APPLICATION OF ACOUSTIC IMAGING FOR UNDERWATER SUBSTRUCTURE INSPECTION AND MAPPING

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ABSTRACT

This discussion presents a system and methodology for the application of high definition Underwater Acoustic Imaging (UAI) in the inspection of submerged structures and the interfaces of those structures with the surrounding water bottom. The UAI methodology utilizes an integrated remote sensing platform to visualize and quantify underwater structures and any external abnormalities associated with the structures, and adjacent water bottom surfaces.

The presentation demonstrates the pitfalls and problems associated with acoustic sonar utilization in substructure inspection and shallow environments, the environmental difficulties, cost effectiveness, and benefits, as well as result capabilities and integration of data sets from the underwater remote sensing systems, High Definition Laser Scanning and surface topography into a comprehensive geo-referenced model of a structure system and the adjacent land mass. It outlines the basic acoustic principles involved in the inspection of substructures, the development of remote sensing equipment capable of generating the necessary resolution and definition for shallow environments, as well as the development of the techniques and methodologies necessary for proper execution of substructure inspections and comprehensive shallow water bottom surface mapping. The discussion also encompasses remarks regarding the economic advantages of remote sensing in substructure inspections.

Several case study examples are shown and briefly discussed. The examples depict integrated modeling capabilities for depicting the inspection results, and a discussion of the problems overcome with execution and data assimilation for a specific case.

APPLICATION

The inspection of underwater structural components of structures such as bridges, dams, locks, flood-gates and other water control structures is crucial if such infrastructure components are to maintain adequate performance throughout their life cycle and attain the maximum length of life cycle. The technology to perform such inspections, until recently was limited to the use of divers and robotic vehicles that perform largely visual and tactile surveys of the structures. This is problematic under inclement environmental conditions such as high current flow, extensive structural surfaces and low to no visibility. Due to the significant impact of these environmental conditions on results and findings, these surveys tend to be extremely subjective and provide only very generalized comparison information from successive surveys. These typically cursory surveys that are very limited in perspective because of visibility limitations, provide a poor

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representation for baseline control of infrastructure condition due to the limited information that is provided.

With the advent of the development of underwater acoustic, steered beam sonar and profiling, remote sensing systems that have the ability to produce very high definition sonar imagery as well as very precise acoustic profile measurement there is now a cost effective alternative to conventional methods of underwater substructure inspections that can provide a control baseline for future surveys, an overall perspective and a non-subjective data set that can be used to compare to previously recorded structure baseline conditions. This methodology can be used to provide a comprehensive spatial element map of underwater structure surfaces and their interface with the water bottom.

METHODOLOGIES

Since the initial forays of Steered beam sonar application to the inspection of underwater structures there have been advances in other acoustic remote sensing systems that have thus far not produced results equivalent to the Steered Beam Sonar systems. The systems that have been used in these efforts are Multi-beam sonar systems and Acoustic Camera systems. They both use the basic principle of sound – detection – and ranging (Sonar) as does the Steered Beam Sonar system. This principle uses sound reflection of a focused beam to determine distance and acoustic intensity of surfaces and targets off of which the directed sound beam bounces. The direction of the reflected signal is assumed to be perpendicular to the face of the transducer on the submerged sensor. The visualization is then mapped by using a time-speed-distance calculation to determine position of mapped intensities and the amplitude of the intensity relative to the general background to generate a visual brightness variation. Although each of these systems use the same principles they process the data and generate a visual rendering of the reflected sound waves in a different manner which causes the system types to have differing resolution capabilities and provide widely differing results in practical use.

The Acoustic camera produces a very high resolution image but is extremely sensitive to angle of reflectance incidence with the surface being mapped and has a very limited field of view and perspective due to a limited range resulting from the very high frequencies used which are greater than 1 MHz. The instrumentation is also several times greater in cost than that of the Steered Beam Sonar system.

The multi-beam sonar system receives reflected pulse returns across a fan array of transducers producing a record that is translated into an image similar to the method that a dot matrix printer uses to create an image. In this case the closer the spacing between the recorded reflected pulses the greater the image resolution. Unfortunately due to the fluid mechanics involved the separation between reflected pulses must be at least two inches for a frequency of 900kHz. This causes the results to be of inferior resolution. The noise generated by the instability in the sensor position, and attitude tracking also adds to the inferior resolution. Again the instrumentation is also several times greater in cost that that of the Steered Beam Sonar system and is much more labor intensive in set-up and initialization.
The following diagrams depict the difference between a multi-beam scan and a Steered Beam Sonar system scan.

Figure 1. Multi-beam Sonar pattern depiction

Figure 2. Steered Beam Sonar pattern depiction

The following Figures 3 and 4 are a comparison of the results obtained in a similar environment from a Steered Beam Sonar system and a Multi-beam Sonar system.
Underwater acoustic imaging and measurement systems contain an emitter and a receiver and rely on the emission of a sound wave and the measurements of the time required for a reflection of the emitted sound pulse to return to the receiver as well as measurement of the intensity or amplitude of the reflected sound pulse. In many systems the emitter and receiver are the same physical sensor or transducer. The physical characteristics of the acoustic pulse wave are critical to the resolution of the sonar imagery and the precision of the acoustic measurement. The main critical physical characteristics are the frequency of the acoustic wave form, the pulse length of the acoustic transmission, the ping rate of the acoustic transmission and the beam pattern of the acoustic wave form. Generally speaking the higher the frequency the greater the resolution but the shorter the effective range becomes. Also a shorter pulse length produces higher definition but becomes compromised by range effectiveness. A narrower, well defined beam pattern also produces higher definition but reaches a trade off limit with scan coverage requirements restricting the speed of the transducer movement or the scan speed. The beam width characteristics are controlled by the physical characteristics of the transducer and thus also reach a point where transducer construction becomes problematic. Thus the best compromise to optimize the physical beam forming characteristics are a fairly high frequency in the range between 500kHz and 900kHz a horizontal beam width of less than 1° and the shortest pulse length that can effectively produce the desired detection range. For acoustic profiling measurement the smallest practical acoustic footprint for the beam produces the greatest range measurement accuracy and reduces the noise from multi-path reflections due to nearby structural components.

2 Courtesy of FENSTERMAKER
3 Courtesy of CodaOctopus Products Ltd.
The configuration of the instrumentation that is utilized in the Fenstermaker process is a dual element, fan beam/conical beam 360° mechanically scanned imaging and profiling sonar that is integrated with a steerable rotator. The system operates at a frequency above 500 kHz and is configured for a horizontal beam width of the fan beam less than 1° and a conical beam of less than 2°. The system is also configured for beam steerability in both the horizontal and vertical planes with redundant steerability in one of the axes. The redundancy axis being defined by the operator.

Figure 5. Steered Beam Sonar system, Acoustic beam pattern and perspective with respect to the imaging plane

Figure 6. Profiling beam pattern and scan geometry

4 Courtesy of Kongsberg Mesotech
The inspection of underwater structural components with high definition acoustic imaging techniques requires significant considerations in the deployment methodology. The sensor must be maintained in a relatively stable position during the scan segment and the sensor orientation must be such that the grazing angle of the acoustic beam across the structure surface being imaged, provides for visualization of surface undulations, projections and abnormalities in the plane of observation. Because of this aspect of the methodology most scenarios will require the ability to vary the sensor orientation in order to remain normal to a specific observational plane that corresponds to a structure surface.

Figure 7 through Figure 11 are examples of visualization of substructure components imaged using a Steered Beam Sonar system.

![Figure 7. Visualization of the longitudinal pier alignment plane](image)

Surface abnormality indicating damage to the concrete fascia of the pier caisson
Figure 8. Steered Beam Sonar Imagery of a Lock System

Figure 9. Bridge Pier Fender Damage assessment
The deployment methodology can be problematic in environments where high water currents or close proximity heavy shipping traffic exists. Fenstermaker has overcome these problems by designing and constructing several self contained deployment mechanisms, that are portable and can be quickly deployed.
The quantitative measurement of profiles of structural abnormalities and the interface between the substructure and the water bottom requires the use of steered beam profiling. By utilizing dual axis steerability we are able to gather quantitative measurement data over areas where abnormalities were observed utilizing underwater acoustic imaging. The steered beam profiling with a narrow conical beam provides for acoustic measurement accuracies of 0.1 at ranges of 75’ on absolute acoustic boundaries and provides the capability to collect profile measurements between narrowly spaced structural members. Small areas of relief depicting the displacement of abnormalities can be mapped utilizing this method.

Figure 12.5 Fenstermaker’s self contained LARS (Launch & Recovery Systems)

5 Courtesy of FENSTERMAKER
The steered beam profiling methodology can also be utilized to generate water bottom elevation models to evaluate scour and deposition, as well as map water bottom erosion patterns. This is depicted in Figure 14.

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Figure 13 \(^6\) – Under Wharf Visualization

\(^6\) Courtesy of FENSTERMAKER, and Project owner The Port of New Orleans
The profiling methodology involves the incorporation of a high precision Motion Reference unit, a heading reference sensor to orient the acoustic remote sensing device and Real Time Kinematic GPS which provides centimeter accuracy for geo-referencing of the acoustic data. The use of instrumentation to determine the speed of propagation of the sound wave in the water column is also necessary to maintain a very high degree of accuracy in the acoustic measurement. This is accomplished by utilization of a velocimeter profile sensor which determines and records the speed of sound in the water column at varying depth intervals as specified by the operator. The speed of sound varies with fluid density which is affected by turbidity and salinity. Temperature and pressure also affect the propagation velocity.

CASE STUDIES

The example shown in Figure 14 is a result of data rendering from a survey performed for a Louisiana Department of Transportation and Development project at D’Arbonne Dam in Union Parish Louisiana. In this case Terrestrial Lidar (HDS) Laser Scanning was utilized to scan the superstructure of the dam and surrounding environment and Fenstermaker’s Underwater Acoustic System was used to scan the submerged structural components of the dam as well as the water bottom upstream and downstream of the concrete spillway structure. The data sets were then integrated to construct a comprehensive “as-found” 3D model of the dam system from which geographic position and metrology can be extracted. This provided a comprehensive baseline, assisted in

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7 Courtesy of FENSTERMAKER, and project owner Louisiana Department of Transportation and Development
identifying areas of concern that were in need of repair or remediation and provided volumetric and measurement data for determining extents of repair and material needs. The resulting model identified the complex erosion pattern and scour characteristics down stream as well as providing data to qualify any differential movement in the spillway apron slabs and the concrete dam structure. The survey also defined possible problematic characteristics at the toe of the concrete structure on the reservoir side of the dam that potentially indicated a piping condition. See Figure 10 and Figure 11. This prompted a recommendation for a more intensive diver aided investigation which was undertaken at a later date. When the diver aided investigation occurred approximately 60 days later, a dynamic situation was observed whereby the depressions in the silt at the toe of the structure that were of concern were considerably larger and had grown together. The Acoustic Imaging system was utilized to guide a pipe probe into the depression and inject dye to define any significant flow prior to sending a diver into the environment. Flow was not observed, however the dye did not pool either. Upon close inspection by divers the hole in the sediment was caused by a compromised joint and seal at the base of the structure allowing water and sediment to be transported through the structure and into the drainage system. This case study shows the multi-faceted role of the acoustic remote sensing system in being utilized to map and identify problems, then assist in defining a safe working environment and finally assist in directing diving efforts expediently to problem sites in conditions of low to no visibility.

Figure 158: Detection of washout holes at the toe of the upstream slabs.

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8 Courtesy of FENSTERMAKER, and project owner Louisiana Department of Transportation and Development
Figure 16. Washout holes and correlated high velocity water discharge downstream, from dispersion blocks on the spillway apron.

Utilizing underwater acoustic imaging and underwater acoustic profiling in conjunction allows for the qualification and quantification of structural and water bottom abnormalities in a cost effective manner. The production rate of area covered relative to other methods provides for a significant cost savings as well as providing a much more extensive and non-subjective data set that can be used for subsequent comparative analysis with future surveys that are performed in the same manner. The geo-referencing of all acoustic data provides for real world displacement measurement along the water bottom and structural surfaces.

An example of the effectiveness of this methodology is the case study of the survey performed on the Huey P. Long bridge over the Mississippi river in New Orleans, Louisiana. This survey was performed for the first time by Fenstermaker April of 2006 prior to commencement of a major construction project to expand the bridge. Fenstermaker was engaged to perform an acoustic imaging inspection of the underwater substructure component of the piers which comprised a total surface area of 78,983 square feet. This survey was completed in five days of field data acquisition with two days for mobilization and de-mobilization. The water current in the river during the survey was 2.3 to 2.7 kts. This effect was magnified when coupled with the close proximity of shipping traffic causing surge in the water column. The amount of turbidity in the water column also generated the condition of zero visibility under water. The

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9 Courtesy of FENSTERMAKER, and project owner Louisiana Department of Transportation and Development
combination of these factors creates not only an extremely difficult situation for divers but also a very unsafe working environment for divers. This project was performed 17% under budget and on time.

While this example may be an extreme case it does demonstrate the effectiveness of this methodology in adverse conditions as well as the cost savings from increased production of surface inspected as well as the capability of operating without having to alter other commercial operations such as shipping, commercial fishing or power production.

REFERENCES


L-3 Communications SeaBeam Instruments, Multibeam Sonar Theory of Operation