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STRAIN MEASUREMENTS - A COMPARISON OF STRAIN GAUGE AND FIBER BRAGG GRATING MEASUREMENTS ON KNM SKJOLD

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8) ABSTRACT

Strain measurements by means of resistive strain gauges and fiber optic Bragg gratings during the sea-keeping tests of KNM Skjold have been analyzed and compared. The resistive strain gauge measurements were severely affected by noise. The signals have been filtered, synchronized and compared using extreme values as well as vector analysis. Results indicate that the two techniques measure the same strain levels, however fiber optic sensor measurements are superior concerning low noise and reliability

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CONTENTS

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1 INTRODUCTION

Strain measurements on the hull of KNM Skjold have been carried during the sea-keeping tests of the vessel. FiReCo has carried out the strength calculations of the hull by means of a finite element method. For verification of the design, some fifty fiber optic Bragg grating (FBG) sensors were installed. Five strain gauges were installed directly next to fiber optic sensors in order to compare the results, and another nine strain gauges were added at new locations. In this context we only deal with the comparison of the two measurement techniques primarily to verify strain measurements by means of FBG's. Description of the sensor locations and mounting procedures are presented in (1). Results from day one of the sea-keeping tests (23 runs in all), and data from one selected pair of sensors (SC4 and C2) are considered in this report. Other resistive sensors possess less similar results to their fiber optic counterpart for several reasons; too much noise (in general), salt water penetration and possibly faulty attachment to the surface.

Both techniques yield the same results, however the noise is orders of magnitude greater using strain gauges, principally because of electromagnetic pickup in the electrical cables. Hence we conclude that FBG's constitute a far better method for measuring strain than conventional resistive strain gauges.

2 SUMMARY OF INSTALLATION AND MEASUREMENT TECHNIQUE

2.1 Fiber optic sensors

The FBG sensors were fixed to the hull using epoxy (see Figure 2.1), and the grating parts of the fiber as well as the rest of the bare fiber, were laminated to the hull by means of epoxy saturated glass fiber strips. The fiber strips were selected in order to avoid influencing the measurements. Several gratings were written in one and the same fiber. Approximately 20m lengths of fiber were routed from the sensor location to the instrument control room. Light emitted from a broad band source (laser pumped Erbium-doped fiber amplifier which amplifies the spontaneous emission) was incident onto the gratings, which each reflect light at a specific wavelength (in the wavelength interval 1530nm - 1560nm). The wavelength of the reflected light was determined using a Fabry-Perot filter and a detector. Furthermore, data containing the reflected wavelength was digitized and stored in a computer at 360Hz sampling rate. When the fiber is elongated (or compressed), the wavelength of the reflected light is shifted to a longer (shorter) wavelength due to the increased period of the grating and, less importantly, the change in index of refraction, as a consequence of the elongation of the fiber (2). The strain is directly proportional to the wavelength shift, which is the measured parameter. This means that the measurement is independent of the light intensity, which means that the sensor may be located far from the read-out electronics without degrading the measurements. Details concerning the measurement technique and placement of the sensors are discussed elsewhere, see (1), (2), (3).

2.2 Strain gauges

The strain gauges (type: TML PFL-20-11) were fixed to the hull using cyanoacrylate adhesive and covered by soft silicon, see Figure 2.1 for a photograph of an installation of both fiber optic and resistive sensor.

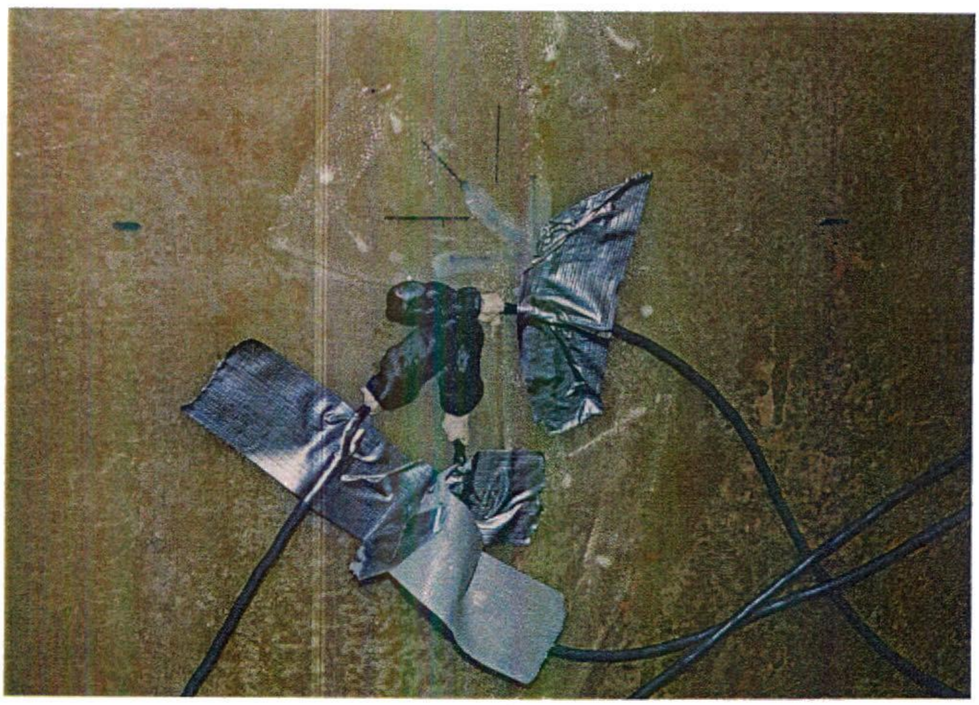

Figure 2.1 *Strain gauges (covered by black silicone) and their fiber optic counterparts (underneath the epoxy seen above the strain gauges). SC4 and C2 are the horizontally mounted sensors. These sensors are installed starboard amidships on the bottom panel*

Approximately 20m cable (four pairs and shielding around all wires) was stretched to the instrument control room.

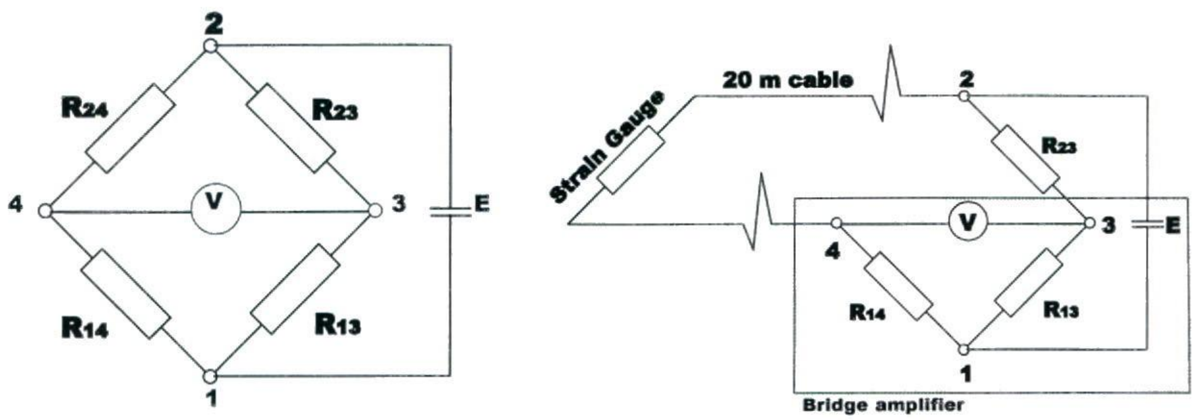

Figure 2.2 The Wheatstone bridge (left) and the configuration used during the measurements (right)

One Wheatstone bridge for each of the strain gauges was used in order to detect the change in resistance, see Figure 2.2. In a Wheatstone bridge the measured voltage is related to the strain as follows:

$$V = E \cdot \left(\frac{R_{24}}{R_{14} + R_{24}} - \frac{R_{13}}{R_{13} + R_{23}} \right) \quad (2.1)$$

For a bridge with all equal resistances, R, which also is the unloaded strain gauge resistance, the voltage over the bridge as function of the strain is given by

$$V = \left(\frac{E}{4/k + 2\varepsilon + 2\dfrac{\Delta R}{kR}} \right) \cdot \left(\varepsilon + \frac{\Delta R}{kR} \right) \quad (2.2)$$

Where k is the gauge factor, ε is strain, E is the excitation voltage and ΔR is the cable resistance. Note that the voltage depends on the cable resistance.

A bridge amplifier (Micro Movements Ltd and Hottinger Baldwin Messtechnik) provided the excitation voltage as well as amplification of the signal. The excitation voltage was set to minimum (1V and 3V for the Hottinger Baldwin and Micro Movements amplifier respectively). The measurement procedure is discussed e g in (4). The signal was sent to an A/D converter (National Instruments PCI-6071 E) and stored in the computer at a sampling rate of 1800Hz. The Micro Movements amplifier had a built in 9kHz analogue filter, which was employed during the measurements, whereas the other used 100 kHz filtering.

3 MEASUREMENTS AND ANALYSIS

During the first day of the sea-keeping tests 23 runs were recorded. The shortest data sets last a few minutes, whereas the majority of the runs lasted twenty minutes. The strain gauges were sampled at approximately 1800Hz, whereas the sampling rate for the FBG sensors in comparison was approximately 360Hz. All strains of interest appear below 20Hz (except for "slamming" which is not considered here), i e the over-sampling is considerable. Consequently, the data have been re-sampled to 45Hz sampling rate and synchronized. Additionally, the mean of each data set was subtracted, such that the data are directly comparable. Strain gauge SC4 and FBG sensor C2 (starboard bottom panel amidships) are the sensors in consideration because SC4 has the least noise of the strain gauges, and this sensor pair seemed to have the best correlation.

Strain measurements during run 3 (sea state 6) and run 8 (sea state 5) are shown in Figure 3.1.

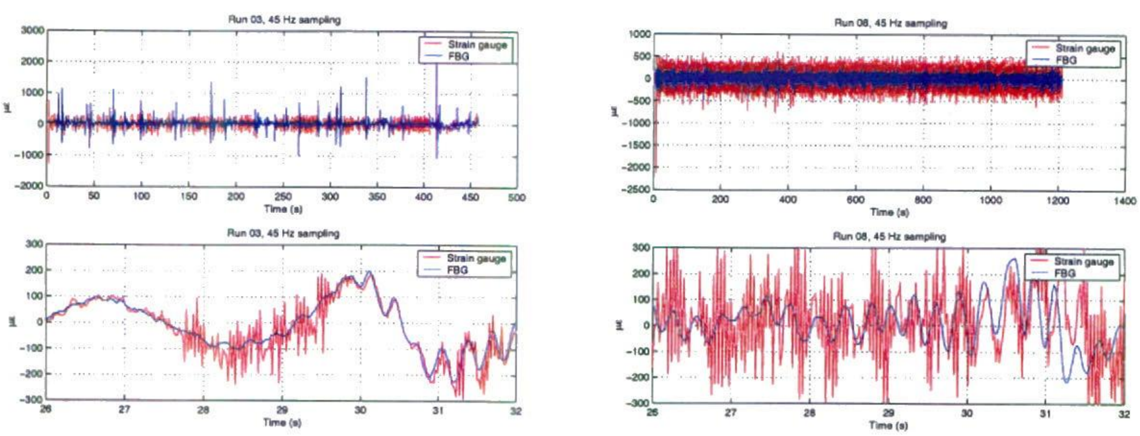

Figure 3.1 Data decimated to 45 Hz sampling rate for run 3, sea-state 6 (left) and run 8, sea-state 5 (right). The noise using the strain gauge is considerably higher. Top: the whole time-series. Bottom: a cut of the top curve showing details of the noise in the strain gauge data. The sensors in consideration are SC4 and C2 (FBG)

The noise appearing in the strain gauge data suggests that the series should be filtered. The power spectrum for the two time series have thus been calculated in order to determine what sort of filter to be used. The high frequency noise in the strain gauge data has been eliminated by means of low-pass filtering. A 200 point finite impulse response (FIR) filter with 6dB corner frequency at 5Hz has been used. The FBG data have been filtered as well. The results are depicted in Figure 3.2. A lower corner frequency would have given even more similar time series, however we do not want to eliminate some of the important physical effects such as whipping (3Hz), which is the fundamental vertical bending mode of the hull.

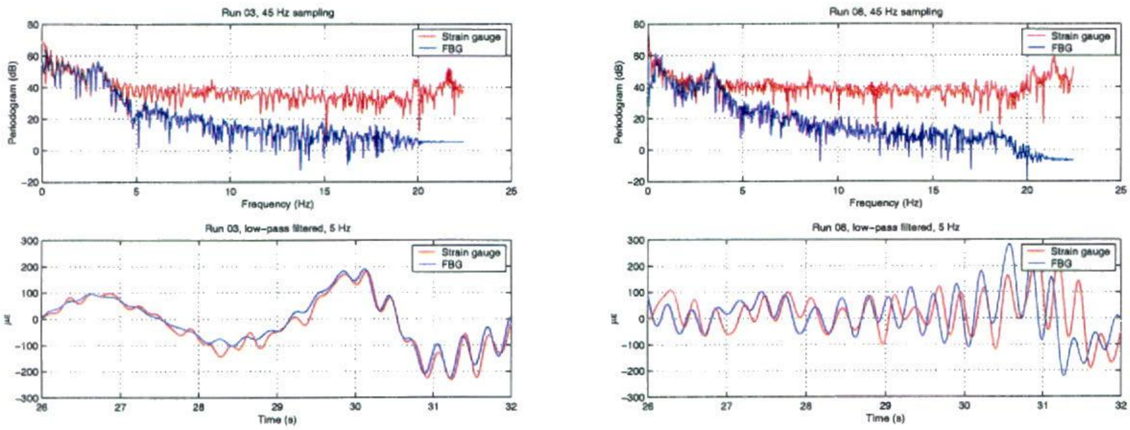

Figure 3.2 *Top curves show the power spectrum for run 3 (left) and run 8 (right), which indicate filtering around 5 Hz. Bottom plots show the filtered time series in the same time scale as the bottom curves in the preceding figure. The data are not well synchronized for run 8*

Another point worth stressing, is the fact that the FBG sensor data and strain gauge data do not seem to be well synchronized. A time discrepancy can be seen in several of the data sets, and the shift varies in some cases with time, e g for run 8 as shown in Figure 3.3.

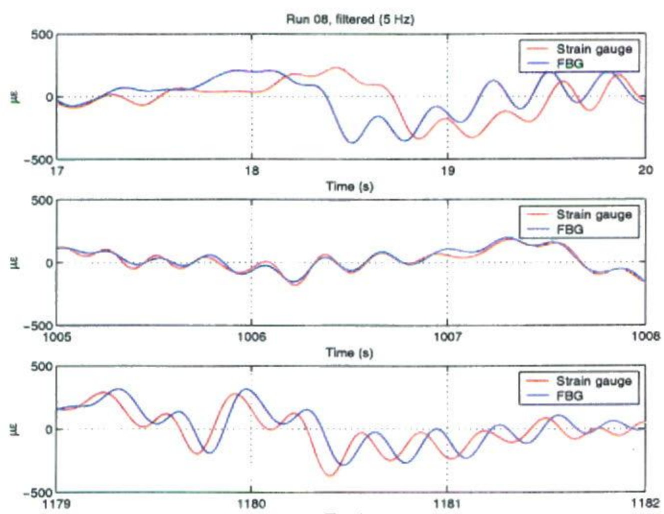

Figure 3.3 *Three cut from the filtered data of run 8. Top: near start of the run, the FBG data lags behind the strain gauge data, middle: the two series are in phase, bottom: the FBG data are ahead*

There is obviously a synchronization problem, stemming probably from an incorrect estimation of the sampling frequency for the strain gauge data. This estimation takes place in the procedure synchronizing FBG and strain gauge data.

There are two alternatives in order to deal with the synchronization problem; to consider a short part of the two data sets where they apparently are synchronized, or to synchronize the data sets. The latter is evidently the most correct. A simple synchronization model is applied in the following comparison; the time discrepancy is found at the beginning and end of the series, and the time scale of the strain gauge data series is shifted such that $t_{new}=a+b*t_{old}$. (This is actually a redefinition of the sampling frequency and a time shift to align the two series). This model has been used on data from run 8, and time series before and after synchronization are shown in Figure 3.3 and Figure 3.4, respectively.

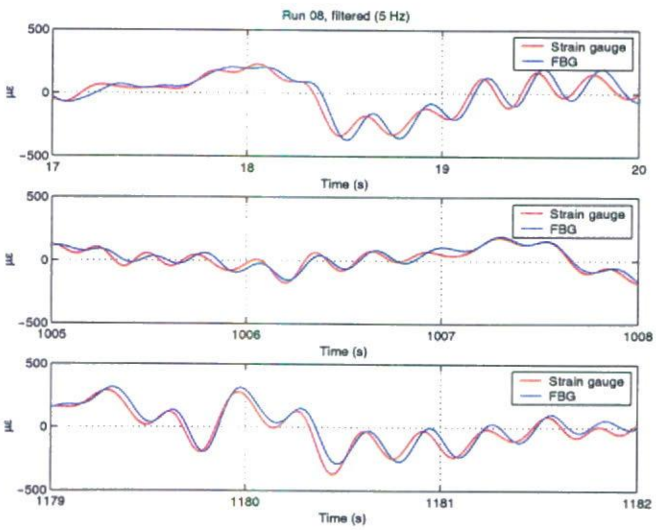

Figure 3.4 Same as previous figure, however after linear fit of the time scale ($t_{new}=a+b*t_{old}$)

Synchronized time series enable a comparison between the two measurement techniques.

3.1 Comparison

The similarity of two time series can be quantified by different means, e g by considering the arithmetic difference at each point, see Figure 3.5.

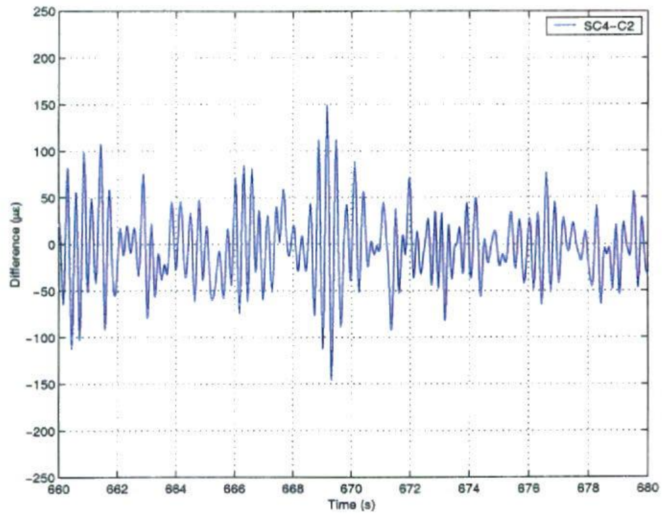

Figure 3.5 Arithmetic difference between the two signals (SC4-C2)

This representation is definitely unsuitable for comparison purposes. It is for instance very sensitive to synchronization problems. Yet better is to consider the relative difference, however we run into serious trouble for values around zero. Another method is to compare extreme values. Extreme values have been compared for run 3, where the maximum and minimum value for seven selected time intervals have been used, see Table 3.1. Intervals containing high strains have been selected for several reasons. First of all, the strain gauge measurements seem to be less influenced by noise for high strain levels. Secondly, division by numbers close to zero is avoided. Finally, the measured extreme values for the two techniques are more likely to coincide where one distinct (physical) maximum and one minimum appear. Hence synchronization problems are avoided. The FBG sensor measures approximately 4% greater extreme values for all intervals in consideration. This is probably a result of the considerable resistance in the cabling between the amplifier and strain gauge, which was measured to 5-10Ω for the different cables. The strain values measured by the resistive sensors presented here have been calculated as a linear function of the voltage. This is a common approximation (4):

$$V = \frac{kE}{4} \cdot \varepsilon \tag{3.1}$$

However, the correct equation, as given in Equation (2.2), yields a different result. For 1000με, the bridge voltage is 0.544mV with no cable resistance, and 0.523mV if the cable resistance were 10Ω (assuming that the balancing of the bridge included the cable resistance). This means that the strain is underestimated by 4%, which is in good agreement with the measurements. The fiber optic system is not influenced by long distances from read-out electronics to sensor because the strain is proportional to the wavelength and is not connected to the intensity of the light.

Interval number	FBG extreme (με)	Strain gauge(με)	Relative deviation
1	1116	1074	4 %
1	-641	-640	0.1 %
2	1084	1060	2 %
2	-687	-673	2 %
3	1375	1332	3 %
3	-625	-573	9 %
4	702	675	4 %
4	-1046	-984	6 %
5	1202	1159	4 %
5	-715	-691	3 %
6	1471	1407	5 %
6	-426	-403	6 %
7	2438	2358	3 %
7	-1131	-1067	6 %
Average			4%
Standard deviation			1.6%

Table 3.1 Extreme values for seven different time intervals during run3

For run 8, the size and variation of the deviation is much greater, hence comparing extreme values does not give a good picture of the situation. This is probably because of noise in the strain gauge measurements and the fact that run 8 has considerably lower strain level (the strain gauge measurements have lower signal to noise ratio than for run 3).

3.2 Vector analysis

A better measure of the conformity of the two techniques is by way of known methods from statistics. The two (synchronized) series are considered as vectors, and the two vectors are compared. First of all, the energies of the two signals are compared by means of the vector norms. Secondly, the vectors are normalized, and the "angle" between the vectors can readily be found (which is the arc cosine of the inner product of the vectors). The signals are identical if the vectors are parallel and have the same norm. These parameters are each a single number for each time series, and a statistic for all the series can easily be handled. For all runs carried out during the first day of the sea keeping tests (23 in all), the parameters in discussion are presented in Table 3.2 and Figure 3.6.

Run	Norm(SC4)/norm(C2)	Inner product	Angle between vectors
1	0.97	0.99	4°
2	1.09	0.94	20°
3	0.99	0.98	10°
4	0.99	0.95	18°
4b	0.99	0.93	22°
4c	0.98	0.53	58°
5	0.97	0.99	4°
6	1.01	0.85	32°
7	1.00	0.42	65°
8	0.98	0.96	16°
9	0.98	0.99	8°
10	1.10	0.82	35°
11	1.04	0.83	34°
11b	1.05	0.95	18°
12	1.06	0.42	65°
13	0.97	0.99	6°
14	1.04	0.90	26°
15	0.99	0.87	30°
16	0.97	0.97	14°
17	0.96	0.99	9°
18	0.95	0.99	8°
19	1.02	0.89	27°
20	1.01	0.67	48°

Table 3.2 Parameters applicable for comparison purposes for different runs

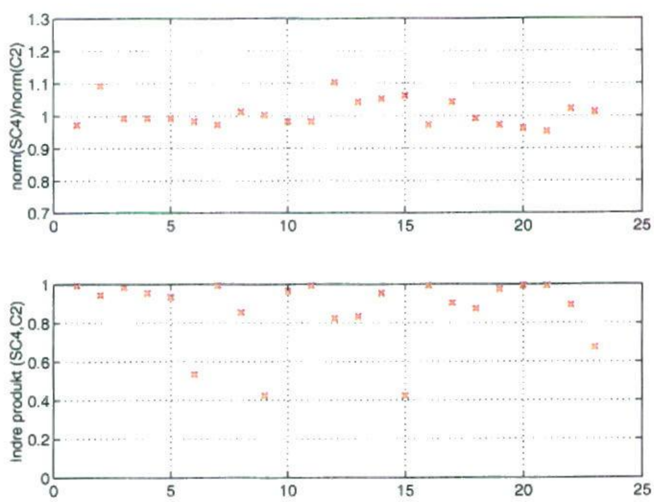

Figure 3.6 The ratio of "energy" in signal SC4 (strain gauge) to C2 (FBG) expressed by means of the vector norms (top), and inner product between the vectors (bottom)

The norms indicate that the two measurement techniques contain the same amount of energy. The inner products also show good resemblance for all except four recordings. For runs 4c, 7, 12 and 20 there are probably synchronization problems, however to verify this demands a closer look at the time series.

For a more thorough analysis for one time series, the "phase difference" between the series can be calculated. This will indicate if there is a discrepancy at specific frequencies. Examples from runs 3 and 8 are shown in Figure 3.7.

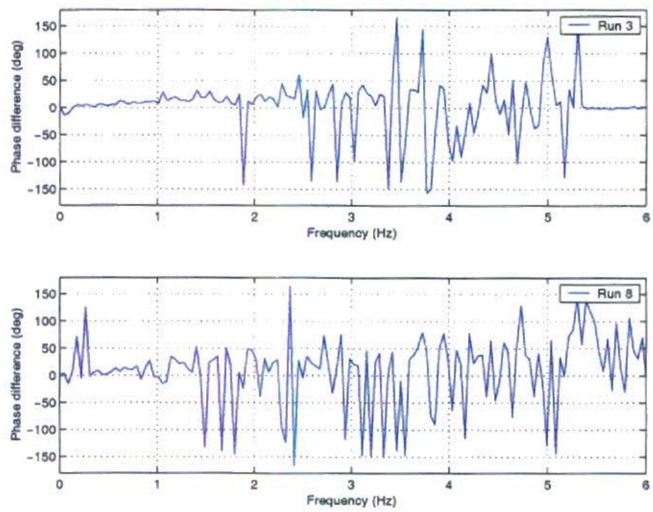

Figure 3.7 *The "phase difference" between the two signals for run3 (top) and run 8 (bottom) indicate that the low frequency response conform well*

The plots indicate that the two techniques have a similar response at low frequencies, whereas the high frequency response is out of phase. This is probably a result of synchronization problems, however noise, electronics or sensor bandwidth could cause the same problems.

4 CONCLUDING REMARKS

4.1 Summary

We conclude that the fiber optic Bragg grating based strain sensors yield far better strain measurements than conventional resistive strain gauges. The strain gauge data are extremely noisy, and a low-pass filter at 5Hz as well as a simple synchronization procedure had to be implemented in order to be able to compare. Owing to a large amount of data, only two sets (runs 3 and 8) have been analyzed in some detail. The rest (another 21 recordings from day one of the sea-keeping tests) have been treated automatically, based on methods developed during the analysis of runs 3 and 8. Comparing extreme values for selected intervals in run 3, the fiber optic sensor measured on the average 4% greater value, as a result of the resistance in the strain gauge cables. For other runs this method resulted in large variations, hence not a representative comparison. Other methods for comparing have been presented, and a vector analysis seems to be the best way in order to compare a large amount of data. The energy contained in data sets from the two techniques is approximately the same, and the vectors are fairly parallel for all but a few measurement series. These sets are probably poorly synchronized.

Our experience is that the fiber optic sensor system has several advantages in preference to conventional strain gauges, leading to more accurate measurements. Some advantages appreciated during the experiments were:

1. Insensitivity to electromagnetic noise
2. Low influence by water and corrosion
3. Small size (integrated part of the fiber)
4. Reliability throughout all tests
5. Low transmission loss enables large distances from read-out electronics to sensor location
6. Several sensors in the same fiber implies less cabling (distributed sensor network)
7. Strain is proportional to wavelength, thus not dependant on light intensity

4.2 Improvements

In order to get better data from the resistive strain gauges several improvements are possible. One is to use cables where each pair of wires as well as the whole cable is shielded. Another is to use shorter cables if possible. In any case, the cable resistance should be taken into account when transforming measured voltage to strain. An alternative is to place the bridge or even better, the bridge amplifier closer to the strain gauge (local amplifiers).

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