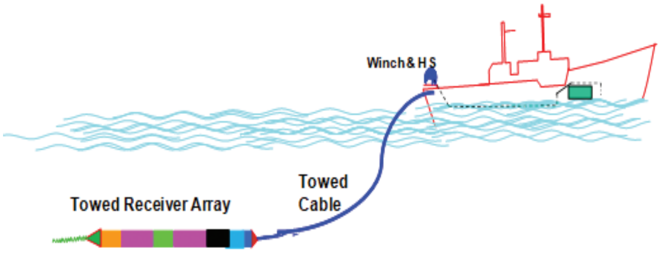

Figure 1. Towed array sonar.

Towed arrays offer the ability to detect the signals at very low frequencies where the absorption losses are lower and consequently higher ranges are possible. As the hydrophone arrays are towed behind the ship it also offers a better signal-to-noise ratio at the sensor level leading to better performance over conventional hull mounted sonars. These characteristics make towed arrays an important component of naval sensors. Typical towed arrays have more than hundreds of hydrophones which are packed along with the sensing electronics in a long flexible tube often filled with oil or some such liquid which will give it neutral buoyancy. A towed array once manufactured, acts as a fully integrated unit and any repair or element level changes are not feasible. The array is expected to be on-board the ship for many years and is deployed whenever sonar operation is deemed necessary.

Lasky *et al* [2] gives an overview of the effects of tow cable, towing speeds and other major environmental effects on the hydrophone signals for towed arrays. Wagstaff[7] described hydrophone and beam-noise levels for towed arrays and proposed automated methods for identifying element failures and ways to represent the array data for better visualization. The effect of element failures on side-lobe suppression has been studied in literature and upper bounds for the maximum side-lobe suppression levels have been derived for uniform linear arrays[8]. While these results give upper bounds on side-lobe levels they do not capture the system level degradation. A measure of the operational degradation experienced due to sub-system failures is essential to make any decisions regarding sonar maintenance and array replacement.

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Condition based health monitoring is applied in many areas to obtain meaningful estimates of remaining useful life for individual systems[4-5]. Such an approach would be very relevant for a complex system like a towed array since individual units on different ships maybe subject to different level of stresses during their operational cycles. In this scenario it is important to have a set of variables which can be monitored to give an indication of the present health of the towed array sonar.

In this paper we analyze the different failure modes which can deteriorate the performance of a towed array and show how they can be identified while the system is in operation. We propose a set of parameters to be monitored for assessing the health of the towed array and ways to estimate them. On-line monitoring of these parameters are shown to give an in-situ understanding of the health of the array and the degradation if any from the designed figure of merit. Detailed simulation results are shown to demonstrate the effectiveness of the proposed metrics in identifying and quantifying sub-system failures. We also present results from various towed array data sets collected over different experimental trials to validate the effectiveness of the proposed metrics. Observing these key metrics while the system is in operation gives an ability to estimate the performance degradation due to onset of failures and also offers the ability to do predictions on the future health of the sonar system.

The paper is organized as follows. Section 2 describes the different failure modes of towed arrays and the effects of these failures. In Section 3 we introduce the new measurement metrics proposed which will identify the effect of these failures along with simulation results. Section 4 demonstrates the results obtained during towing trials with various arrays under different conditions for each of the proposed measurement metrics. Section 5 concludes the paper.

2. FAILURE MODES AND EFFECTS IN TOWED ARRAY SONARS

The typical structure of a passive towed array is given in Figure 2. The principal components of a towed array sonar are the towed hydrophone array including the acoustic and non-acoustic modules, the tow cable, handling systems for launch and retrieval and the on-board electronics hardware. A detailed view of the wet end part reveals that the towed array consists of typically four modules which are the electro-mechanical connector and fiber-optic-module (FOM) in the first part, the forward vibration isolation module (VIM), the acoustic array and the aft vibration isolation module (AVIM). The aft-vibration isolation module is often followed by a long tail rope or a drogue which helps to keep the array under tension while it is being towed.

Figure 2. Parts of a towed array.

Each module in the towed portion has a specific function to perform during the operation of the sonar. The tow cable is the link which connects the wet end sensor to the processing platform on-board. Tow cable carries power to the wet end sensor system and also carries the sensor information back to the processing unit. Tow cable is also responsible for depth keeping as it is made negatively buoyant so that depth control can be achieved either by paying out more cable or by reeling in some length of the cable. The electromechanical connector interfaces the array to the cable and is also a load bearing unit. The fiber-optic-module sits near to the connector and converts the electrical signals coming through the array to optical signals so that it can be transmitted over the optical fiber cables contained in the tow cable.

The tow cable is susceptible to longitudinal vibrations due to the dynamic forces acting on it while the array is being towed[6]. The vibration isolation modules and at times cable fairings are used to attenuate the vibrations felt by the acoustic sensor array. The array is powered from on-board through a direct current supply from which each individual subsystems in the array draw their power. The telemetry to the ship is through optical fibers and digital communication methods are employed for sending data packets from the array to on-board. Failure modes of the towed array can be attributed to the major system components of the towed array. Each component can fail in different ways and can affect the system functionality. They are detailed in the figure 3 and are classified as element level failures, mechanical failures, electrical failures and telemetry failures.

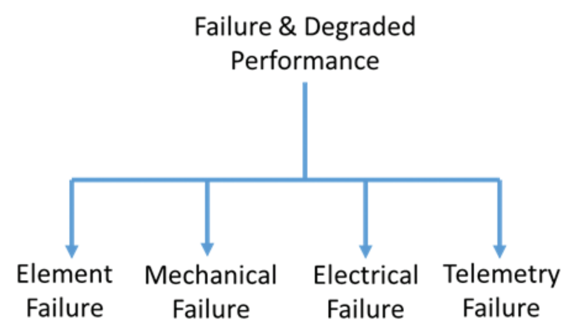

Figure 3. Fault tree for a towed array.

2.1 Element Level Failures

The towed array is expected to have identical hydrophones, with an inter-element spacing corresponding to half the wavelength of the maximum frequency of operation for which the array is designed. Due to the various deployment and retrieval cycles undergone by the towed array, positional variations in the hydrophones positions start to occur. As hydrophones age their sensitivity and phases responses also change. These positional variations and phase variations which occur over time are the first failure modes of the towed array. Progressively they lead to element level failures and the towed array performance deteriorates. The most significant effect of element failures is that the side-lobe levels are increased significantly[9].

In the case of towed arrays, the strongest target in the vicinity of the array is the own ship which is towing the array. While this appears as on target in the forward-looking direction with respect to the array, a part of the energy of own-ship will leak through the side-lobes when the towed array sonar is looking at any other direction. It is the side-lobe suppression achieved by the towed array which really mitigates this own-ship interference problem. In case of element failures, the side-lobe suppression is inadequate to sufficiently mitigate own-ship noise and often causes the sonar to underperform.

2.2 Mechanical Failures

The towed array sensor is susceptible to various hydrodynamic forces while under tow. The vibrations induced in the array by vortex shedding associated with hydrodynamic flow over the tow cable are a prominent source of low frequency noise which is coupled into the array[10]. The acoustic sensors are sensitive to vibration and vibration induced noise is a significant noise source when trying to pick up acoustic sources at low signal to noise ratios. Towed array sonar systems use two mechanisms to mitigate the effect of vibration induced noises, namely use of faired tow cables and vibration isolation modules[11]. Tow cable fairings are attached to the tow cable and vibration isolation modules are often placed before and after the acoustic part of the sensor array.

Any failure in the vibration isolation module or tow-cable fairings directly translates to significantly increased vibration induced noises in the towed array. The hydrophones pick up these vibrational modes as well as the desired acoustic pressure signals. When the pick-up due to the vibrational modes are more the signal detection capability deteriorates as the signal to noise ratio at the sensor level itself is reduced. Flow noise is another noise source which is a cause of concern. Experimental results have shown that for towed arrays with larger diameter the flow noise effects are relevant at only very low frequencies[12]. Hence mechanical failure modes are primarily the failures or reduced efficiency of the vibrational isolation modules and the tow-cable fairings. These can occur due to cyclical loads being exerted while in operation and due to wear and tear due to multiple deployment and retrieval cycles.

2.3 Electrical Failures

Supplying power to the towed array is a critical aspect of towed array-based data acquisition. The power has to be supplied from on-board over the tow cable to the sensor array. Often the sensing electronics are all low power devices and the scheme of power transfer is usually to transmit high voltage direct current to the array and use individual DC-DC converters in the array modules to generate the power supplies to individual chips. While this is the most efficient method of delivering power such an approach also introduces certain noise sources.

The primary noise source is the power supply ripple which gets modulated on to the sampled signal from the hydrophone. Another equally important noise source is the high frequency ripple especially from the switched mode power supplies which gets coupled to the input signal through electro-magnetic interference[13]. The power supply ripple is a low frequency noise and the switching noise is a high frequency noise source. Both these noises are periodic in nature and turn up as false alarms in spectral analysis of hydrophone signals. The noise signals are coupled to the hydrophone channels via electro-magnetic interference. This mode of failure is very common as the towed array ages as the electronics components and filters tend to fail with time. It is thus imperative to have a mechanism to identify such hidden failures in the towed array.

2.4 Telemetry Failures

Telemetry refers to the data transfer between the towed array and the on-board processing station. Different techniques are used for telemetry depending on the cable length and data rates. For long towed arrays which are towed more than hundreds of meters behind the ship, especially for passive detection arrays, ethernet based telemetry over optical fibers are made use of[14]. The data acquisition and telemetry scheme for a 64 element towed array configuration is shown in Figure 4.

The array is considered as a networked towed array with a hierarchical system of sampling and data transfer. Each hydrophone is coupled with a pre-amplifier which is co-located with the hydrophone on a special housing which supports both the hydrophone and the pre-amplifier. There is a common analog to digital conversion card for eight channels

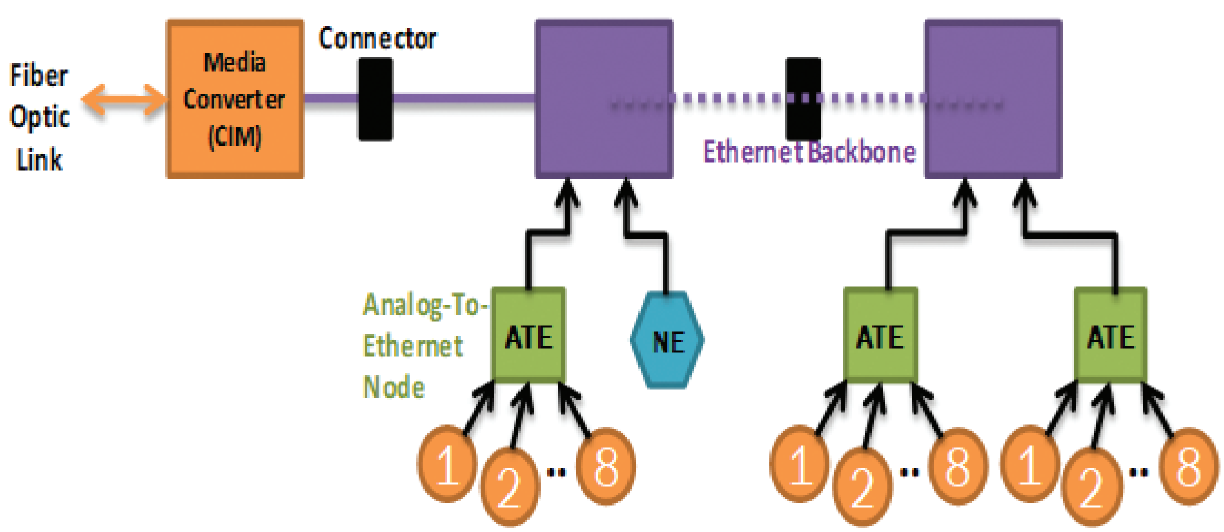

Figure 4. Telemetry in towed arrays.

of hydrophone. The analog to digital converter samples each of the eight channels in a serial fashion at the desired sampling rate and passes this sampled information to an ethernet node within the array. The ethernet node accumulates these samples till enough samples to be sent in an ethernet packet is available and then sends it over ethernet. The array is made up of a daisy chained network of ethernet switches and the data packets are routed forward till the end connector[15].

Telemetry failures can occur in the array as well as during the data transfer. Catastrophic failures like the breaking of fibre-optic lines or failure at the connector points are possible but are easily identifiable due to sudden loss of data. More subtle are failures in the link due to packet losses in between as the array data cascades through the network of ethernet switches and the effect of some data losses when the media converters misbehave intermittently. The array being a synchronous data acquisition system the data rates and through put are fixed and any loss in between will get reflected in the data rates achieved and the number of packets received per second at the receiver side.

3. FAILURE IDENTIFICATION AND ANALYSIS

This section details the effects of each failure mode listed in section 2 and brings out measurable parameters, which captures the degradation caused by each failure. These measurement metrics can be monitored online and used to identify the onset and effect for each type of failure mode. They will also give an indication of the performance degradation experienced by the sonar due to the failure.

3.1 Effect of Element Level Failures

The figure of merit of a passive towed array sonar is given by

$$FOM = RNL - (NL - DI) - DT \quad (1)$$

where RNL is the radiated noise level of the target, NL is the ambient noise level, DI is the directivity index and DT is the detection threshold of the processing[16]. The level of ambient-noise suppression achieved from the sensor level to the beam output level is given by (NL-DI). This is the beam noise level, or the noise background at the output of every beam over which detection has to take place.

The self-noise of the ship is a directional source and often the principal noise source in the vicinity of the towed array. For every beam the output contribution due to own-noise can be calculated as (ONL-SLS) where ONL is the noise level experienced the beam looking towards own-ship and SLS is the side-lobe suppression achieved. Whenever SLS values go down own-ship noise leaks into other beams through the side-lobes. In this case the higher value of the two, one being ambient noise reduced by the directivity index (NL – DI) and the other being the own-ship noise reduced by the side-lobe level (ONL – SLS) sets the background above which detection needs to take place. To summarize, the beam-noise level (BNL) in any beam in the direction θ, is

$$BNL(\theta) = Max\{NL - DI(\theta), ONL - SLS(\theta)\} \quad (2)$$

In places close to forward end-fire direction it is often the (ONL-SLS) which dominates and sets the background and towards aft end-fire direction (NL- DI) is the dominant factor. The beam-noise levels across the different beams give a good indication about the efficacy of the sensor system. Wherever targets are present the beam-noise levels are indicative of the target energy in that beam and on all other beams the beam-noise levels are supposed to be ambient noise reduced by the directivity index factor.

The achieved side lobe suppression value for a towed array sonar can be inferred from the average beam-noise level of the noise only directions. For any sonar, the lower quartile of the beam energy levels when they are ordered in the descending order, corresponds to the noise only output beams. Defining the average beam-noise level as the mean of the lower quartile (MLQ) of the beams, we can have an estimate of the system beam-noise level. The achieved side-lobe suppression (ASL) is defined as the difference between the peak value in the energy output and the system beam noise level estimated. For any sonar this has to be close to the designed value for ideal operational cases. Further, any degradation due to sensor failures are easily measured by the ASL value estimated from the energy detector

$$ASL = Max(ED) - MLQ \quad (3)$$

Figure 5 plots the beam-outputs for a 32 element array case with a significant own-ship target with and without failures. Five randomly chosen elements are set to zero to simulate failures. The graph clearly shows the elevated noise levels for the end-fire directions and significant decrease in the achieved side-lobe suppression.

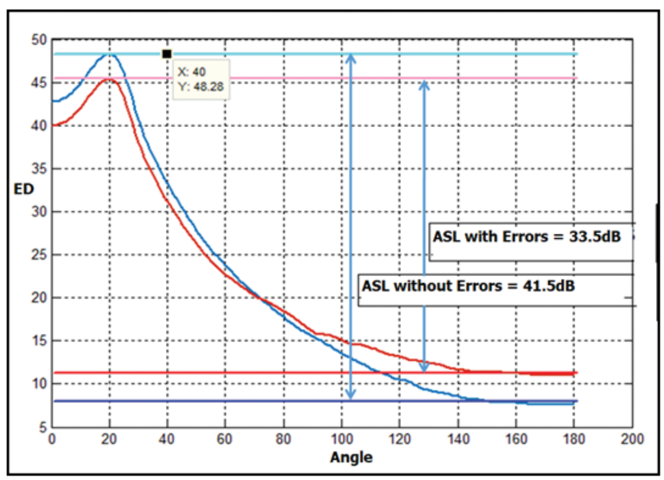

Figure 5. Achieved SLL with and without failures.

The ASL for no failures is 41.5dB and with five failures is 33.5dB, which translates to an 8db loss in the metric. Thus ASL is a very good metric to identify operational degradation experienced by the towed array due to element failures.

3.2 Effect of Mechanical failures

Failures in vibration-isolation modules and fairings increase the mechanically coupled noises felt by the towed array. The tow cable vibrations in the axial directions of the tow cable are coupled to the towed array and manifest themselves as noises in the hydrophone outputs. The principal difference between a vibration induced noise and an acoustic signal is the velocity of the signal induced. Typical velocities of vibration induced signals are much lower than the sound velocity for which the sonar system is designed for. Again, the vibration induced noises are always present along the forward-looking directions.

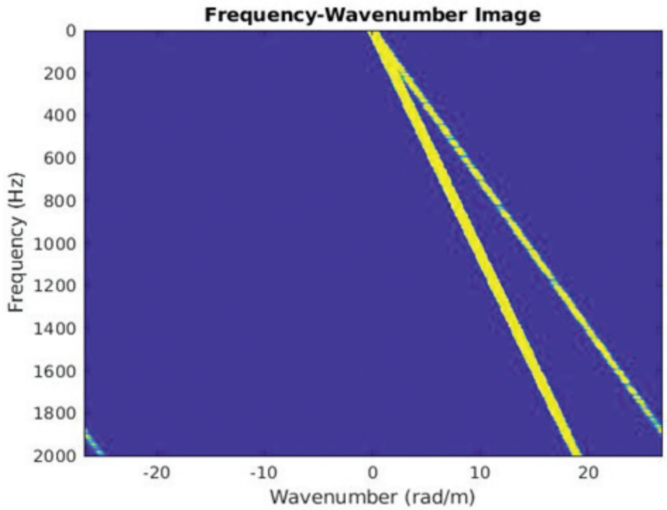

Figure 6. Frequency-wavenumber plot for 2 velocities.

With these characteristics a frequency wave-number spectrum can specifically show the presence of these noises in the sensor data set[17]. The frequency-wavenumber spectrum presents a two-dimensional graph which clearly marks out the acoustic part of the spectrum and non-acoustic part of the spectrum. Significant noise sources in the non-acoustic part can leak through side-lobes to the acoustic region when beam-forming is done and interfere with target detection capability[18]. Figure 6 shows the typical frequency wavenumber spectrum for the case of two signals, one an acoustic target at broadside and a vibrational noise source along the end-fire direction whose wave-velocity is different. This is a simulation exercise to demonstrate the effectiveness of frequency wavenumber spectrum in identifying the non-acoustic source in a cluttered data acquisition environment.

A measure of how severe is the effect of vibration induced noise in the sonar performance can be gained from the ratio of non-acoustic to acoustic energy at each frequency especially at low frequencies where the effects of vibration is dominant. A simple metric is to find the ratio of the sum of energy in the non-acoustic part to the acoustic part of the frequency wave-number spectrum below a certain threshold frequency. When the sonar is functional this ratio would have to be less than or close to unity. Any variation in this ratio is a pointer to some degradation in the vibration isolation modules or the loss of effectiveness of the fairings.

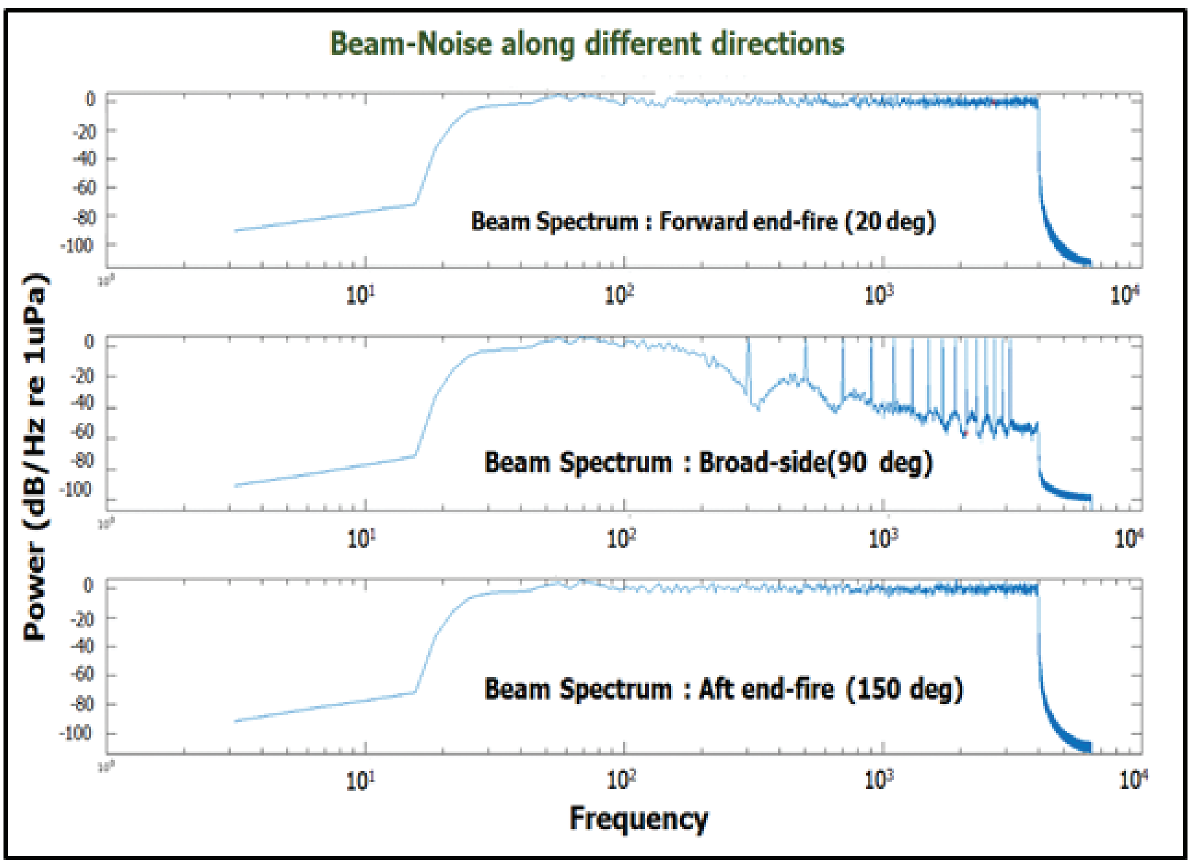

Figure 7. Electronic Noise in the broad-side beam.

3.3 Effect of Electrical Failures

Electronic noises which affect the towed array sonar can be generally attributed to two kinds. One type is due to random electronic noise being picked up at each channel which are uncorrelated between themselves. The uncorrelated electronic noise would be incoherently added up by a beam former and would present at the output in a similar fashion as ambient noise in the beam output.

The second type of electronic noise is the noise which is coupled by means of electro-magnetic interference. The principal characteristic of such induced signals is that such noise couplings appear simultaneously on every channel. Any variation in power supply which is coupled to the sensors will appear as a common signal in all channels. Another way of interpreting this is that the electrical noise which is coupled due to power supply variations or switching noise will appear as correlated noise sources with similar time varying characteristics at all sensors. Naturally such signals will add up in phase when we add them up in the beam-forming processing at zero delay which is corresponding to the broad-side beam.

The effect of such noise sources would be felt at more significantly on broad-side beam alone. The spectral analysis of the broad-side beam shows large number of harmonics when electronic noises are dominant. They are easily identifiable by virtue of these harmonics showing no variations in their frequencies over time. Any acoustic source which marks up as a tonal is susceptible to Doppler shifts by virtue of the relative motion between the sonar and the target. This is evident when the vessel takes a turn or when there is high relative velocity between both the platforms. Tonals generated by electronic noise has large number of harmonics and show no Doppler variation at all. Figure 7 shows the spectral analysis results of three beams in a simulated scenario with two targets one at forward end-fire, one at aft-end fire with the effect of electronic noise coupling simulated at the sensor level. We have added a common signal which consists of a tonal at 100Hz and its harmonics to all channels as would happen with a noise coupling from power supply source.

It is shown that if the spectrum of the broad-side beam is cluttered with static harmonic tonals while the other beams are free of such harmonics this is an indication of electronic noise being coupled into the system. A good approach to automate the detection of such cases is find the cepstrum of the broad-side beam. Cepstral analysis is usually used in vibration monitoring systems as well as audio processing to identify periodicities in the spectrum[19]. Periodicities in the broad-side beam is a key indicator for electronic noise.

3.4 Effect of Telemetry Failures

The measure of a successful telemetry is the speed and data rates achieved. The packet loss being currently experienced by the system and the average through put measured are good indicators of system telemetry health[20]. Both these parameters are easily measured by comparing the number of packets received per unit time to the expected packet rate as per design.

The effect of data packet losses due to telemetry failures can be modeled as follows. The FOM of the passive sonar was given in equation (1). The detection threshold (DT is the required signal to noise ratio at the input of the detector to achieve a desired probability of detection and probability of false alarm. The DT is dependent on the number of samples being integrated in a given time period.

$$DT = 5\log d - 5\log(BT) \tag{4}$$

where B is the band-width of the signal and T is the time duration. The event of data-loss can be modeled as a random variable, where the data loss intervals can be modeled as an exponential distribution.

$$P(T > t) = \exp(-\lambda t);\ f_T(t) = \lambda \exp(-\lambda t); \tag{5}$$

The mean interval between successive data losses can be obtained as

$$E(T) = \int_0^\infty t\lambda \exp(-\lambda t) = \frac{1}{\lambda} \tag{6}$$

In the event of a data loss, let Np be the number of packets lost, Fs be the sampling rate and Ns be the number of samples in each packet, the total number of samples lost is given by

$$L = NsNp \tag{7}$$

The effective pulse-width, or time-period in this scenario now is given by

$$T_{eff} = T - T\lambda \frac{L}{Fs} \tag{8}$$

This translates to a new detection threshold where T is replaced by T_{eff}

$$DT = 5\log d - 5\log(BT_{eff}) \tag{9}$$

This degradation will be evident in the performance of both active and passive modes of the sonar operation. So the packet loss rate which can be measured can be mapped to a degradation experienced by the sonar.

4. EXPERIMENTAL RESULTS

We have tried to capture the effect of the proposed metrics on the towed array data which has been collected over various sea trials. We have analyzed sets of data in-which the array elements had different kinds of failures. We present the results of each of these cases so that the effect of the proposed matrices are evaluated on these real field data sets.

4.1 Effect of Element Level Failures

The Figure 8 denotes the beam-noise level plots for an array with 64 elements with an inter-element spacing of 33.75 cm which corresponds to a maximum frequency of 2 kHz. The array had a failure of in one node and lost a set of eight elements, leading to only 56 elements being functional. The beam-noise levels in a scenario where there are no targets are shown. We see that towards forward end-fire we have higher beam-noise levels due to own-ship signature. But for almost all other angles from broad-side to aft end-fire we have significantly high beam noise levels. Ideally we had expected a side-lobe suppression of 50 dB due in the design, but we see that only about 30 dB has been achieved.

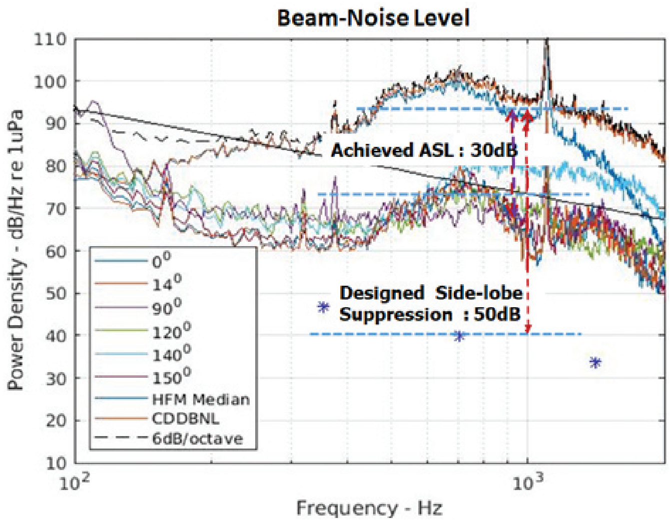

Figure 8. Achieved ASL v/s Designed on trial data.

The effect of mechanical failures as shown by the frequency wave number plots are given in Figures 9 and 10. Figure 9 shows the frequency wave-number plot at a low tow- speed of 6 knots whereas figure 10 shows the same at a higher speed of 12 knots. As we can see from the figures, at higher speeds at lower frequencies, especially below 200Hz region there is significant presence of non-acoustic noise. This is due to the much higher tow cable vibrations felt at high speeds. These vibrations are coupled to the hydrophones in the towed array and they turn up as significant noise sources in the low frequency areas. The effect would be similar if any failure occurred in the vibration isolation module and tow cable fairings. We can calculate the ratio of the non-acoustic to acoustic noise in these two scenarios and see that in the high speed case the ratio is much smaller.

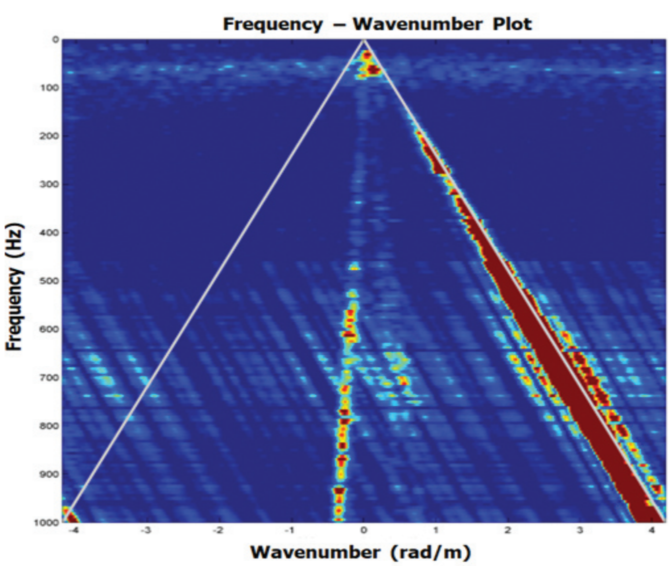

Figure 9. F-K plot of the trial data at 6 knots speed.

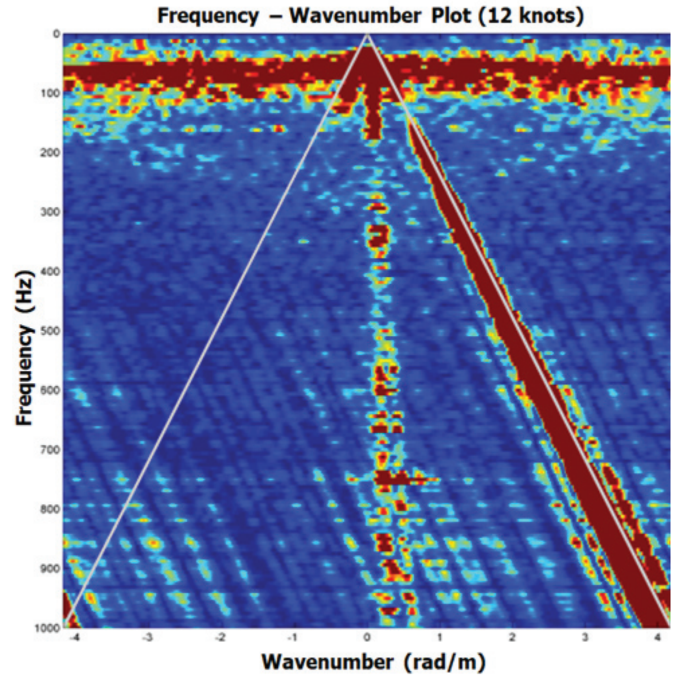

Figure 10. F-K plot of the trial data at 12 knots speed.

Table 1 lists the calculated the ratio of the non-acoustic to acoustic noise power ratios for the frequencies below 500Hz. As is evident in the very low frequencies ranges only a small portion of the total wave-number space contributes to acoustic noise and non-acoustic noise contribution is much more.

Any failure in the vibration isolation unit (VIM) or the tow cable fairings will give the same effect. This ratio is a good indicator for the health of mechanical vibration isolation units as well as tow cable fairings.

Table 1. Non-acoustic to acoustic noise ratio

	Speed (knots)	Non-acoustic to acoustic ratio (for <500Hz)
1	6	1.31
2	12	6.44

4.2 Effect of Electrical Failures

Figure 11 shows the beam-noise levels across different beams for an array which had certain grounding issues which lead to ripples in the power supply being coupled into the sensor signals. As can be seen from the figure the beam spectrum along the broad-side direction (light blue-color (90°)) has a number of sharp spikes in its spectrum as compared to other beams which have a smoother spectral signature. Also in the figure 8, the broad-side beam of an array which had element failures, but no electrical issues, had not manifested any such discrete lines in the spectrum. So this presence of high frequency tonals in the broad-side beam is a sign of electrical noise leaking into the sensor data.

4.3 Effect of Telemetry Failures

The effect of telemetry failures can be quantified in an objective manner as described in section 3. Here we present

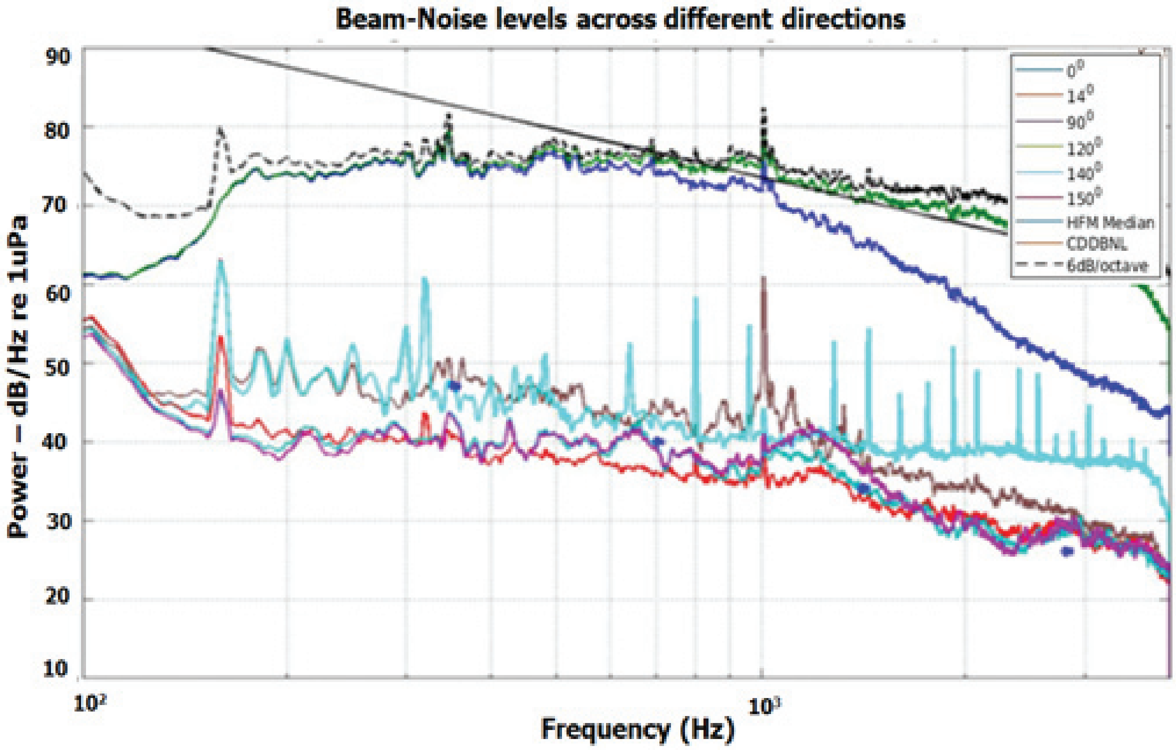

Figure 11. Electrical noise pick up on 90 broad-side beam.

the degradation estimated for two separate towing conditions depending on the data loss measured during the tow and confirmed during recorded data analysis at lab. The packet loss estimates seen from the data analysis were between 2 % and 10 % respectively for a normal and degraded case respectively. The degradation in FOM can be calculated based on Eqn. (9).

Table 2. FOM degradation due to packet loss

	Packet Loss	Degradation in FOM
1	2 %	0.05dB
2	10 %	0.23dB

5. CONCLUSION

In this paper we have proposed a few metrics which can be monitored online for estimating the health of a towed array sonar. These metrics are derived from the fault tree analysis of the towed array, wherein the principal failure causes for each module were identified and their effects studied. The defined metrics identify different failure modes and also offer an appreciation of the degradation experienced due to the failure in the present condition. The efficacy of these metrics to identify and measure the degradation has been shown through simulation examples. We have also shown that these metrics work well in real conditions by calculating them on recorded data files from previous experimental towed arrays. The experimental validation confirms that these metrics would be good indicators for in-situ monitoring of the health of towed arrays and can be extended into giving predictions regarding system performance limitations for future times.

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