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Ice load signatures for ridge actions on wind turbines with conical collars

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ABSTRACT

Wind turbine structures are usually tall and slender. This makes them very susceptible to vibrations. To reduce vibrations in ice, conical shapes at the ice line which fail the ice in bending are often preferred.
Conical shapes can be sloped either up or down. Ice loads from level ice can be shown theoretically to be lower for downward breaking.

For design, the structural engineer requires ice load signatures (load vs time) to feed into dynamic structural analyses (in which the cyclic wind loads are also included). A method for synthesizing load signatures for sloping structures when subject to level ice is described in ISO 19906 and applied in this work to produce stochastic load-time series

In recent years, there has been a move to extend wind turbines into deeper water and pack ice regions. A current project is to place turbines in Lake Erie beyond the landfast ice. In pack ice, ridges will usually dominate the ice loads. No guidance is provided in ISO 19906 either for the quasi-static ridge loads for downward breaking or for load signatures from ice ridges.

In this work, ice load signatures are developed for the example structure first for level ice and the method further advanced to create ice load signatures for ridges. Example ice loads and ice load signatures for a downward breaking cone for level ice and ridges for a Lake Erie location are developed.

KEY WORDS: Ice; Loads; Wind-turbines; Cones; Ridges.

1.0 INTRODUCTION

To function efficiently, wind turbine towers need to be as slender as possible. This can present structural engineering challenges, especially in the context of cyclic loads which may create vibrations with resulting dynamic magnification and fatigue damage. Offshore, cyclic loads will occur through the water line from either waves or ice as depicted in Figure 1.

Most offshore wind turbine experience has been in ice free regions. Recently, locations where ice is or can be present are being exploited; e.g. the Pori project in the Baltic. The work described in this paper was done to support the LEEDCo "IceBreaker" project which is to place wind turbines in Lake Erie about 12km offshore Cleveland, Ohio.

In current wind turbine practice the relevant codes (e.g. DNV-OS-J101, 2014; IEC 61400-3, 2009) devote considerable content to how wave loads are specified and combined with the wind turbine blade loads. The structure and foundation are designed for the maximum quasi-static loads, dynamic responses and fatigue.

The codes also require the same general approach to be used in ice covered regions. In general, ice loads will be higher than wave loads, so the design of wind turbines in ice areas can present a greater challenge. The cyclic nature of ice loads can be critical because the frequencies of the ice load cycles can be closer to the structure's natural frequencies.

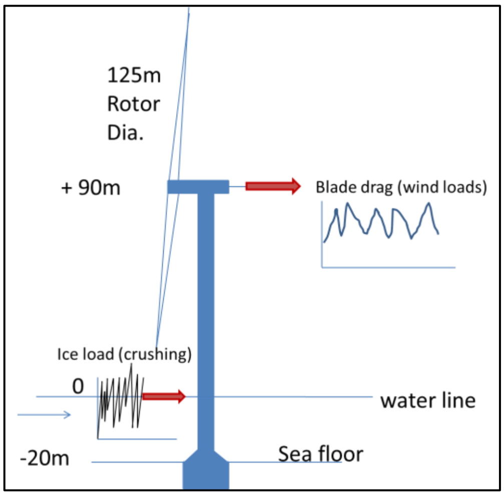

Figure1. Typical wind turbine configuration showing key loads

2.0 THE CYCLIC NATURE OF ICE LOADS

2.1 Crushing

Initial experience with slender light piers in the Baltic led to considerable research on this topic by investigators such as Määttänen (1987) and Kärnä (Kärnä and Turunen, 1989). This work was further extended when the Molikpaq drilling platform suffered from severe vibrations in the Beaufort Sea in 1986 (Jefferies and Wright, 1988). The topic is quite complex and this paper is not concerned with vibrations due to crushing, however a simplified overview helps to set the scene for conical shapes and cyclic bending failures of the ice.

Ice crushing on a vertical face gives typical cyclic loads as shown in Figure 2. These were measured during indenter tests conducted by one of the authors and his colleagues in the Caspian Sea in 2003.

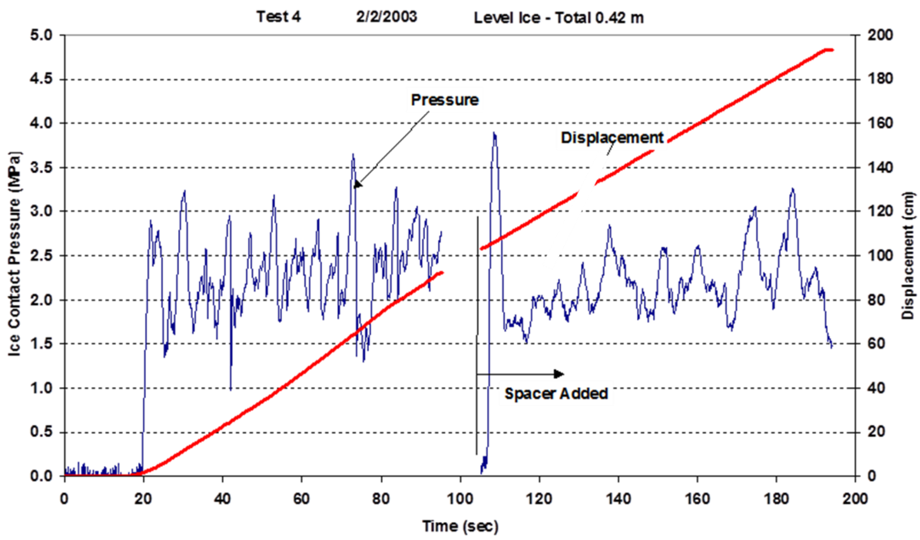

Figure 2: Measured ice signature: crushing of 0.42m ice with a 0.5m diameter indenter

The load trace shown in Figure 2 is a typical forcing function of ice crushing. In this case, there is no flexible structure involved. The nature of the load trace is that load peaks occur at distances apart which are a fraction of the ice thickness. This is depicted in Figure 3.

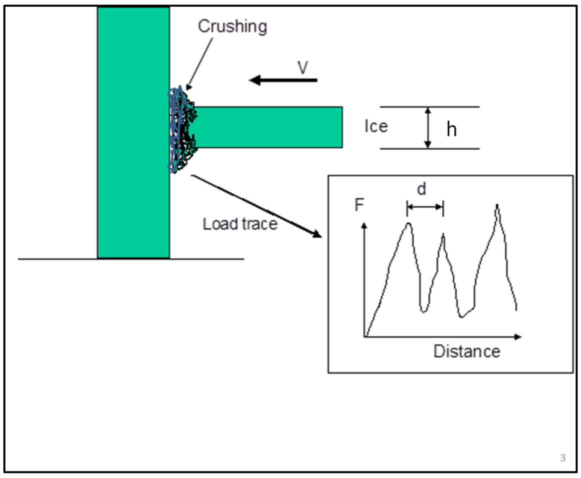

Figure 3: Load signature derivation - crushing

The distance between peaks can be defined as,

$$d = kh \quad (1)$$

where k is a factor. The frequency (f) can be derived as a function of ice velocity (v) as,

$$f = v/kh \quad (2)$$

For crushing, k has been assessed from full scale and model test data. A value of 0.05 has been suggested based on small scale tests (Sodhi, 1989). In the indentation test shown in Figure 2, it can be seen that there are a mixture of frequencies within the load trace, but picking off the dominant peaks gives approximately 4 peaks every 20 cm which is 1 peak every 5 cm, hence for 42 cm ice gives $k = 5/42 = 0.12$ – say about 0.1.

Therefore if the ice speed was 0.5m/s and the ice thickness was 0.6m, then the ice load forcing frequency would be about, $f = 0.5/0.1/0.6 = 8.3$Hz

Furthermore, ice speeds can be at any speed from zero up to the maximum. So if the structure has a natural frequency below 8.3 Hz, then at some ice speed below 0.5m/s (in this example), the forcing and natural frequencies will coincide.

In ISO 19906 there are three regimes discussed; a) Intermittent crushing; b) Frequency lock-in; c) Continuous brittle crushing. The crushing load trace in Figure 1 would be typical of that which could create frequency lock-in. In this regime, due to feedback between the rate of structural deflection and the ice speed the structure can vibrate over a range of ice speeds close to the critical ice speeds which coincide with natural frequencies of the structure. For better insights into vibrations on vertical structures, the reader is referred to ISO 19906 and other recent research (Hendrikse et al, 2017). It is sufficient to say that vertical slender structures are vulnerable to ice induced vibrations because of the close proximity of the ice crushing forcing function and the structure's resonant frequencies.

2.2 Bending failures

In the work on Baltic light piers and Bohai Bay platforms, it was found that ice load frequencies could be lowered and moved away from the natural periods of the structure by fitting conical collars. A conical shape at the ice line changes the ice failure mode from crushing to bending.

For sloping structures, the distance between breaking peaks is a much greater factor on thickness than 0.1 (k for ice crushing). This is shown conceptually in Figure 5. Observing flexural failures and block sizes in nature (ridge and rubble building) suggests that the factor is at least 3 to 5 (typical block lengths to thickness).

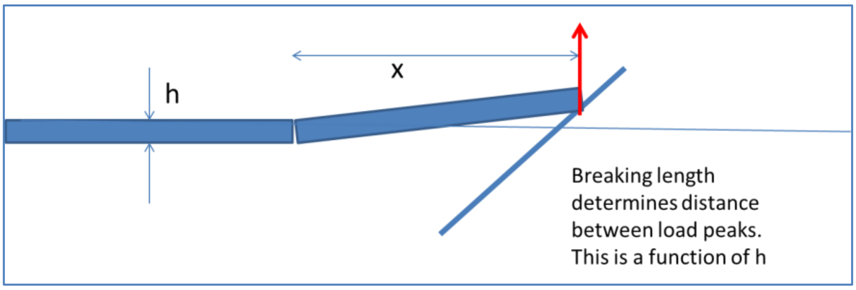

Figure 5: Concept of breaking length for flexural failure

In models based on plate/beam bending on elastic foundations (Croasdale et al, 1994, ISO 19906, 2010, Croasdale et al, 2016) it is shown that the initial breaking length is given by,

$$L_b = L_c \, \pi/4 \tag{3}$$

Where Lc is the characteristic length given by

$$L_c = \left(\frac{Eh^3}{12\rho_w g(1-\nu^2)}\right)^{1/4} \tag{4}$$

Where, E is the elastic modulus of the ice, h is ice thickness, ρ_w water density and v is Poisson's ratio.

For an ice sheet 0.6m thick and using typical values for the other inputs, the value of L_c is 6.9m. This is a k value of about 11.5 which seems large compared to the observations in nature mentioned above. However, in the latest model by Croasdale et al. (2016), it is shown that secondary bending failures will occur, which in this example would reduce the block lengths to about 3m. Secondary failures are of interest, and result in realistic block sizes but the load peak frequency is dominated by the first breaking length.

Research and full scale measurements relating to the Bohai Bay structures (Li et al, 2003) gives a relationship which would result in a k value of about 10 for this situation.

In DNV-OS-J101 two methods are given for block length between load peaks. One is similar to Eq. 3; the other includes an ice strength term. Applying this to the example gives a block length of about 6m compared to the 6.9m developed from the flexural model (that is a value of k of about 10).

A comparison of approaches is shown in Table 1. The column labelled "Frequency" uses Eqs. 2 to 4; the sensitivities use the breaking lengths proposed by DNV and the method from Bohai Bay research referred to earlier. In this work going forward, Eqs. 2 to 4 will be used in association with the flexural model by Croasdale et al (2016).

Table 1: Forcing frequencies for 0.6m ice failing on a 60 degree upwards cone

Wind speed	Ice speed	Frequency	Sensitivities	
m/s	m/s	Hz	DNV	Bohai
2.5	0.05	0.007	0.008	0.008
5	0.1	0.015	0.015	0.017
7.5	0.15	0.022	0.023	0.025
10	0.2	0.029	0.031	0.033
15	0.3	0.044	0.046	0.050
20	0.4	0.058	0.062	0.067
25	0.5	0.073	0.077	0.083

To complete the overview, Figure 7 shows a plot of typical forcing frequencies for both crushing and flexure. This plot shows why conical shapes are preferred when structural excitation due to ice loads is a potential problem. This benefit is over and above the lower ice loads in bending than in crushing which will be commented on later. Downward breaking cones have some advantages over upward cones in that the clearing loads are lower and the top of the downward cone provides a good platform on which to land personnel for maintenance. For these reasons the base-case design for the Lake Erie project uses 60 degree sloped downward breaking cones. The shaft diameter is 5m and the cone water line diameter about 8m. This case will be carried forward in this paper.

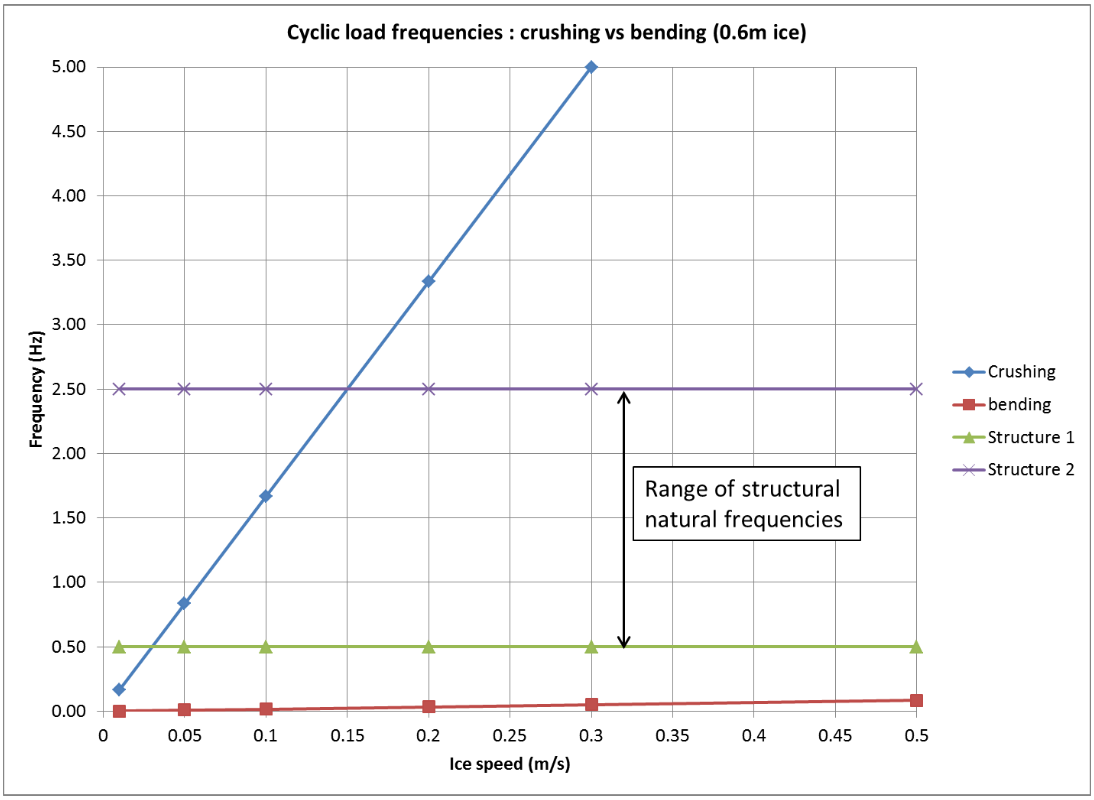

Figure 7: Comparison of typical cyclic load frequencies in crushing and bending

3.0 ICE LOAD SIGNATURES FOR LEVEL ICE IN BENDING

The design methods for wind turbine bases in open water utilize a method of structural dynamic analysis which requires the input of wave load signatures over a time series of about 800 seconds (DNV, 2014 and IEC, 2009). To enable the same methods to be used for ice, such a time series was requested by the structural engineers. Wave inputs also recognize the reality that randomness in wave spectra exists in the real world. This is also true of cyclic ice loads, so the final results must incorporate this stochastic variability.

The approach used in this study was to first develop the load signatures based on constant inputs and then randomize the signatures based on the methods suggested in ISO 19906 (2010).

3.1 Example: 0.6m level ice; 60 degree downward cone

The arrangement is summarized in Figure 8 where the design ice loads for the 50 year ice thickness of 0.6m (for Lake Erie) are summarized (based on the model by Croasdale et al, 2016).

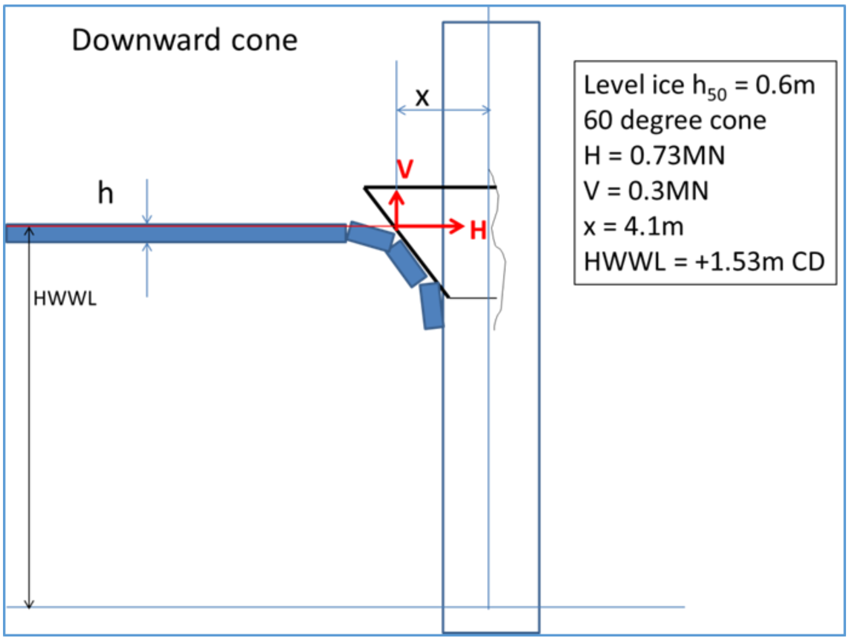

Figure 8: Base case of 0.6m of level ice acting on a 60 degree downward cone.

The ice load is specified as the horizontal load due to moving ice at relevant velocities; the ice thickness is again 0.6m. The loads are derived for the assumed flexural strength of the fresh water ice in Lake Erie of 500kPa (Daly, 2016).

The peak loads are shown on Figure 8; the peak horizontal load is 0.73MN acting at the high winter water level (HWWL). The accompanying vertical load is 0.3MN upwards applied at 4.1m from the centre line of the shaft. These peaks are separated by the distance moved by the ice equal to the breaking length. In the case of 0.6m of ice with an ice modulus of 3GPa, the initial break forms a circumferential crack with a radius of 6.9m; this is the breaking length of interest.

Detailed analysis (using Croasdale et al, 2016) shows that there is a second break reducing the ice piece to about 3m at a slightly higher load than the first break load. This leads to a double peak but the separation is less than the ice thickness and the load does not drop between them. Therefore a good approximation is to retain the 6.9m distance between the peaks and use the load associated with the second break. This load also includes ride down and clearing terms. For an ideal load trace these can be assumed to be the base load to which the load cycle drops to. Because this is a downward cone the base load is quite small at 0.06MN.

This cycle can be provided as a time series by dividing distance by ice speed. In the case of this project the 50 year ice speed was developed from wind speeds to be 0.5m/s.

The derived uniform cycle load trace is shown in Figure 9 for the first 150 secs.

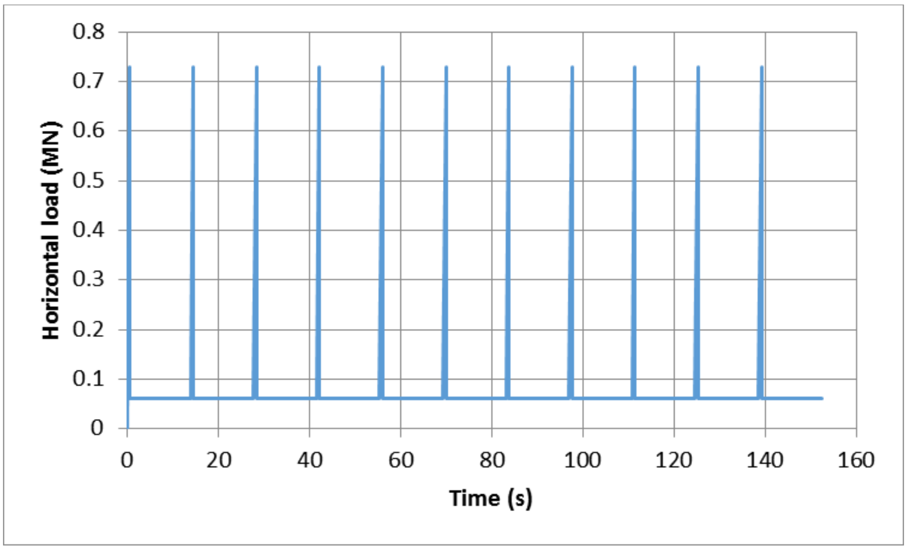

Figure 9: Part of steady time series: 0.6m ice moving at 0.5m/s: downward 60 degree cone.

3.2 Derivation of a stochastic time series – level ice 0.6m

For dynamic analyses, IEC 61400-3 (2009) allows a uniform time series such as those already derived. But in the real world they will never be uniform but somewhat random (stochastic). This is due to various effects; a) the ice thickness is not perfectly uniform; b) the ice properties can also vary during an interaction; c) the ice speed also might fluctuate even within the bounds of a uniform average, and finally; d) the actual ice interaction physics has randomness due to non-simultaneous breaking actions and ice clearing. A stochastic load signature can be created based on the physics of varying these parameters, but this would be very labour intensive.

DNV suggests the method in ISO 19906 be used to develop a stochastic ice load signature. In ISO 19906 (Paragraph A.8.2.6.2), the basic load signature is varied statistically based on real world measurements of ice load traces. The approach is now applied to this example. Figure 10 defines the characteristics of the load cycles.

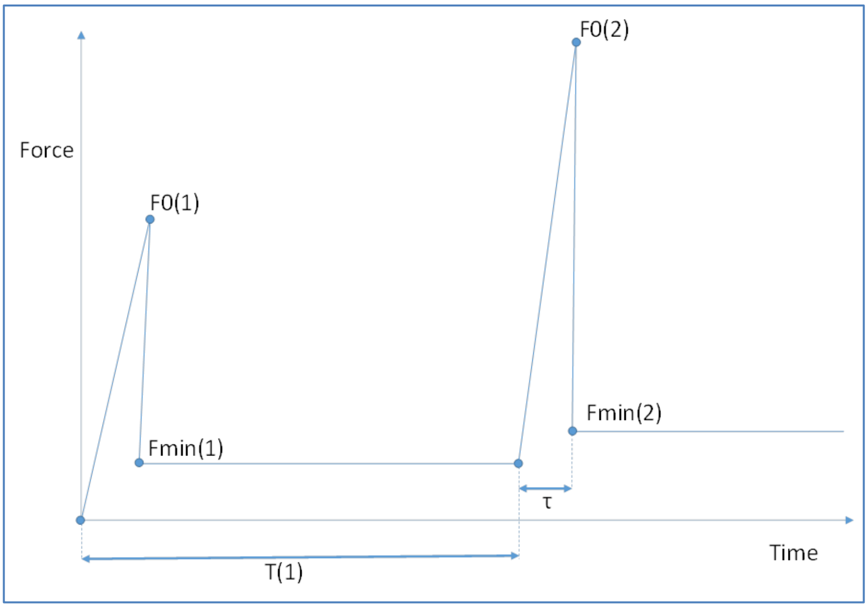

Figure 10: Characteristics of the load cycle

Where F0 is the peak load in a cycle; Fmin is the minimum load in a cycle; T is the period (time between peaks); τ is the duration of the loading/unloading cycle.

As in the uniform cycle, the breaking length is given by Eq. 3

The analytical method used shows that the peak load F occurs at about a vertical lift of about one ice thickness (h). Therefore, the time duration of the load peak for a 60 degree cone becomes $\tau = h / V / \tan(60)$; where V is ice speed.

The deterministic value of F0 has been derived for 0.6m of ice and a 60 degree downward breaking cone as 0.73MN (see Figure 8). The corresponding value of Fmin is 0.06MN

To create a stochastic series, period T values are drawn from a normal distribution:

Mean = Lb / V; Sigma = 0.5* Mean; T is resampled if T < h / V
The values of F0 and Fmin are also randomized based on a normal distribution according to the method in ISO 19906
A sample of a 150s time series is shown in Figure 11. The total 800s series (as required for a dynamic analysis) is shown in Figure 12. Statistical results are shown in Figure 13. It can be seen that the most dominant cycle frequency is very close to the simple deterministic value of 0.073Hz (Table 1).

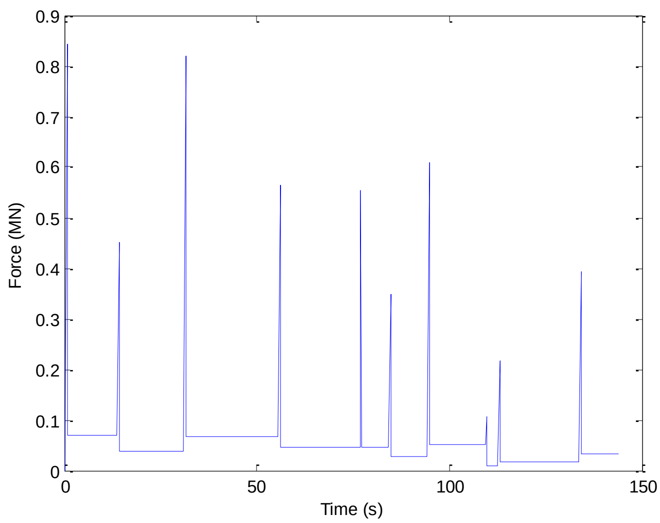

Figure 11: Stochastic ice load time series: 0.6m ice; 0.5m/s: 60 degree downward cone

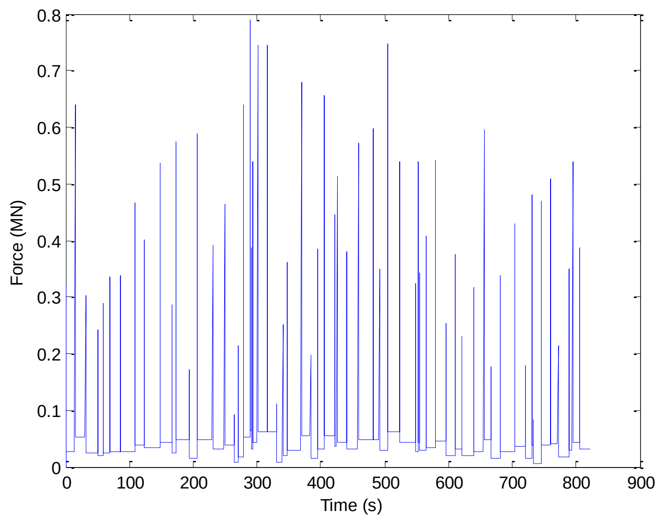

Figure 12: Sample of 800s stochastic ice load time series: 0.6m ice at 0.5m/s: 60 degree downward cone.

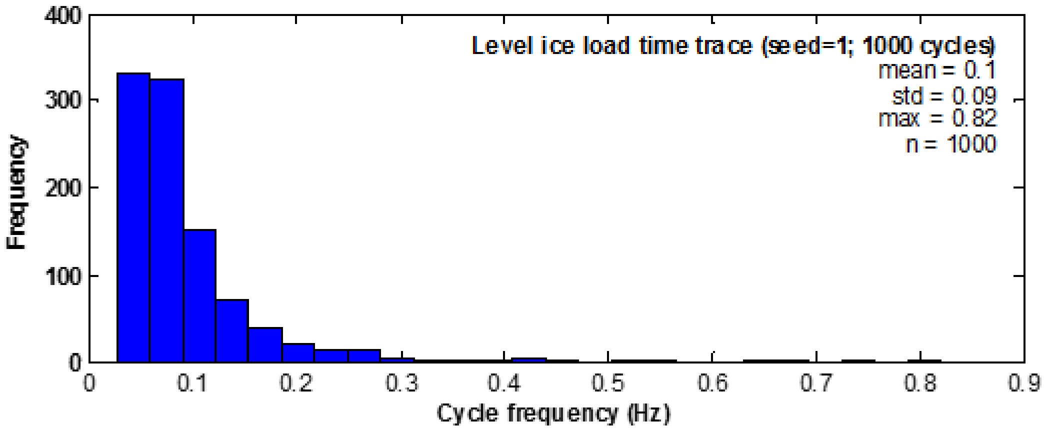

Figure 13: Characteristics of a typical stochastic load time series for 0.6m level ice

4.0 LOADS AND LOAD SIGNATURES DUE TO RIDGES

When wind turbine structures are placed in pack ice (beyond the landfast ice zone), the loads and load signatures from pressure ridges are also required and ridges will usually control the design global ice loads.

4.1 Typical ridge loads

The details of developing the ridge loads on the proposed Lake Erie turbines have been described in Croasdale et al (2018).The results can be summarized as shown in Figure 14. The methodology to develop the ice loads is based on that in ISO 19906 and Palmer and Croasdale (2013) in which the load from the ridge keel is added to the load from the consolidated layer of the ridge. In this case the critical ridge load occurs from a ridge with a keel depth of 16m and a consolidated later thickness of 1.1m. The total load is 7.2MN of which the largest component is from the keel (over 5MN). The keel load is calculated using the methodology in ISO 19906 which idealizes the ridge to a granular material made up of ice blocks; also see Palmer and Croasdale (2013).

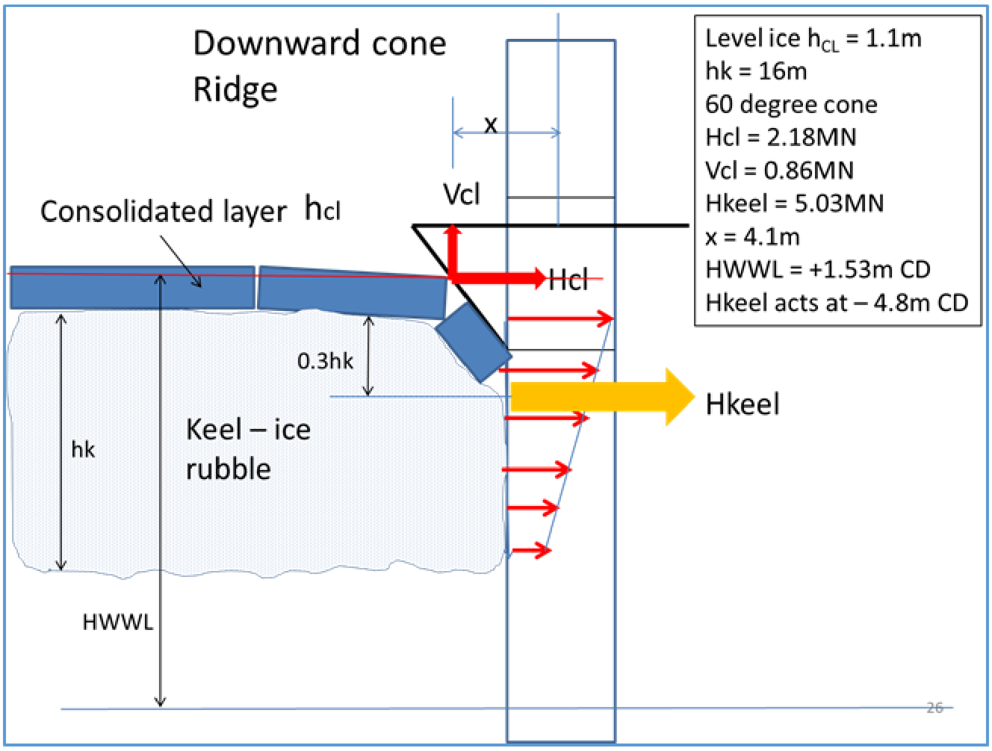

Figure 14: Ridge acting on a downward sloping cone

4.2 Keel Load and signature

The predicted maximum keel load = 5.03 MN. The idealized development and decay of this load is shown in Figure 15 for an ice velocity of 0.5m/s.

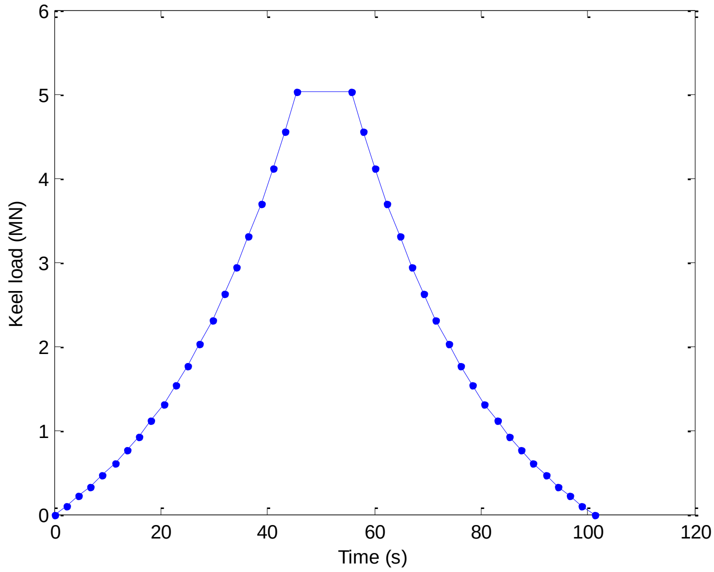

Figure 15: Theoretical ridge keel load as a function of time at an ice speed of 0.5m/s

It is of interest to show how the theoretical load signature compares to some recent model tests in which the author was involved. The tests were on a multi-leg structure so each leg had a load trace and not all legs saw an undamaged ice sheet. The blue load trace was a leading leg experiencing an undamaged sheet. Also note that the shaft was vertical through the ice line so that crushing was occurring and therefore the high frequency components added to the keel load are not typical of a flexural failure.

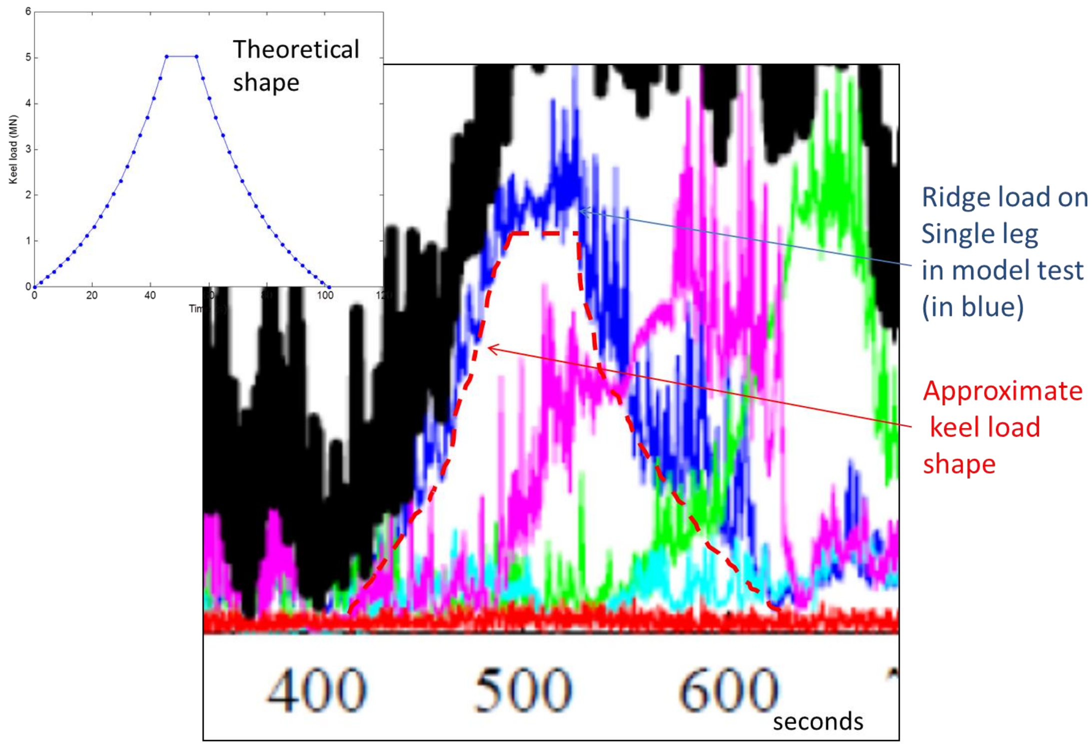

Figure 16: Comparison of keel load shape with experimental data

4.3 Ridge consolidated layer load and signature

The downward breaking consolidated layer load model is derived in Croasdale et al. (2016). For downward breaking into the keel rubble, there is increased resistance compared to water, which leads to higher loads than for a level ice sheet. As well, the breaking length is shortened due to an increased "foundation" modulus. In this case the breaking length is 4.6m and the peak load is 2.18MN.

The following are the additional inputs to derive the time series of the contribution from the consolidated layer. In this case only a uniform time series is proposed, but the ridge will be embedded into a stochastic level ice time series.

Ice speed: V = 0.5 m/s: Breaking distance x = 4.6 m: Constant period T = x / v = 9.2 s: Constant peak breaking load F0=2.18MN: Constant minimum load Fmin=0.06 MN.

4.4 Load signature for the complete ridge

To generate a stochastic load signature, the ridge is placed in approximate centre of level ice load trace: Note again that the consolidated contribution to the load is included as a steady state cycle. This could also be made stochastic but the steady state is expected to be a worst case. The result is shown in Figure 17.

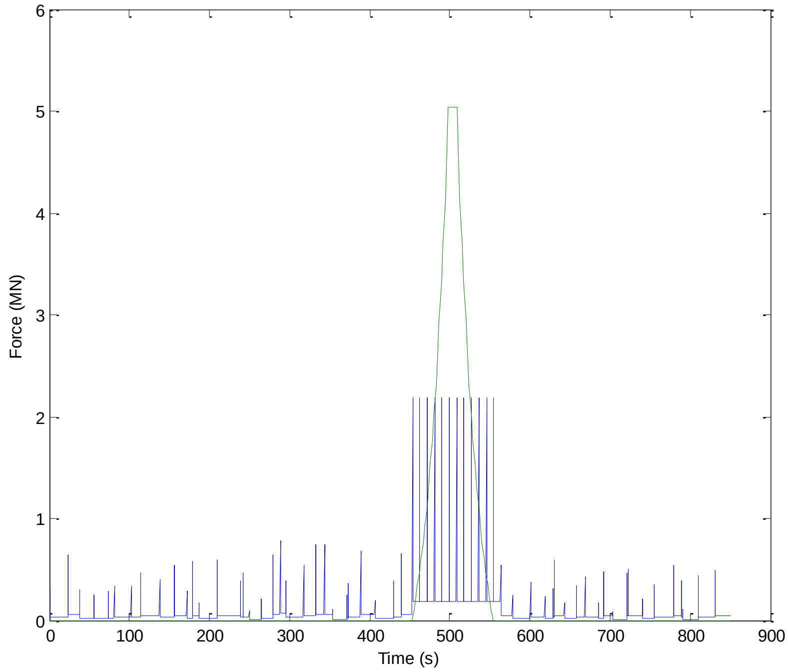

Figure 17: Ridge embedded in level ice time series (green is ridge keel, blue is level ice and consolidated layer of ridge).

5.0 CONCLUSIONS

Wind turbine structures are tall and slender and susceptible to vibrations. In ice there are advantages in using a conical shape at the water line. The ice then fails in bending rather than crushing on a vertical face and the cyclic ice load frequencies are less likely to coincide with the structure's natural frequencies, hence avoiding excessive vibrations. A downward breaking cone has advantages in reducing ice loads as well as being a practical shape for operations.

For structural analysis, a stochastic ice load signature is required. This paper shows how this can be done using the most recent ice load algorithms for conical structures. Example ice load signatures are derived for a downward breaking cone subject to level ice 0.6m thick. The method is extended to ice ridges.

For 0.6m level ice on a 60 degree downward cone and ice moving at 0.5m/s, the mean cyclic load frequency is 0.09Hz with dominant frequencies in the range of about 0.04 to 0.08Hz. These are well below the equivalent crushing frequency of about 8Hz and also below typical natural frequencies of turbine structures.

The nature of pressure ridge action is a slow increase of the load due to the ridge keel extended over about 50 seconds. This is not an issue in terms of dynamics. However the consolidated layer of the ridge will act similarly to level ice with repeated load cycles at about a frequency of 0.11Hz extending over the width of the ridge (about 50m).

The global quasi-static ice load (required for Ultimate Limit State design) for the design ice ridge for Lake Erie is about 7.5MN compared to 0.75MN for level ice; so the ridge controls global design; however the large number of ice load cycles from level ice may need to be accounted for in fatigue assessment (Although in the case of this project it was concluded that fatigue damage due to ice was well below that due to waves).

Finally, for global loads, the design value of 7.5MN for the cone configuration compares to about 13MN for an equivalent 5m diameter vertical cylinder (which would also have poor dynamics and not recommended).

6.0 ACKNOWLEDGEMENTS

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