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THE EFFECT OF LOW PASS FILTERS IN THE MOLIKPAQ DATA ACQUISITION SYSTEM ON "PHASE LOCK" INTERACTION SIGNALS

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ABSTRACT

During the deployment of the Molikpaq in the Canadian Beaufort Sea, in the 1980's, various data signals were recorded by a digital data acquisition system. As part of this system an analog low-pass anti-aliasing filter was incorporated. The frequency response of this filter has been found to be far from ideal, resulting in significant changes in the amplitudes and wave shapes of data sampled at 50 Hz. Because of this distortion the severity and understanding of 'phase lock' interactions may have been in error. As an example, peak caisson accelerations have been reported in the literature to be up to about 10%g. The current investigation into the effect of the filter indicates that the peak accelerations are 50% to 75% larger.

In this paper, we discuss the filter frequency response and its effect on the strain-gauge and acceleration data recorded in the 50 Hz ("Burst") files with the emphasis on phase lock interactions. We also discuss aspects of the interpretation of the phase lock phenomena. It will be shown that there are consequences for the material contained in Section A.8.2.6, dealing with Dynamic Ice Actions, of the proposed ISO 19906 Standard.

INTRODUCTION

There is ongoing study of ice interactions on narrow and wide structures. The classic example of dynamic ice interaction with wide structures occurred during the Beaufort Sea deployment of the Molikpaq at Amauligak I-65 during the winter season 1985-6. Because of the newly released ISO 19906 Standard (International Standards Organization, 2010), and the role of the Molikpaq data in that standard, it is timely to reassess a fundamental, yet largely overlooked issue underlying the Molikpaq data.

The Molikpaq oil exploration structure was deployed in the Canadian Beaufort Sea at four sites during 1984-9 (Tarsiut P-45, Amauligak I-65, Amauligak F-24, and Isserk I-15). The Molikpaq was equipped with more than five hundred sensors to monitor the ice actions and the structural response, including MEDOF panels, strain gauges, accelerometers and caisson displacement gauges. The various data signals were recorded on a digital data acquisition system (DAS) and stored at various data rates. "Fast" files were stored at a 1 Hz rate on an essentially continuous basis. An event trigger was part of the DAS and when a significant event was detected, a 50 to

90 second segment of the data were sampled and stored at 50 Hz, referred to as ”Burst” files. Details on the instrumentation and data acquisition system are given in Jefferies et al. (1989).

Analogue anti-aliasing low-pass filters were incorporated as part of the signal conditioning prior to sampling with the DAS. It became evident by the late 1980s that the frequency response of these filters was far from expected and had distorted both the wave shapes and amplitudes of the recorded signals in the Burst files (Jefferies and Spencer, 1989; Hardy et al., 1996). A review of the literature indicates that the distortion of wave shapes and amplitudes appears to be unappreciated.

In this paper we investigate the effect of the low-pass filter on some of the recorded signals in the Burst files and the interpretation of the phase lock interactions. Examples of events recorded on 17 February, 12 April and 12 May 1986 are used. Implications for the section of the ISO 19906 Standard that describes these dynamic ice actions and structural response are also included in this publication.

LOW-PASS FILTER FREQUENCY RESPONSE

Following the ice loading events in spring 1986 (see Jefferies & Wright, 1988, for an accessible description), and the resulting interest in ‘dynamic’ ice loading, a signal conditioning board was retrieved from the Molikpaq and tested as part of the general investigation into the recorded data. The measured amplitude response of the tested filter to a sine-wave “sweep” is given in Figure 1 (Jefferies and Spencer, 1989). The dots indicate the measurement points and a modelled digital filter response is also shown. The phase response of the Molikpaq low-pass filter was not available. In contrast to the actual response, the filter was expected to have unity gain up to 10 Hz and then decrease at higher frequencies – consistent with anti-aliasing requirements for a 50 Hz scan rate.

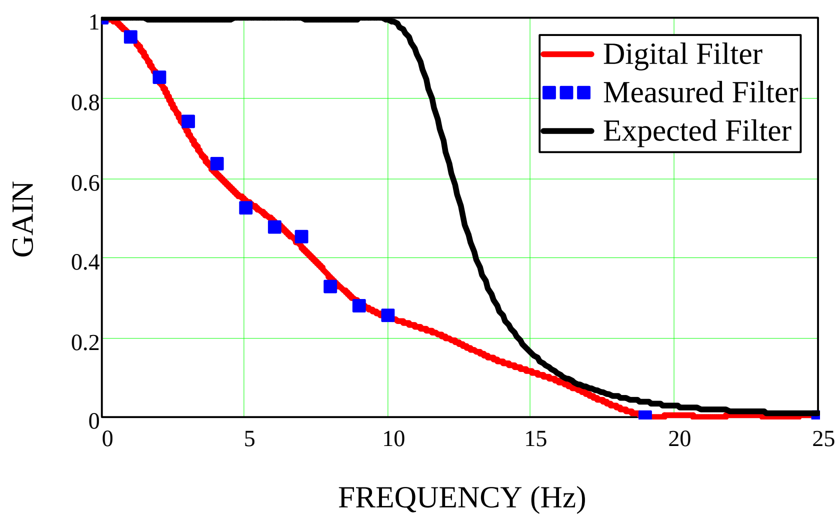

Figure 1. Modelled, Measured and Expected Filter Frequency Response

The consequences of the amplitude reduction as a function of frequency are very important and must be understood when interpreting Molikpaq Burst file data. A sine wave, upon passing through the filter, will have its amplitude reduced to the gain at that frequency. The amplitude will be centred at the average voltage. More complex signals will have their individual frequency components similarly reduced in amplitude, making prediction of the signal after filtering difficult.

To aid in the interpretation and analysis of the recorded data signals, a 25 tap digital Finite Impulse Response (FIR) filter, was designed for the 50 Hz sampling rate (Kuo et al., 2006), that reproduced the measured frequency response of the analogue filter given in Figure 1. The digital filter gain matched the analogue filter gain to better than about 0.03 at frequencies of less than 10 Hz and better than 0.01 at higher frequencies.

DE-CONVOLUTION

The modelled filter response was used to quantify the effect on the recorded signals of the introduced amplitude distortion. This was done by de-convolving (Kuo et al., 2006) the recorded signals with the modelled FIR filter shown in Figure 1. In investigating this de-convolution process it was noted that excessive high frequency noise was introduced. This noise was believed to be due to the non-zero FIR filter gain at the higher frequencies and the finite amplitude resolution of the DAS sampling. The high frequency noise was substantially reduced by passing the de-convolved signals through a second low-pass digital FIR filter with unity gain below 14 Hz. Note that in general, the true wave-shapes are unknown since their high frequency content was not recorded by the DAS. The process described here adjusts the lower frequency part of the signals for the amplitude distortion caused by the anti-aliasing filter in the DAS.

We now present examples of the changes in the strain-gauge and caisson acceleration signals recorded on Burst files after de-convolution processing. The following aspects regarding the processed signals should be noted: (i) the digital filtering introduced a time shift in the data. This time shift has been removed to aid in the comparison between the original and de-convolved signals; (ii) the relationship between the as-recorded signals and the de-convolved signals is not one-to-one since the amount of the adjustment depends on the time varying frequency content of the signals. When the signal is slowly varying, for example in the load traces given in Figure 2, the de-convolved signals do not vary greatly from the as-recorded signals. For the strain gauge loads in Figure 3 and the acceleration signals in Figures 4 and 5 the differences are much larger. The origin of the time axis in Figures 2 to 5 is arbitrary. The load values given in Figures 2 and 3 use the “strain-gauge-factors” presented in Jefferies and Spencer (1989). The de-convolution process could be applied on a systematic basis for all the various data channels recorded in the Burst files to assist in any future analysis.

From our analysis, representative values for the effect of the filter are: (i) for the strain gauge loads the amplitude of the load drop has increased by about 10% with peak amplitudes being about 5 to 10% higher for loadings with durations of less than about 1 second; (ii) for the acceleration signals, the peak amplitudes are 50 to 75% higher than the as-recorded versions. In the examples provided in Figures 4 and 5 a maximum acceleration of 15% of g should be noted as opposed to the 10% of g in the as-recorded data. These finding suggest that peak strain-gauge derived loads from rapidly varying signals may be under-represented by 5 to 10% and that any dynamic modelling of the Molikpaq that relies on a comparison with measured accelerations be re-assessed.

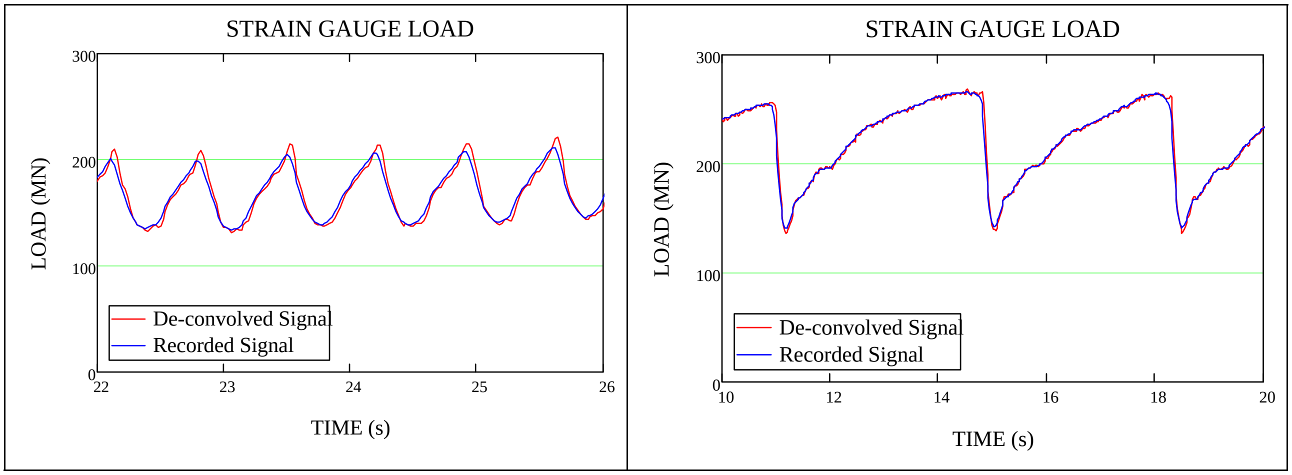

Figure 2. Strain Gauge Derived Load 12 May 1986

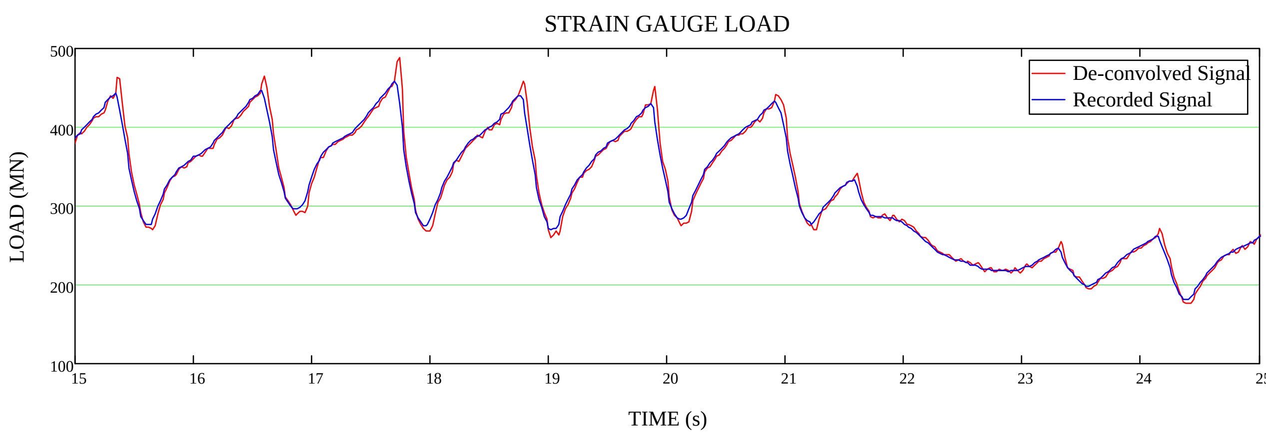

Figure 3. Strain Gauge Derived Load 12 April 1986

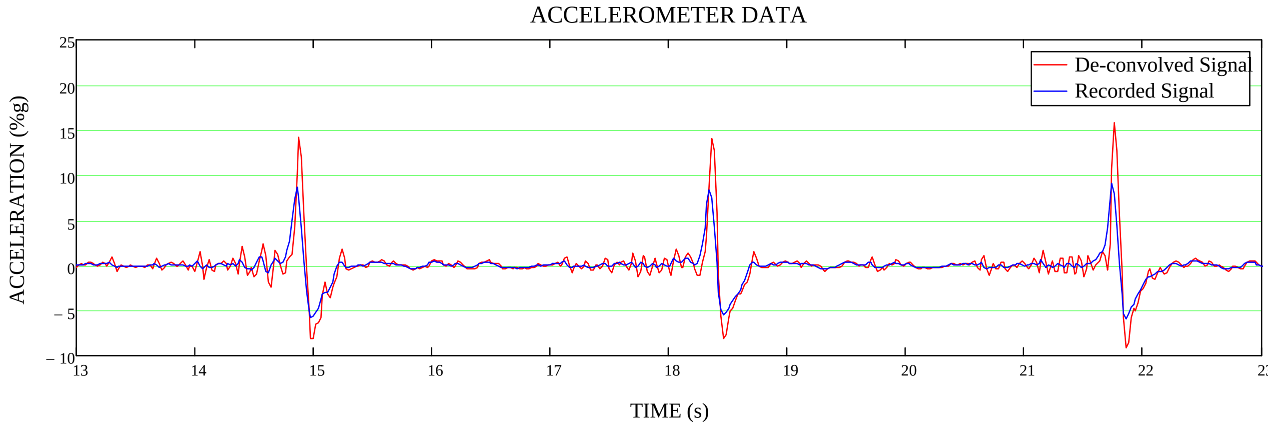

Figure 4. Acceleration 12 May 1986

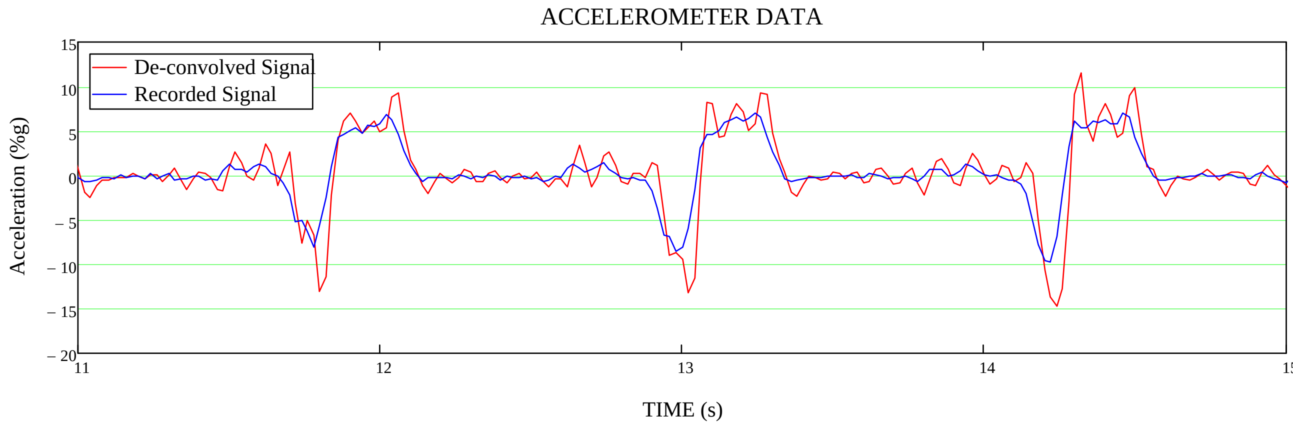

Figure 5. Acceleration 12 April 1986

FILTERING OF SYNTHETIC SIGNALS AND THE PHASE LOCK PHENOMENA

As noted in the previous section, the true wave-shapes of the actual sensor signals can only be estimated from the recorded signals. During the testing and implementation of the digital version of the low-pass filter, various synthetic signals were passed through the digital filter. It was found that some of the load characteristics recorded during phase lock interactions could be largely explained as an artefact of the filter response.

The data presented in Figure 6 illustrates a synthetic linear ramp sequence of varying amplitude and varying ramp period that was input to the digital filter representing the analogue anti-aliasing filter in the Molikpaq DAS, in addition to showing the filter output. The signal distortion of short period ramp signals is much larger than for long period ramp signals as can be noted from a comparison of the ramps at 1.1 s and at 5.0 s. The wave shapes for the linear ramp were however not a good match to many of the observed strain-gauge wave shapes, in particular see the data presented in Figure 2.

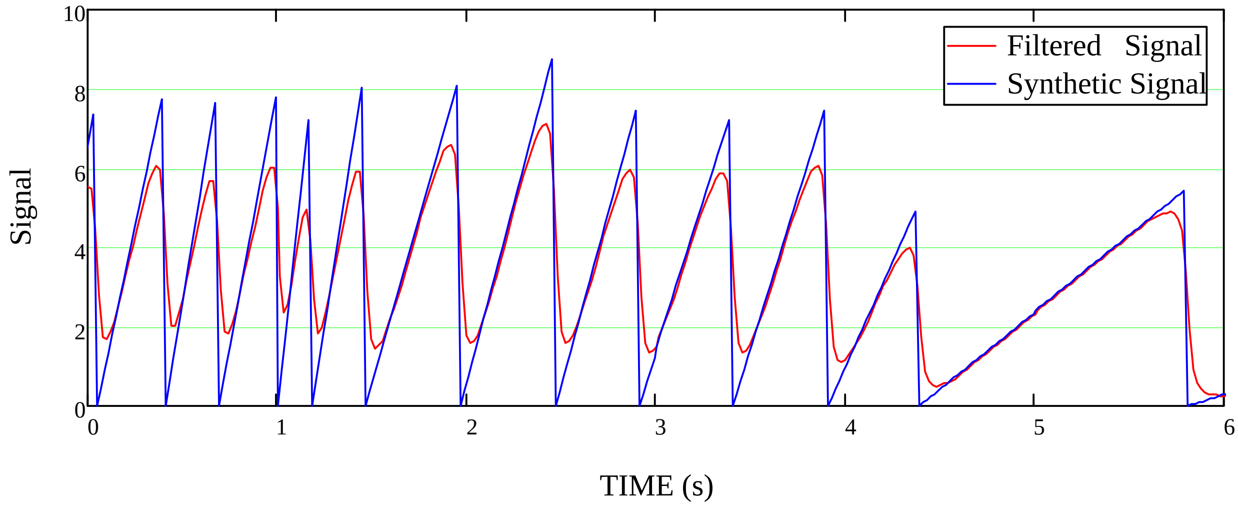

Figure 6. Linear Synthetic Ramp Signal and Filtering

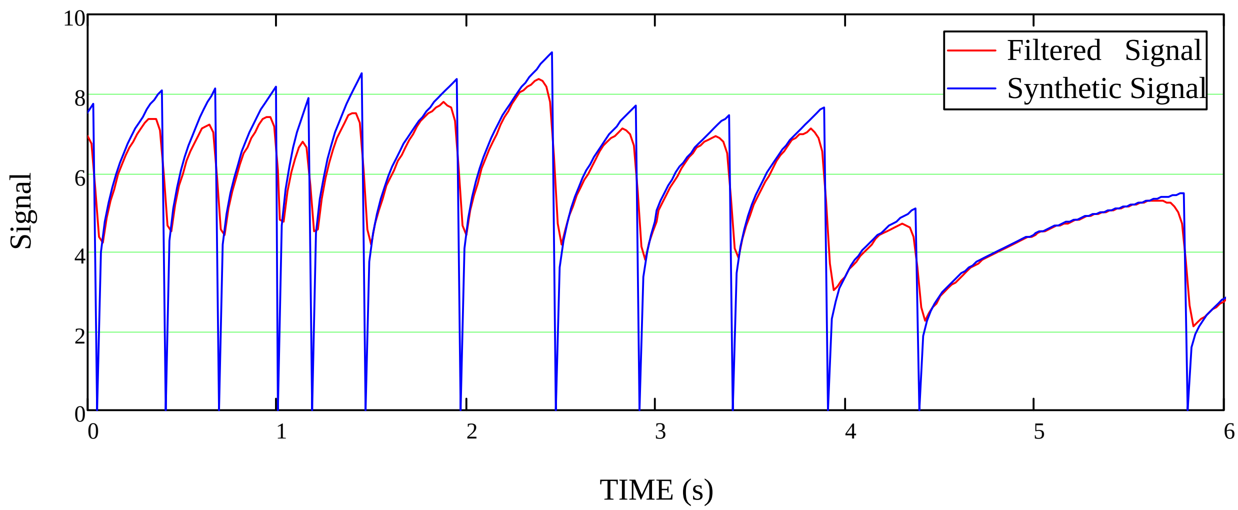

Figure 7. Non-linear Synthetic Ramp Signal and Filtering

A non-linear ramp function was generated from the linear ramp by raising the linear amplitude to a power. An exponent of 0.25 has been used since this value generated signals that closely matched many of the observed strain gauge wave shapes. The data presented in Figure 7 are the non-linear ramp signal along with the output of the digital filter. Notice: (i) the rather large reduction in cyclic amplitude of the “filtered” versus “synthetic” signal; (ii) the similarity of this filtered data to that observed and shown in Figure 2 and (iii) that the filtered signals do not drop to zero unlike the synthetic input signals. There are two main parameters of these filtered signals, the peak-to-trough amplitude of the load drop of each ramp and the peak-to-trough amplitude divided by the peak amplitude.

For a comparison of the non-linear ramp signals with observed event data, of interest are the interactions that occurred during the 17 Feb 1986 event. The ice loaded the East and South-East faces of the structure (Jefferies and Spencer, 1989). This interaction was reported to be due a 0.5 to 0.7 m thick level first-year ice sheet with very little ridging. This event represents as uncomplicated a situation as possible compared to other events that had ice with varying thickness, types and with pressure ridges. Figure 8 contains data showing the measured amplitude of each load drop obtained from three Burst files collected on 17 February 1986, each of which was a 'phase lock' interaction. The load drop, in tonnes, is the difference between the peak and trough amplitudes for an individual load cycle, each "cross" plotted represents a single cycle within the extended record. Phase-lock cycles were observed to be between 0.2 Hz and 4.0 Hz and not outside of this frequency range. As can be seen from Figure 8, the amplitude of the load drops decrease from about 2400 tonnes at 0.2 Hz to about 1000 tonnes at 4.0 Hz

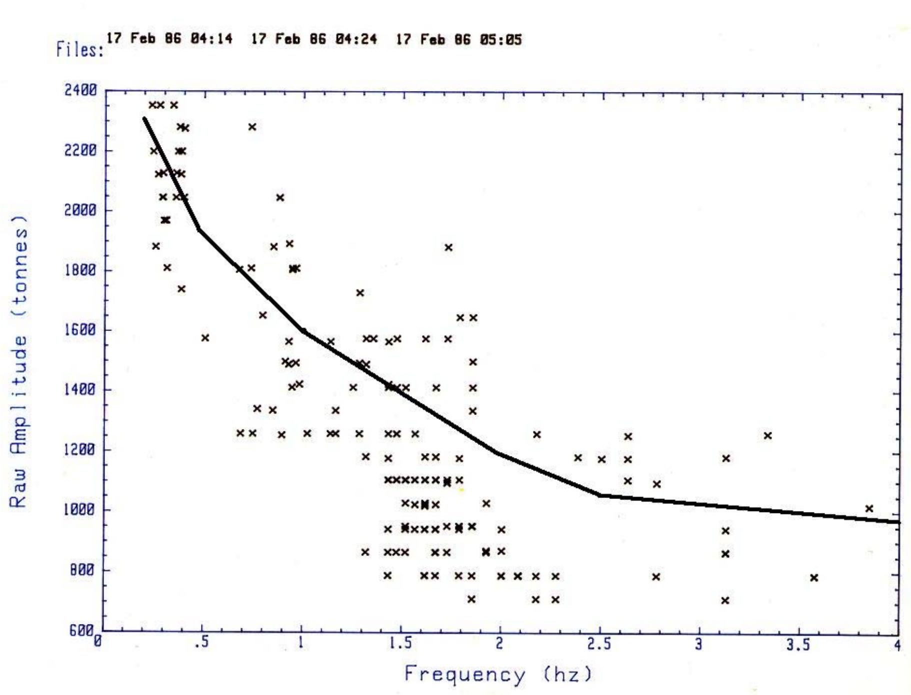

Figure 8. Cyclic Amplitude and Trend Line for 17 February 1986 Phase Lock Interactions

Overlaid on Figure 8 is a trend line generated by passing the unit amplitude non-linear ramp through the filter, at frequency values between 0.2 Hz and 4.0 Hz. The trend line had to be normalized and was done by setting the load drop to be 1600 tonnes at a frequency of 1.0 Hz. If the DAS was capable of measuring the higher frequency components of the signals accurately one would expect maximum load drops of 2400 tonnes throughout the frequency range of 0.2 to 4 Hz. Thus a large part of the amplitude-frequency trend in phase lock signals appears to be an artefact of the low-pass filter. A consequence is that the input loading to the Molikpaq would then be independent of the frequency or period of the phase lock interaction. Brown et al., (1992) calculated that the Molikpaq had a fundamental horizontal mode frequency of 1.3 Hz and for a loaded wall a mode frequency of 5.6 Hz. As shown in Figure 8, there is no evidence for a dynamic amplification at a defined structural resonance, in the phase-lock amplitudes in the 0.2 to 4 Hz range.

To merge observations from different phase-lock events, the cyclic load amplitude ('load drop') is divided by the peak load to form a cyclic loading amplitude ratio. This ratio was computed for eleven different phase lock interaction events that occurred between 17 February and 25 June

1986 (Jefferies and Spencer, 1989). The data in Figure 9 are from a mixture of events involving first-year and multi-year ice – the range of ice thickness is from 0.5 m to at least 4.5 m. There is some clustering in the data for individual events but there is an overall trend of the fraction of the load drop decreasing with increasing cycle frequency over the 0.2 to 4.0 Hz frequency range. Note that Figures 8 and 9 have been scanned from the original 1989 report (Jefferies and Spencer, 1989). The data contained in Figure 9 has been presented, in a different format in Jefferies et al., (2008).

The trend line in Figure 9 was generated by passing different frequency unit amplitude non-linear ramps through the filter. Since the Molikpaq data in Figure 9 are given as a ratio, in contrast to load in tonnes given in Figure 8, no normalization or fitting of the trend line was required. The trend line is a reasonable bounding curve for the observed data set. The normalized amplitude given in Figure 9 incorporates both the load drop and the peak load thus is also sensitive to the trough amplitude for these load cycles. The important aspect is that again, a large part of the observed phase-lock amplitude trend in Figure 9 can be explained as an artefact of the low-pass filter in combination with the frequency independent non-linear ramp.

The data presented in Figures 8 and 9 unfortunately do not shed light on the conditions for phase lock but rather they suggest that in any modelling of the process the ice loading can be represented as being independent of the frequency or period of the phase lock signal.

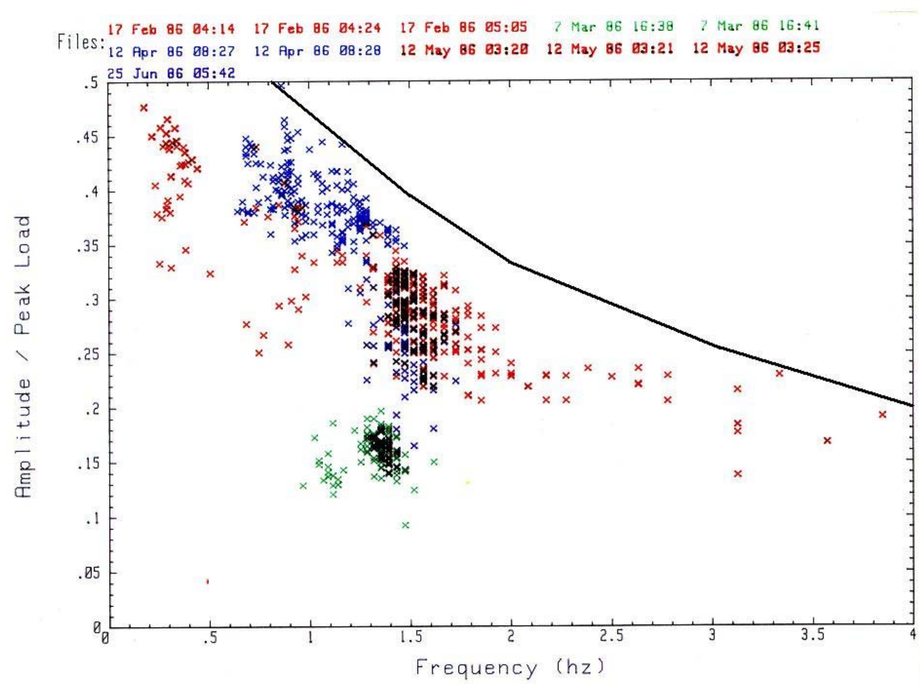

Figure 9. Observed Normalized Cyclic Amplitude and Filter Trend Line for Eleven Phase Lock Events, 17 February 1986 to 25 June 1986

PHASE LOCK IN ISO 19906

Sections A.8.2.6.1.1 and A.8.2.6.1.4 of ISO 19906 provide guidance regarding the phase lock effects. The following quotes are extracted.

> *Detailed studies should be conducted for the assessment of vibrations for wide structures. Narrow vertical structures can be sensitive to several kinds of dynamic ice-structure interactions.*
>
> *Based on field measurements and observations, the ice failure frequency typically locks in to some of the lowest natural modes of the structure. For complex structures, lock-in frequency is not always immediately apparent and an eigenvalue analysis is required to determine the lock-in frequency.*
>
> *The suggested value for θ was obtained from studies with stiff and narrow structures in the Baltic Sea. For wide or compliant structures, an appropriate value of θ should be estimated.*

Now compare these extracts from the Standard with the trends seen in the Molikpaq data. The implication from the Standard is that the same techniques and processes that are used for narrow structures can be used for wide structures. From plots such as given in Figures 8 and 9 there is very little evidence, if any, of structural resonance in the Molikpaq phase lock data even though from Brown et al., (1992) the 1.3Hz mode is within the observed frequency range of 0.2 Hz to 4.0 Hz. Of importance is that the 5.6 Hz mode frequency of the wall (Brown et al., 1992) is high enough so that the wall can respond to the rapid load drops. This is not a resonance effect (e.g. Jefferies et al., 2008) but a consequence of the loading frequency being lower than the resonance frequency. Moreover, based on the analysis presented here, the amplitudes of the Molikpaq phase lock signals should be treated with caution – the reported cyclic amplitude reduction with increasing frequency can credibly be an artefact of the installed anti-aliasing filters. In contrast to the indications provided in section A.8.2.4.3.3 of ISO 19906 dealing with global ice pressure on wide structures, the phase lock amplitudes may be under-represented not over-represented. A reassessment of the mechanism for dynamic ice forcing of wide structures is appropriate.

Detailed assessment of damping of wide structures under a variety of ice loading conditions is also recommended since the filter characteristics will have affected interpretation of this aspect of the interaction.

CONCLUSIONS

An implementation of a digital filter has been used to de-convolve 50 Hz Burst file data obtained by the Molikpaq data acquisition system. The major findings are:

- Much of the apparent frequency dependence of amplitudes of phase lock loading can be explained by the inadequacy of the filter, rather than having to invoke ice mechanics reasoning.
- Accelerations of the Molikpaq caisson are 50 to 75% greater than previously reported.
- Loads derived from strain gauges are up to approximately 10% greater than previously reported.
- A reassessment of dynamic ice loading on wide structures is appropriate.

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