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# A SUMMARY OF PROJECT 711 "FIBEROPTISK SKROGOVERVÅKNING" (CHESS)

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## 1 INTRODUCTION

This report summarizes the work that has been carried out in connection with the Composite Hull Embedded Sensor System (CHESS) project. This has been a collaboration between FFI project 711 "Fiberoptisk skrogovervåkning" and the Optical Techniques Branch at Naval Research Laboratory. The collaboration rest on a Memorandum of Understanding (MOU) between the US Department of Defense and the Norwegian Ministry of Defence. The MOU states the following:

> The objective of the Composite Hull Embedded Sensor System (CHESS) Project is to design, develop, fabricate, and install experimental strain monitoring systems using distributed fiber optic sensors for ships and hull structures. The sensor systems will be used to monitor loads on ship hulls. The sensor systems will also be used to study the effect of wave slamming on the composite materials and to investigate methods for early detection of damage. The following actions will be undertaken:
>
> - develop and optimize the fiber Bragg grating (FBG) sensor array for monitoring the strains in composite hull structures
> - perform modelling and finite element analysis to determine measurement requirements and sensor placement
> - develop data acquisition and processing concepts for the CHESS system
> - embed or attach FBG sensors in composite specimens and sample hull structures for testing
> - conduct testing on air-cushion catamaran vessels in servise (mine countermeasures vessels) and on scale models to validate concepts
> - conduct full scale testing on a prototype fast patrol boat air-cushion catamaran vessel

In the following we will give a more or less chronologic account of the activities that have taken place as a part of CHESS, with references to CHESS technical reports and other publications, as well as to more basic studies carried out by students at FFI.

## 2 INITIAL PHASE

The project started before the Fast Patrol Boat (FPB) was built, and thus the initial testing was carried out on surface effect ships (SES) of the Oksøy class. We also did some slamming experiments early on to gain knowledge about what we should prepare for in later field tests.

## 2.1 Test installation on MCMV

The project kick-off was installation of a limited system on the mine counter-measure vessel KNM Hinnøy (1, 2). Three four-grating arrays were installed: Two in one of the side hulls at amidships and the third on the wet deck approximately at amidships. The sensors were attached with fairly hard five-minute epoxy and the lead fibre was covered by a more compliant polyurethane adhesive. We were able to monitor one array at a time using a 1x4 WDM and Phase Generated Carrier demodulation. Switching between the arrays was done using a fibre optic ST-connector placed near the two arrays in the side hull. Data was recorded with a bandwidth of 2.5kHz on a TEAC tape recorder.

The test provided us with data on which to experiment with data processing routines, and was important enough in that respect. In addition we saw on return to the vessel about a year later that the connector in the side hull had deteriorated substantially and parts of the arrays had been worn away. We concluded that there should be no connectors in the permanent installations, and that the arrays with lead fibre should be thoroughly protected from mechanical wear.

We also found that there seemed to be no significant signals at frequencies above about 50Hz for these measurements. We believe that we mainly saw effects of global deformations of the hull and local panel vibrations. The sea-state on the trip varied from SS0-SS1 up to SS6. However, we did not record any wet deck slamming, so conclusions on the necessary measurement bandwidth was drawn with the reservation that wet deck slamming was yet to be characterized.

This initial test was presented at SPIE's International Symposium on Smart Structures and Materials in 1997 (3), and the demodulation and processing schemes presented at Optical Fiber Sensors Conference 1997 (4).

## 2.2 Slamming experiments - drop test with sandwich panel

Wet deck slams are rare events, and in order to gain experience with that type of hull loading we carried out controlled experiments on a sandwich panel in a wave tank at Marintek, Trondheim in august 1997. An effort was made to design a panel which resembled a wet deck panel on a full scale vessel (5). Finite element analyses were carried out in order to predict the natural frequencies of the panel, and experiments were done in a Material Test Machine on a sample panel (6).

The drop test itself was performed by attaching the test panel to a rig which could be dropped while guided by rails onto the water surface (7). The panel was instrumented with

16 FBGs and a number of conventional sensors. The analysis of the results show that only the fundamental mode of the panel is excited in an impact between water and panel (8). Due to the added mass of the water this frequency is significantly down shifted compared to the natural frequency of the fundamental mode in air. We found that the frequency response peak varied in frequency between 33Hz and 80Hz. The higher frequency was for lower velocity impacts on a wave flank. Both a smaller angle between water surface and panel as well as increasing drop velocity tended to reduce the resonance frequency. In the experiments the maximum impact velocity was 6m/s. To facilitate the analysis all the data were structured and saved in Matlab binary files for subsequent Matlab analysis (9).

In connection with this test we tried surface embedding the sensors and lead fibre under a woven epoxy-saturated glass fibre strip. This seemed to protect the fibre well: We suffered no fibre breakage during the violent and repeated slamming of the panel on the water surface, and we decided to continue this practise. The sensor elements were mounted using a cyanoacrylate and catalyst normally used for foil strain gauge mounting. Although this method provides a very good bond between the grating and the composite, it demands more of the operator and is more difficult to use under field conditions.

The drop test was presented as a post-deadline paper at the Optical Fiber Sensors Conference 1997 (10) and at the European Workshop on Optical Fiber Sensors 1998 (11). Results from the analysis have been accepted for publication in Composites B (12).

## 3 NEW FIELD TESTS - EXPANDED INSTALLATION ON MCMV

In April 1998 we carried out an expanded installation on the MCMV KNM Hinnøy. The arrays that had been broken in the interim period were replaced in somewhat different locations and some new locations were introduced, among them one of the waterjet tubes. The installation, read-out systems and signal analyses are presented in (13).

The system included 27 strain measuring FBGs and four experimental fibre optic FBG-based accelerometers. The FBGs were to some extent placed on opposite sides of the neutral axis of different bending modes of the hull to provide data on global moments. In addition to the interferometric read-out technique used in the initial test, we employed a scanning Fabry-Perot filter technique which is computer controlled. This technique has a lower maximum sampling rate limited by the scanning rate of the filter, but it is more flexible and can monitor a larger number of sensors simultaneously. In addition data are stored on a harddrive which reduces the complexity of reading and processing data.

Through the analysis we were able to qualitatively identify modes, but without detailed knowledge about the material properties of the hull a quantitative analysis was impossible. Eigenfrequencies of the most prominent of the modes were identified. However, due to the low sea states during the five measurement days these data are only representative for low seas and high speeds. We see a significant propagation of impeller related frequency components in the MCMV hull.

Results and experiences from this field test were presented at the 13th Optical Fiber Sensors Conference 1999 (14, 15, 16).

## 4 TOWARDS A REAL-TIME SIGNAL PROCESSING SYSTEM

It was clear from the start of the project that real-time signal acquisition, processing and presentation systems would be necessary for the success of the project. Several masters studens were supervised at FFI while studying the application of wavelets for the signal processing tasks. Some of the ideas and results from these works were presented at SPIE's Smart Structures and Materials 1998 (17).

To attain flexibility with regard to the size of the final processing problem, it was decided that a PC network based system was desirable. A first system was implemented under Microsoft NT using MS Visual C++ (18). It contained basic routines for information exchange over a network, a graphical user interface and data collection units for reading Fabry-Perot generated data files as well as control of a data acquisition card.

There were several problems with this implementation. We had hoped to control the Fabry-Perot system directly using an NT machine. However, the FP electronics are interrupt driven, and NT's interrupt response turned out to be insufficient. In addition we were unable to achieve more than a small fraction of the A/D-card's nominal sample acquisition rate. Several different graphics packages were tried out, but none of the packages we tested enabled us to plot a reasonable stream of data points to the graphical user interface.

On this background we migrated to a real-time distribution of Linux, where the previous system was reimplemented (19). The real-time properties of the system allowed us to control the FP electronics using the processing PCs. A graphical user interface has been implemented using QT from Troll Tech.

## 5 FULL SCALE TEST ON FPB

Prior to the installation on the Fast Patrol Boat KNM Skjold, we were in close contact with FiReCo who have done most of the FEM analyses for the FPB. They provided us with essential information on where to put sensors and the approximate maximum strain levels we should be able to measure. Using this information we installed 56 sensors distributed on eleven fibres (20). These sensors were distributed over the hull with the ambition of measuring the most important global moments, strains due to stress concentrations in the fore ship, wet deck slamming and loading of the waterjet tubes.

## 5.1 Participation in systematic sea-keeping test

The system was initially employed during systematic sea-keeping test were a matrix of speeds, headings relative to the prevailing wave direction and air-cushion condition (on/off) was followed in three different sea-states. The data were collected using the previously developed PC network with two PCs running under Linux controlling two FP systems and one PC running under NT controlling an A/D-card for data acquisition from interferometrically interrogated FBGs. The computer clocks were synchronised using a Network Time Protocol.

As part of his PhD work Alf Egil Jensen refined the existing FE model of the FPB and carried out furter analysis. On the basis of the FEM results, a matrix relation was obtained between the global moments and forces acting on the hull and the strain in the FBG locations (21). This method was applied to the existing data and has been incorporated into the CHESS signal processing system. The data were also analysed with respect to the Tsai-Wu Last Ply Failure criterion and the forces acting in the fore ship. These analyses were carried out in close collaboration with FiReCo and the results are presented in a FiReCo report (22).

For the sake of comparison under real world conditions some electrical resistance strain gauges(ERSG) were installed next to some of the FBGs (20, 23). It turned out that the ERSGs/shielded electrical cables had picked up large amounts of EMI along the 30m path from the sensor location to the operations room where the data acquisition equipment was placed. Heavy filtering of the ERSG signals was necessary before we were able to make the comparison, and we conclude that the FBGs advantages over the conventional sensors has been proved for this application.

Papers on structural health monitoring based on experiences and results from both the MCMV tests and the FPB test have been presented at the 2nd International Workshop on Structural Health Monitoring (24) and at the International Modal Analysis Conference (25). The instrumentation that was employed during the FPB sea-keeping test will be presented at SPIE's Smart Structures Conference 2000 (26).

## 5.2 Cannon firing tests

Following the successfull sea-keeping tests we were asked to measure the effects on the hull beam of cannon firing. The amidships FBG sensors were used together with a single FP box and the results were delivered to FiReCo for analysis. In addition we measured the blast pressure against one of the wheelhouse windows using three surface mounted pressure gauges (27). An attempt was made at measuring relative rotations between the cannon foundation, the datum (instrument room) and the radar position in the mast used for targeting. The measurements were done using accelerometers. The measurements and a method for interpretation has been described and evaluated in (28). The results from this test are inconclusive due to problems with the accelerometers, but the method should be applicable in future measurements of this type.

## 6 RELATED STUDIES

Several students have performed thesis work related to the activities in CHESS. The following gives a short description of the theses topics and the conclusions. The students have either been involved in studies of FBGs for sensing applications or signal processing methods.

### 6.1 Work on fibre Bragg gratings

While CHESS was in it's planning phase in the autumn 1994, two theses on Bragg gratings and their multiplexing were carried out by Havsgård and Pran (29, 30). They collected an up to date literature database and did some basic experiments on Bragg grating sensitivity and properties. Pran produced a numerical computer routine for calculating the amplitude and phase response of Bragg gratings while Havsgård studied read-out and multiplexing techniques.

The following autumn the students Bjørnson and Karlsson studied Bragg grating fibre lasers (31, 32), and the laser's and sensor's behaviour under dynamic strains. Theoretical predictions were made using Pran's computer program, and experiments were carried out that showed a certain sluggishness in the response due to the fairly long lifetimes of the excited states in the Er-doped, Al co-doped fibre.

Severinsen did a study of strain gradient measurements using FBGs (33). The conclusion was that such measurements are possible, but impose certain limitations on the nature of the signal.

An analysis of the effect on interferometric interrogation of FBGs of different inhomogeneous loads on a grating was performed by Pran and presented at OFS99 (34).

Kjerre developed a setup for detailed experimental characterization of FBGs, and did several experiments with transverse loading of gratings (35). This work was very successful and we hope to be able to apply the method for detailed measurements on composite embedded FBGs.

### 6.2 Signal processing

In the spring of 1996 the first work on signal processing for CHESS was carried out. It was anticipated that the signals would show transient characteristics, and an initial study of the application of wavelets for structure monitoring was performed by Eriksen (36). This study concluded that wavelets are an interesting technique for applications where we wish to detect and characterize transient events.

After the initial sea-test of CHESS, the assumption of transient data was confirmed and further studies of wavelets for our specific application was carried out by Urnes (37) and later by Bremer (38). Urnes generated several functions using the Matlab Wavelet toolbox, among them detection and counting routines that allowed the generation of histograms of wave impacts. Bremer translated these routines to C++ and optimised them. Later he studied in more detail wavelet packets and did preliminary evaluations of system identification techniques for characterizing the hull's response to wave loading (39).

## 7 CONCLUSIONS

It is our opinion that CHESS has fulfilled the ambitions that were drawn up at the initiation of the project. Through this work we have established ourselves in the international fibre sensors and smart structures community and we have demonstrated to the marine community in general and the Norwegian Navy in particular that fibre optic sensors provide the means for developing comprehensive hull monitoring systems.

We have drawn up a set of requirements for a fibre optic hull monitoring system in the report "Design proposal for a fibre optic structure monitoring system for surface effect ships"(40). This report also points out some of the problems that have not been addressed in CHESS and presents a fairly detailed suggestion for a system that meets the stated requirements.

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