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ADVANCES IN MONITORING AND MITIGATION OF SHIP SIGNATURES

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Abstract

Signatures are the physical manifestations of a ship that can be exploited by military systems to detect, identify, track, or target it. Signature management is a strategy to minimize a ship's susceptibility to attack by reducing its signatures. For the past ten years Defence R&D Canada - Atlantic has been developing an experimental Ship Signature Management System (SSMS) which performs real-time monitoring of the ship's systems and environment in order to estimate its underwater acoustic and above water infrared signatures. The acoustic signature is derived primarily from the measurement of hull and machinery vibrations. The vibrations are further analyzed to track tonals which identify machinery or equipment that produce abnormal or unacceptable vibration levels. The infrared contrast signature is estimated from an array of temperature sensors and measurement of the background infrared radiance. The results of recent experiments with SSMS on Canadian research vessel CFAV *Quest* are reported here.

1. INTRODUCTION

The goal of signature management is to reduce the probability of a ship being detected, identified, tracked, or targeted. Collectively, these probabilities are referred to as the ship's susceptibility. Traditionally the signature of a ship was considered to be only acoustic but recently the term has come to refer to all influences which can be exploited to sense a ship. These include underwater magnetic and electric fields and above water visible, infrared (IR) and radar cross section signatures. Deliberate emissions from a ship such as radio communications, electronic countermeasures and radar are not considered signatures. DRDC Atlantic's (DRDC Atlantic) experimental Ship Signature Management System (SSMS) is being demonstrated on Canadian research vessel CFAV *Quest* shown in Fig. 1. SSMS a testbed for several signature management concepts. Of particular importance are the systems for acoustic and infrared signature monitoring and reduction. These systems are considered in detail in this paper.

Figure 1. Canadian Forces Auxiliary Vessel (CFAV) *Quest*. *Quest* is 76 × 12.6 × 4.8 m (length × beam × draft) and displaces 2200 tonnes. *Quest's* top speed is 15 knots on both propulsion diesel engines (twin shafts, twin rudders) and 10 kts on gas turbine.

2. SSMS OVERVIEW

SSMS has been designed with a generalized approach that applies to all signature types. The basic processes; Acquisition, Processing, Analysis and Response, have been described in Ref. 1 in the context of acoustic signatures. The impact of environmental effects on the range at which the ship can be detected underwater by passive sonar is described in Ref. 2. Extension of SSMS to include IR signature monitoring and mitigation was first described in Ref. 3.

Evaluation of *Quest's* signatures requires detailed information about the ship's operating state and environment. SSMS monitors the status of all ship machinery via the Integrated Machinery Control System (IMCS) which provides 250 data elements ranging from diesel engine oil pressure to status of the galley fan.

Data from a wide range of specially installed sensors is also monitored. These include vibration sensors (accelerometers) which are installed throughout the ship on the hull plates and frames, on selected machinery and in the void space overhanging the propellers. Data from the vibration sensors is used to estimate the acoustic signature. Ship motions are measured with a 6-axis solid state gyroscopic motion sensor. The motion of the ship affects propeller cavitation and thus the amount of radiated noise. Temperature sensors embedded in the hull and in the engine exhaust uptakes, combined with fuel consumption and propulsion configuration allow the IR signature of the ship to be estimated.

Environmental conditions around the ship directly affect some signatures and determine the propagation environment for all of them. In addition to the usual suite of meteorological sensors, *Quest* has instruments to measure solar irradiance in the visible and IR bands and visibility as well as the IR radiance of the horizon background. Data from these instruments and the surface water temperature, are required to model the IR signature, its contrast with the background and how it diminishes with range due to atmospheric attenuation. The suite of special purpose sensors on Quest is shown in Fig. 2.

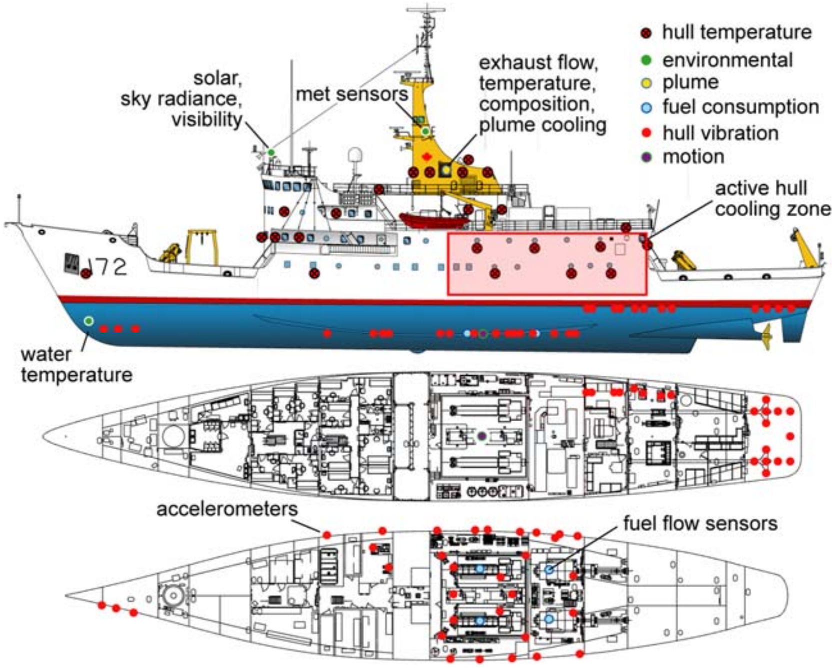

Figure 2. Suite of special-purpose sensors on board *Quest* including 52 vibrations sensors and 37 hull temperature sensors.

3. ACOUSTIC SIGNATURE MANAGEMENT SYSTEM

3.1 Prediction of acoustic radiated noise

The estimated acoustic radiated noise is based on real-time vibration measurements combined with the known local structural-acoustic transfer function of the ship, as well as on a database of measured acoustic signatures. The objective is to achieve radiated noise estimates that agree with measured noise to within 3 dB over the frequency range 10 Hz to 10 kHz. The semi-empirical approach used is described in Ref. 2. Recently a study was done to determine optimal sensor placement and to improve the transfer functions (Ref. 4).

Prediction of far-field radiated noise using a combination of finite element and boundary element methods is also under investigation for use at very low frequencies from zero to approximately 50 Hz. A finite element structural model of *Quest* has been developed which can predict hull vibrations from both engine and propeller-induced loads. The calculated hull vibrations are then used to predict far field noise using the boundary element computer program AVAST (Acoustic Vibration And STructrual analysis) developed by Martec Ltd., Halifax, Canada (Ref. 5). AVAST is also capable of predicting far field noise from measured hull vibrations using a reciprocal technique. This involves calculating the pressure field (amplitude and phase) over the hull from an acoustic source located at the desired acoustic field point and interpolating/extrapolating the measured data based on this field. The resulting complete hull vibration set can then be used to calculate the radiated field.

3.2 Acoustic processing

The vibration signals are monitored continuously to detect acoustic events (transient noise) and acoustic faults, which are sustained elevated vibration levels associated with specific equipment. A complete description of the acoustic analysis functions of SSMS may be found in Ref. 6. Here we discuss two functions, the tonal tracker and cavitation monitor.

3.3 Tonal tracker

The SSMS signal processor converts vibration data to power spectra and tracks the time evolution of prominent tonals. The tonal tracker associates tonals with particular locations and machinery on the ship and also flags tonals that exceed given thresholds of intensity or frequency. Examples of physical events that could cause a tonal frequency to wander include rotating machinery that is out-of-balance or changing to adjust to a new load, propellers changing speed due to variations in the sea state, or a change in maneuvering.

An example of the tonal tracker display is shown in Fig. 3. It is a plot of power spectra as a function of time also known as a LOFARgram (LOw Frequency Analysis and Ranging). The display provides information on tonal through color coding. Green indicates the presence of a spectral peak that is not yet being tracked. Brighter green indicates greater power. A blue line is a tonal that is being tracked. A white line indicates tonals were there but they are not being detected anymore. Black, the background, are areas where the SNR value is less than a user specified minimum.

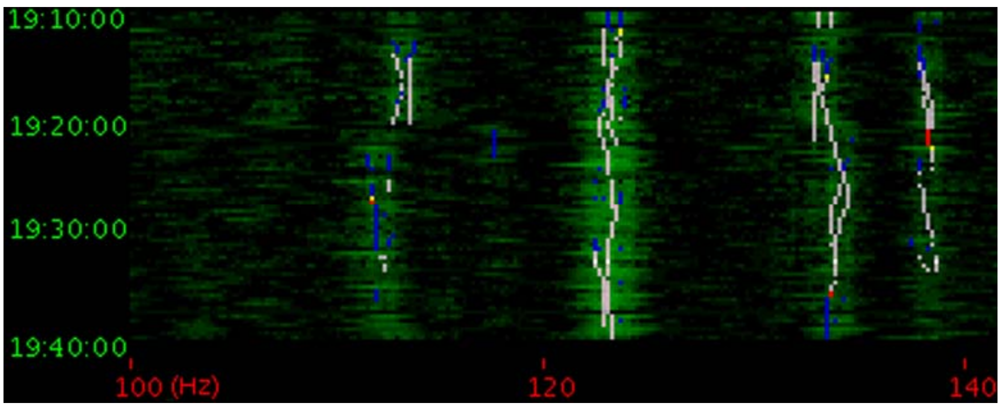

Figure 3. SSMS tonal tracker display (green = detected, blue = tracked, white = was there, black = SNR < threshold, yellow = fade in, red = fade out.

For sharp and unambiguous tonals in a low noise background, tonal detection is straight-forward. Broad and fuzzy tonals are a greater challenge to detect. Even when the tonal signal-to-noise ratio (SNR) is sufficient for the tonal to detect by eye, it may be difficult for the detection and tracking algorithms to handle.

Recently, the SSMS tonal detection and tracker algorithms underwent further development to improve performance under the following circumstances; fade in - a tonal that was hidden by the previous background appears, fade out - a previously existing tonal becomes hidden by the background, lines cross - two or more tonals cross with the result that the tonal tracker tracks the wrong line.

Tracked tonals are correlated with each other to identify any that arise from the same acoustic source. The process of tonal association is carried out for tonals from individual sensors as well as for all sensors together. Typically tonal associations are attributed to a particular piece of ship equipment. Thus the contribution of specific machinery to the over all acoustic signature can be determined. The relationship between tonal groups and machinery is determined by correlating the timing of acoustic events with data on machinery state available on the ship's IMCS which provides a continuous, real-time, stream of 250 pieces of information related to approximately 140 pieces of equipment.

3.4 Cavitation monitor

There are two major contributions to a ship's acoustic signature; noise created by on-board machinery, and noise due to propeller cavitation. At low speeds, shipboard noise is the greatest contributor. At high speeds, the cavitating propellers dominate the acoustic signature. The onset of cavitation is usually quite sudden as speed increases. The cavitation inception speed varies with ship motion, speed, sea state and running configuration.

SSMS has a monitor function that detects the on-set of cavitation. Signals from 13 accelerometers located on the hull near *Quest's* two propellers are synchronously averaged using the shaft rotation as the phase reference. The accelerometer signals are very noisy since they detects many different sources of vibrations. A frequency domain analysis can detect the onset of cavitation but takes much longer than synchronous averaging. Typically, in the frequency range of interest, 50-100 propeller rotations are needed to achieve good frequency domain results. With synchronous-averaging, this can be achieved with 5-10 rotations.

Synchronously averaged signals from some of the accelerometers near *Quest's* propellers are shown in Fig. 4. The accelerometers are located in the void space (tiller flats) over the propellers. The ordinate axes of the plots represent power and the abscissa is the propeller rotation phase relative to the reference. The numbers on each plot is the standard deviation of the averaged signal. We have found that values of standard deviation larger than unity indicate the presence cavitation. Under the particular circumstances of the measurement, the starboard propeller was cavitating while the port propeller was not. Note that the five peaks in the cavitation plots are due to the five-bladed propellers used on *Quest*.

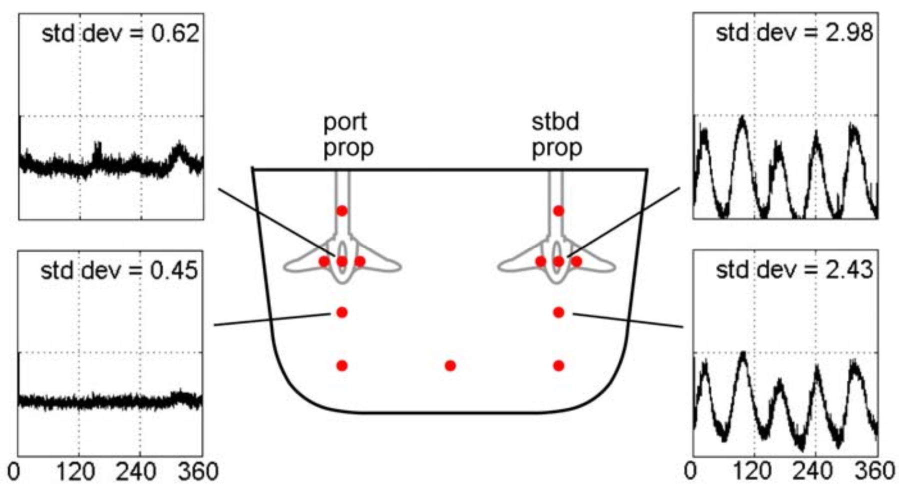

Figure 4. Synchronously averaged accelerometer signals near *Quest's* propellers showing cavitation on the starboard prop but not on the port. Results were confirmed by audio pick-up.

4. INFRARED SIGNATURE MANAGEMENT SYSTEM

The acoustic signature management module of SSMS described in the previous section uses data from shipboard sensors to monitor acoustic events and to estimate the radiated acoustic noise signature. Similarly, the IR signature management module uses a network of 37 embedded temperature sensors, shown in Fig. 2, to estimate the IR radiance of the ship in real time. It is the contrast between the ship and its background that is the most important aspect of the IR signature. To determine the contrast, the radiance of the background sky is measured with a sensor known as a pyrgeometer and compared to the ship radiance.

4.1 Infrared signature estimate

The IR signature of *Quest* is modelled with ShipIR developed by W.R. Davis Engineering Ltd, Ottawa, Canada (Refs. 8 & 9). ShipIR is recognized as a NATO standard, has been accredited by the US Navy and is used by more than 30 marine and aerospace organizations. ShipIR has been extensively validated, mostly through comparison with IR images of *Quest*.

The form, materials and coatings of the ship are represented in the model including the optical and radiative properties of the surfaces, internal heat sources and the IR emission of the plume. Radiative exchange between the ship and its environment is calculated and requires inputs such as the position (or absence) of the sun, air and water temperature, wind and ship speed. The output of the model is the IR radiance as function of aspect and elevation angles, contrast with the background radiance and simulated IR imagery of the ship.

An example of a comparison between an IR image of *Quest* in the 3-5 um band and one modelled in ShipIR is shown in Fig. 4. The close correspondence of radiances between the two images is clearly demonstrated. Note that in this example, taken near sunset, ShipIR has successfully resolved a strong glint from the sun on the aft quarter of the ship.

Quantitative comparison between measured ship temperatures and ShipIR predictions indicate that model is consistently within 2 deg C of the measurements. Residual errors vary with solar and thermal cloud conditions, with best results occurring with overcast skies.

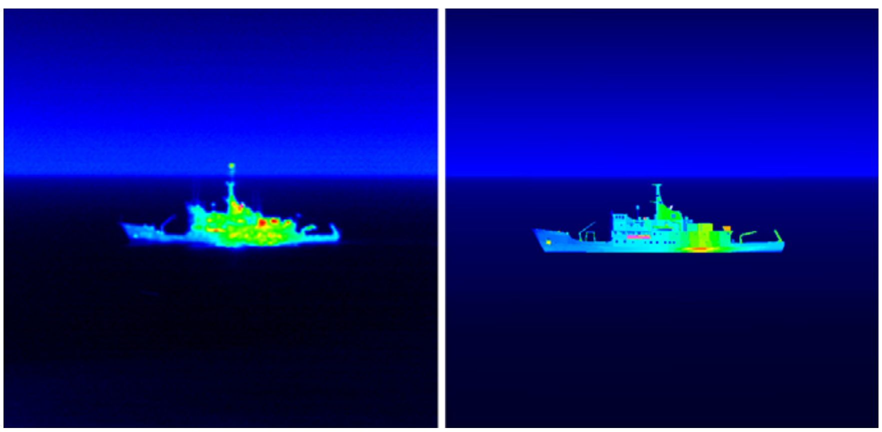

Figure 4. Comparison of IR image of *Quest* in the 3-5 um band (left) and modelled in ShipIR (right) using environmental parameters from the measurement.

4.2 Active IR signature management

Earlier forms of IR signature management were passive which meant that external power was not required to operate them. These were mainly methods of mixing ambient air into the exhaust plume to cool it and hot metal on the exhaust uptakes. Today, more aggressive active IR signature management approaches are required to defeat smarter threats. Two techniques being studied on *Quest* are active hull cooling (AHC) and sea-water injection (SWI). Both the AHC and SWI can be controlled automatically by a central control unit which also monitors IR-related environmental parameters, such as air and water temperature, sky radiance and the status of the ship's machinery through the IMCS data stream.

4.3 Active hull cooling

The AHC works by applying a film of sea water to the hull of the ship to cool it thus reducing the IR radiance. Water is pumped through three specially designed nozzles onto the AHC test area on the aft port hull. Feedback is provided by internally mounted temperature sensors. Given the temperature of the hull, and of the sea water, the hull can be maintained at an intermediate temperature indefinitely by cycling the water flow on and off. The AHC has been tested twice during trials in Sept. 2005 and Oct. 2006. The algorithm that controls the water flow is being optimized based on result from the two trials.

AHC is intended to match the radiance of the ship's hull or superstructure to the sea or horizon background. However this is only possible if the temperature of the available sea water is such that it can cool (or warm) the hull by the required amount. Figure 5 shows a IR image of *Quest* with the AHC turned on. The green rectangle seen on the aft quarter of the ship is the AHC zone. It is being cooled to match the radiance of the horizon sky.

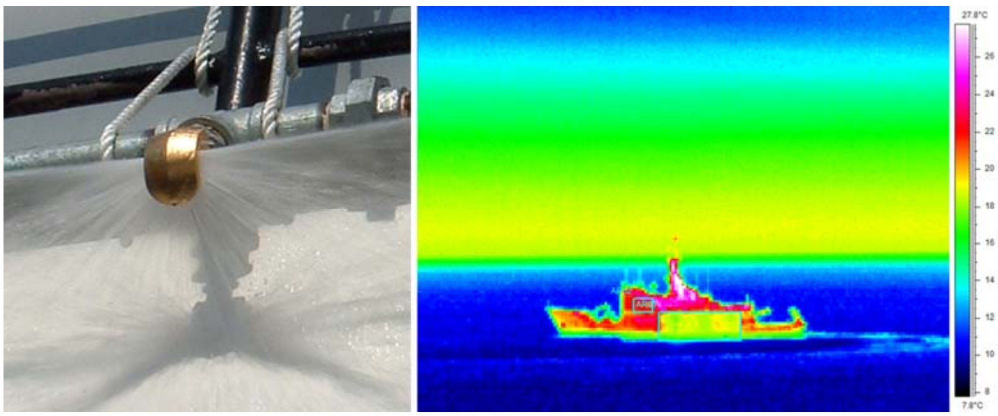

Figure 5. AHC nozzle spraying sea water on the hull of *Quest* (left). IR image in the 3-5 um band with AHC activated. The green rectangle covering most of the aft port hull is the AHC zone (right).

4.4 Sea water injection

SWI is a concept where sea water, in the form of an aerosol, is injected directly into the engine exhaust. Evaporation of the droplets absorbs a large amount of the heat content of the plume, thereby reducing its IR emissions. A SWI system designed and built by WR Davis Engineering has recently been installed on Quest (see Fig. 6). The SWI swill also be automatically controlled by the central control unit. The first test of the SWI system is scheduled for May 2007. This is believed to be the first test of the SWI concept on a ship.

Figure 6. Water distribution system on one of *Quest's* 16-inch dia. main propulsion diesel engine (MPDE) exhaust uptakes (left) The two MPDE exhausts with passive IR cooling structure.

5. SUMMARY AND FUTURE WORK

We have described the experimental ship signature management system (SSMS) being demonstrated on Canadian defence research vessel *Quest*. For acoustic signatures, SSMS is capable of estimating the underwater radiated noise in the frequency band 10 Hz to 10 kHz using real-time vibration measurements with structural-acoustic transfer functions of the ship and using a combination of finite element and boundary element methods for frequencies below 50 Hz. SSMS has well developed capabilities to monitor tonals and to detect acoustic events and faults. A capability to detect the onset of cavitation has been demonstrated.

The accuracy of the far field acoustic predictions is currently being determined through comparison with static and dynamic acoustic ranging measurements. Work in the immediate future on the SSMS acoustic signature management system involves installing extensive new hardware for data acquisition, signal processing and signature prediction.

SSMS also has an IR signature management component which includes monitoring and predicting the IR contrast radiance and active IR signature management concepts Active Hull Cooling (AHC) and sea water injection (SWI). The active IR signature management systems can be centrally controlled based on user defined signature target levels. Installation of the IR systems was complete in March 2007 with the first full test scheduled for May 2007. Data gathered on the next and subsequent trials will allows us to measure and optimize the performance of AHC and SWI. The algorithms used to control these systems will be improved and the ability to model both in ShipIR will be developed.

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