BLADED

Historic issues with coherence in Bladed wind file generation

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1 INTRODUCTION

An update to the turbulent wind file creation algorithm was implemented in Bladed 4.4. This resolves some deficiencies related to the coherence model which could appear in wind files created with previous Bladed versions. This technical note gives an overview of the topic, describes the changes which were made to the algorithm in Bladed and also gives some information on how this change may affect the calculation of turbine fatigue loading.

2 BACKGROUND

2.1 Overview of wind models

Bladed is capable of generating three dimensional turbulent wind fields containing time histories of wind speed variations over a user defined grid. There are three different turbulence models available in Bladed:

- Kaimal model
- Von Karman model
- Mann model

For the first two models, the well-known Veers method /3/ is used to generate the wind fields. The Mann model uses a completely different method. This note applies only to wind fields generated using the Veers method – the implementation of the Mann model is not affected.

For the Veers method, each component of turbulence is defined by a power spectral density function and coherence function. The power spectral density function defines the frequency content of the time history at each grid point in the wind file. The coherence function describes the correlation of the turbulence time histories between grid points in the wind file which are separated laterally and vertically, as a function of frequency. As the coherence is a function of separation, points which are close together will be more highly correlated and therefore have a greater coherence than those which are located further away from each other. Similarly correlations (and therefore coherence) are greater for low frequency variations than for high frequency variations. Physically this means that wind conditions at points which are close together in the wind file will vary in a similar way.

Figure 2-1 shows that the black points on the grid on the left will have a greater coherence than the points on the grid on the right. This is because the points on the left are closer together and thus we would expect a greater coherence between them.

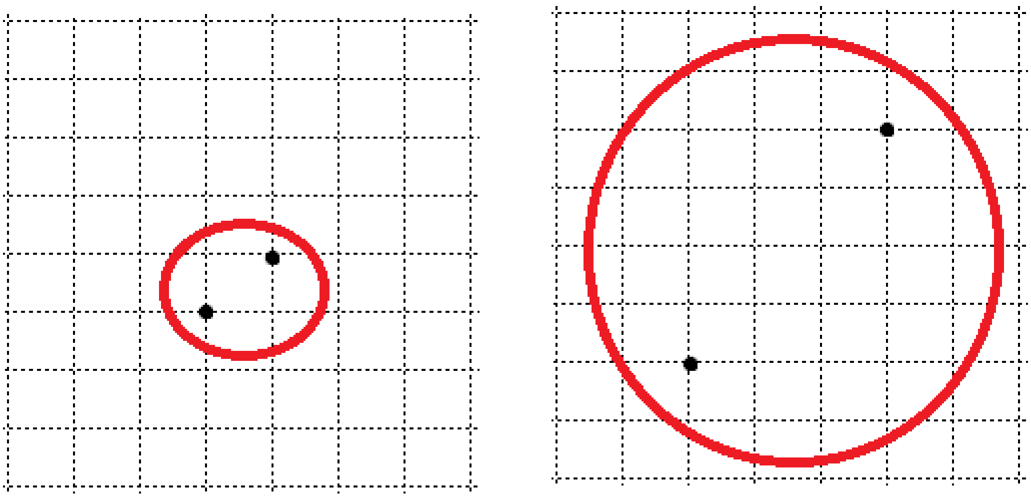

Figure 2-1 - Example wind file grids

When generating turbulent wind files in Bladed, the user must input parameters as shown in Figure 2-2. Input parameters must be entered which dictate the size of the wind file in the rotor plane (‘Volume width Y’, ‘Volume height Z’) and also define the number of grid points in the wind file in each direction

(‘Number of points along Y’, ‘Number of points along Z’). These parameters are used to define the spacing of the grid points in the Y-Z plane (i.e. the rotor plane).

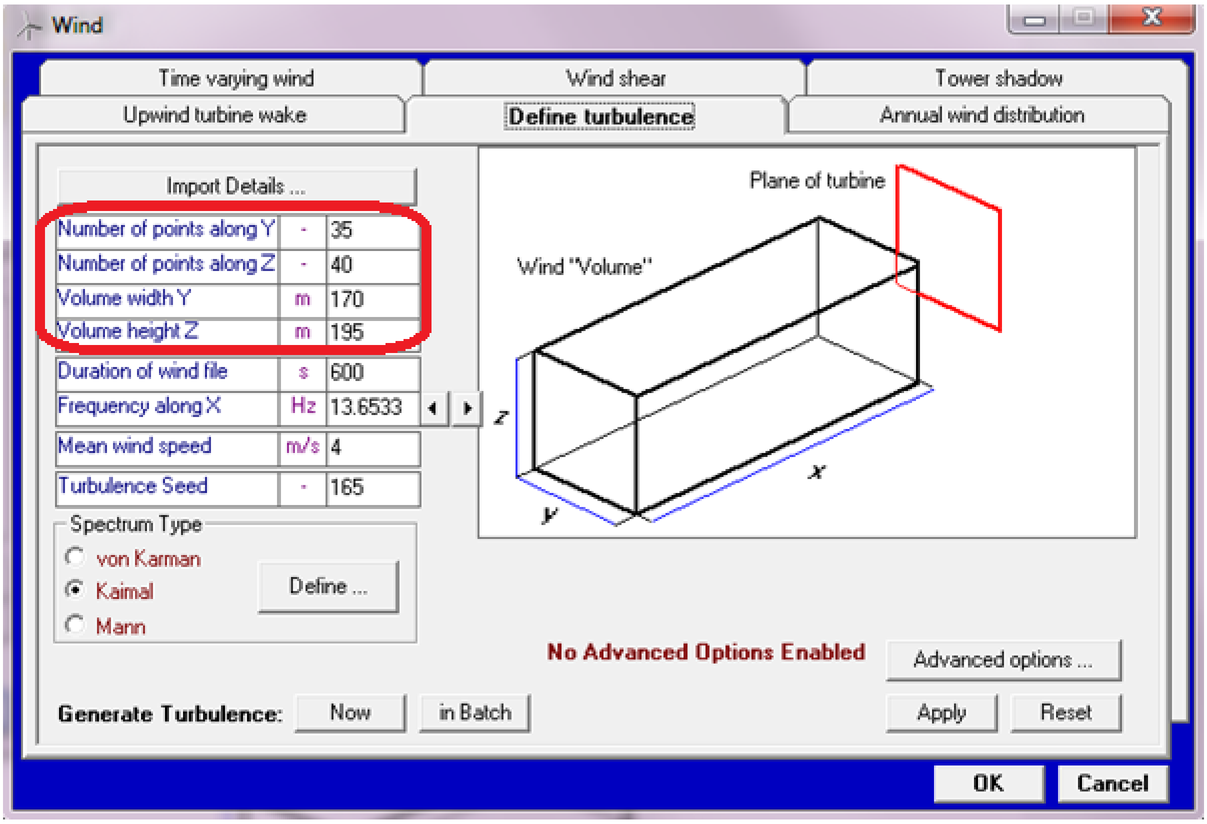

Figure 2-2 Bladed turbulence input screen

This report uses the following notation:

NY = Number of points along Y (i.e. laterally)

NZ = Number of points along Z (i.e. vertically)

Δy = lateral grid point spacing = (‘Volume width Y’) / (NY – 1)

Δz = vertical grid point spacing = (‘Volume width Z’) / (NZ – 1)

NYZ = total number of grid points = NY*NZ

The x-direction is parallel to the mean wind direction.

3 IMPLEMENTATION OF THE VEERS METHOD IN BLADED

The basis of the Veers method is to generate a turbulence time history for each grid point, such that the desired spectral and coherence properties are reproduced in the resulting spatial wind field. Firstly the frequency range is split up into discrete frequencies, from the lowest, defined by the length of the required wind file, to the highest, which is defined by the required spacing of points in the x-direction (the Nyquist frequency). Then for each grid point, the time history is generated as a linear superposition of sinusoids, one at each discrete frequency, with its amplitude determined by the magnitude of the spectrum at that frequency, and its phase determined by a random number generator (different realisations of turbulence with the same spectral properties are then achieved by using different random number seeds).

For each discrete frequency, let $\underline{R}$ be a vector of random numbers of length NYZ, i.e. one random number for each grid point. If this vector is used to provide the phases of the sinusoids, the time histories at the different grid points will be uncorrelated. Using the Veers method, a matrix L (size NYZ x NYZ) is used to transform R into a new vector $\underline{P}$ = L $\underline{R}$, each element of which is made up of a linear combination of elements of $\underline{R}$, such that there is a certain correlation between the elements of $\underline{P}$. The matrix L is calculated for convenience as a lower triangular matrix such that $LL^T = H$. The matrix H is actually a (real square symmetric) matrix giving the coherence (at the given frequency) between each pair of grid points, and being of size NYZ x NYZ, the decompositon of this matrix to give L (at each frequency) is by far the most time-consuming part of the Veers process.

At high frequencies, the coherence, even between adjacent grid points, becomes very small. Then H tends to an identity matrix, and L is also an identity matrix. Therefore this time-consuming calculation can be avoided for all frequencies where all the pair-wise coherences are small enough. Bladed uses a tolerance to determine whether any pair-wise coherence is small enough to ignore, and if all of them are small enough, the matrix decomposition is omitted and L is taken to be the identity matrix.

The problem which is the subject of this report concerns the algorithm used to determine whether all the pair-wise coherences at a particular frequency are small enough to ignore.

3.1 Calculation of the coherence matrix

Since a regular grid is used in Bladed, the matrix H will contain many repeated values. For illustration, an example grid is shown below in Figure 3-1. The H value corresponding to the red pair of points will be identical to the H value corresponding to the green pair, because the spacings are identical. (To be precise, each pair of points provides two identical entries in H, reflected one each side of the diagonal, which is why H is symmetric.)

In fact, every element of H is also an element of the much smaller coherence matrix C which gives pair-wise coherence only as a function of the spacings between points in the Y and Z directions, and not depending on absolute position in the grid. This is a matrix of size NY x NZ, and can be thought of as giving the coherence between one corner point and every other point in the grid. This matrix contains NYZ values, of which just one is unity (representing the coherence between the corner point and itself). In the general case, these NYZ values are all different, each one of which must be calculated from the coherence function. Bladed calculates C, and uses its elements to populate the H matrix, and hence L is calculated, and used to transform a random vectore $\underline{R}$ into correlated phases $\underline{P}$.

As it calculates each element of C, Bladed counts how many of them are small enough to ignore (according to default tolerance settings). If all of them are small enough (apart from the one which is unity), the creation and decomposition of the H matrix is skipped for that frequency, and P is just populated with independent random phases.

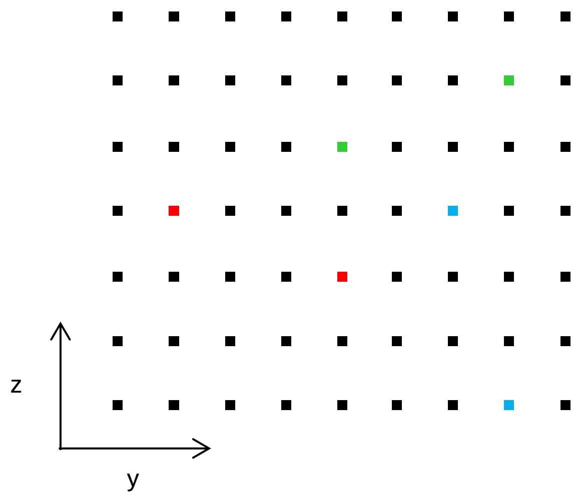

Figure 3-1 – Example wind file grid with NY = 9, NZ = 7

There is a special case in which Bladed makes use of Y-Z symmetry. For this to occur, the grid point spacings must be identical in the Y and Z directions ($\Delta y = \Delta z$), and also the coherence function must be symmetrical between the Y and Z directions, which means that the length scales are the same in those two directions. In this case, the coherence between the blue pair of points in Figure 3-1 will be identical to the coherence between the red points (and the green points). Note that C cannot be called a symmetric matrix in the normal sense in the case that NY $\neq$ NZ; however we will still refer to this here as a "symmetrical" case. The C matrix then consists of a truly symmetric square matrix plus some additional columns (if NY > NZ) or rows (if NZ > NY). Because part of the matrix is symmetric, the number of independent pair-wise coherences which need to be calculated is no longer NYZ (including the unity value), but a smaller number N_{indep} calculated as follows:

If NY = NZ = N: $N_{indep} = ½N^2 + ½N$

If NY > NZ: $N_{indep} = ½NZ^2 + ½NZ + (NY\text{-}NZ)*NZ$

If NZ > NY: $N_{indep} = ½NY^2 + ½NY + (NZ\text{-}NY)*NY$

3.2 The problem with earlier Bladed versions

The problem which this report addresses concerns the difference between "symmetrical" and "non-symmetrical" situations. Bladed's implementation of the Veers method dates back over two decades, at which time turbulence was only applied to the turbine rotor, not to the tower, so the grid of points was always square and centred on the hub: as well as NY = NZ, identical spacings were always used ($\Delta y = \Delta z$). Furthermore, the coherence model was always such that the length scales were identical in the Y and Z directions. Consequently, only "symmetrical" cases were ever considered. As the C matrix was calculated, symmetry was invoked to avoid calculating some of the elements twice, i.e. only the independent elements were calculated, and the number of these independent elements which were small enough to ignore were counted. If for any frequency this number reached N_{indep} – 1, the turbulence was assumed fully incoherent at this frequency and the H-decomposition could be omitted.

In later years, firstly the Improved von Karman model was introduced, in which the length scales are no longer the same in the Y and Z directions; secondly, with the advent of higher-definition modelling of the tower it became common practice to apply turbulence also to the tower: wind files were then no longer square, and in particular Δy and Δz were often different. For both reasons, “non-symmetrical” situations started to become common. Now the full set of NYZ coherence values had to be calculated, and the number of elements small enough to ignore was calculated correctly; but the criterion for determining whether the wind at a given frequency could be considered fully incoherent still compared this number to N_{indep} – 1 (as defined above), instead of to the larger number NYZ - 1 as would be appropriate for the “non-symmetrical” case. Consequently, the turbulence was deemed fully incoherent already at some lower frequency, when some of the coherences were still significantly non-zero. Effectively, these non-zero coherences were erroneously ignored at all frequencies where the number of ‘small’ values had reached N_{indep} – 1 but had not yet reached NYZ – 1. This was corrected in Bladed 4.4.

3.3 Summary of the problem

In summary, “symmetrical” wind files have always been correct, but “non-symmetrical” wind files calculated by Bladed 4.3 or earlier erroneously ignored some of the coherence in the wind above a certain frequency, where:

- A “symmetrical” wind file is one with <u>equal</u> grid point spacings in the Y and Z directions ($\Delta y = \Delta z$) **and** <u>equal</u> length scales in the Y and Z directions as is the case for the Kaimal model;
- A “non-symmetrical” wind file is one with <u>unequal</u> grid point spacings in the Y and Z directions ($\Delta y \neq \Delta z$) **and/or** <u>unequal</u> length scales in the Y and Z directions as is the case for the Improved von Karman model.

The frequency at which coherences started to be erroneously ignored is not easy to define as it depends on the size of the grid, the grid spacings, and (for the Improved von Karman model) the length scales. However, the smaller the ratio N_{indep}/NYZ, the lower the frequency at which the problem starts to occur, and since N_{indep} is smallest when NY = NZ (when the fraction approaches ½ for large N), we can say that the problem will be most apparent in this situation.

Wind files generated with Bladed 4.4 or later do not have this problem. Note that such wind files can still be used as input to simulations run with Bladed 4.3 or earlier. Therefore if, for any reason, it is desired to use Bladed 4.3 or earlier for simulations, it is recommended to run them using wind files generated with Bladed 4.4 or later, at least if the wind file setup is “non-symmetrical”.

4 COHERENCE COMPARISON

As a means to ensure that the coherence has now been implemented correctly when generating turbulent wind files in Bladed 4.4 and also to check the extent of the problem with the coherence in wind files in older Bladed versions, a comparison of the measured coherence from Bladed wind files was made with the theoretical wind model coherence function.

The coherence of two points in the wind files can be measured by dividing the complex magnitude of the cross-spectral density of the longitudinal wind velocity components at two spatially separated points by the root of the product of the spectra at each of the points /1/. (N.B. in this case $S_{11} = S_{22}$)

$$C(\Delta r,\ n) = \frac{|S_{12}(n)|}{\sqrt{S_{11}(n)S_{22}(n)}}$$

A Matlab script was used to calculate the coherence between two points in a Bladed wind file and compare it with the theoretical coherence. Wind files created using Bladed 4.4 (which include the coherence correction) and also wind files created in Bladed 4.3 with unequal grid spacing (i.e. which were found to have a problem with the calculation of the coherence) were examined.

When calculating the coherence for a single pair of points the coherence can be noisy and it's difficult to observe the trend. As a means to improve this, the coherence was measured at a large number of pairs of points in each wind file (up to 900 pairs of points were used) and averaged. This method of averaging has been used both in Figure 4-1 and Figure 4-2

The theoretical Kaimal turbulence model coherence function is shown below /2/

$$\mathrm{Coh}(r,f) = \exp\left[-12\left(\left(f \cdot r / V_{\mathrm{hub}}\right)^2 + \left(0{,}12\, r / L_c\right)^2\right)^{0{,}5}\right]$$

r is the magnitude of the projection of the separation vector between the two points on to a plane normal to the average wind direction;

f is the frequency in Hertz;

$L_c = 8{,}1\Lambda_1$ is the coherence scale parameter.

The theoretical Improved Von Karman coherence function is shown overleaf /1/

$$C_u(\Delta r, n) = 0.994(A_{5/6}(\eta_u) - \tfrac{1}{2}\eta_u^{\ 5/3} A_{1/6}(\eta_u))$$

Here $A_j(x) = x^j K_j(x)$ where K is a fractional order modified Bessel function, and

$$\eta_i = \sqrt{\left(\frac{0.747\Delta r}{2L_i}\right)^2 + \left(c\frac{2\pi n\Delta r}{U}\right)^2} \qquad \text{for } i = u$$

The local length scale $L_u(\Delta r,n)$ is defined by:

$$L_u(\Delta r, n) = \sqrt{\frac{({}^yL_u\Delta y)^2 + ({}^zL_u\Delta z)^2}{\Delta y^2 + \Delta z^2}}$$

while

$$c = \max(1.0, \frac{1.6(\Delta r / 2L_u)^{0.13}}{\eta_0^{\ b}})$$

with

$$b = 0.35(\Delta r / 2L_u)^{0.2}$$

and

$$\eta_0 = \sqrt{\left(\frac{0.747\Delta r}{2L_u}\right)^2 + \left(\frac{2\pi n\Delta r}{U}\right)^2}$$

Δy and Δz are the lateral and vertical components of the separation Δr, and ${}^yL_u$ and ${}^zL_u$ are the lateral and vertical length scales for the longitudinal component of turbulence.

Figure 4-1 shows a comparison of the theoretical Kaimal coherence with coherence measured from Bladed 4.3 and Bladed 4.6 wind files. Figure 4-2 shows a comparison of the theoretical Improved Von Karman coherence with coherence measured from Bladed 4.3 and Bladed 4.6 wind files. Note that the wind file creation code has not been modified between versions 4.4 and 4.6 and thus these versions are equivalent.

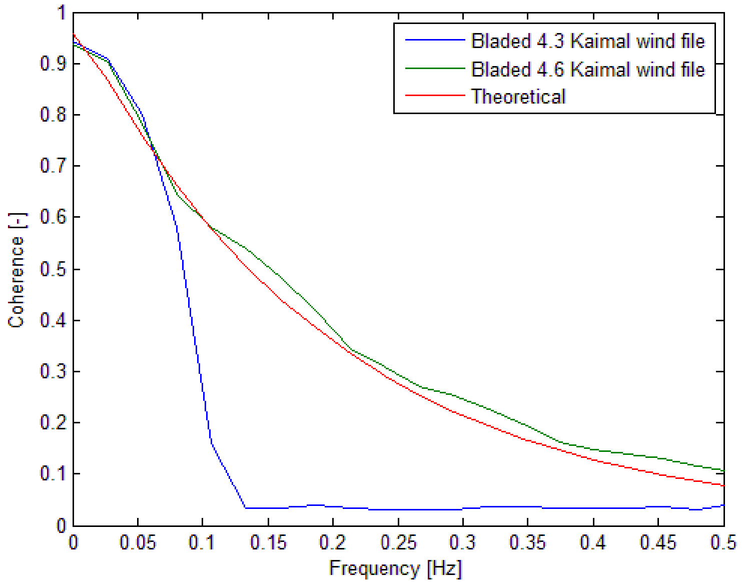

Figure 4-1 – Coherence of adjacent grid point estimated from Bladed Kaimal wind file compared against the theoretical Kaimal coherence for a "non-symmetrical" case with grid spacing 5.1m by 5.15m. Wind speed 24ms.

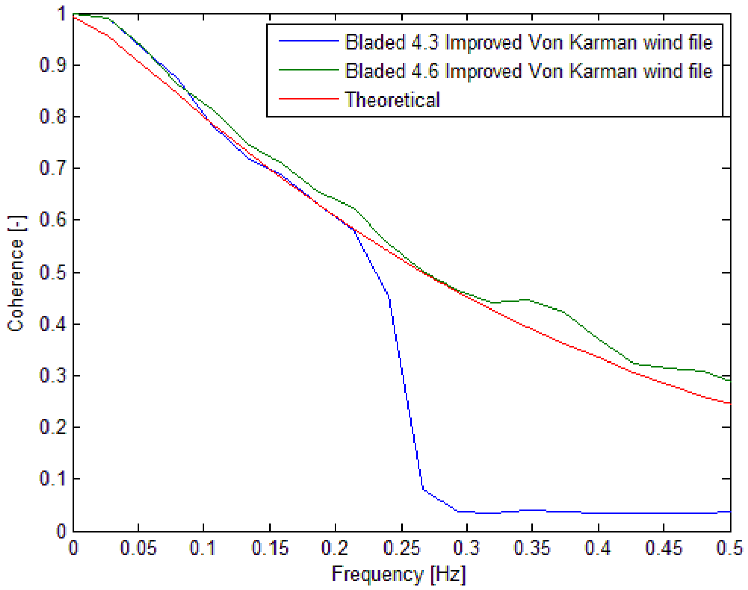

Figure 4-2 - Coherence of adjacent grid point estimated from Bladed Von Karman wind files compared against the theoretical Von Karman coherence with grid spacing 5.15m by 5.13m. Wind speed 24ms.

In all cases, the coherence is modelled correctly at the lowest frequencies, but at higher frequencies, the measured coherence from the wind files created in Bladed 4.3 then drops off rapidly to zero at all higher frequencies. This confirms that the coherence in Bladed 4.3 and earlier was not calculating the coherence correctly for ‘non-symmetrical’ cases (as defined above. This means that the higher-frequency variations within the time series at each of the grid points were uncorrelated, which can be interpreted as meaning that if a ‘relatively small’ gust is seen at one grid point, no trace of it will appear at other nearby grid points, whereas in reality this should only be the case for ‘very small’ gusts (smaller than the grid point spacing). In contrast, ‘large’ gusts (represented by the lowest frequencies) will be detected correctly at adjacent grid points. This means that the wind field superficially looks reasonable: slow variations are visible right across the rotor, as expected, and the variations at each grid point taken in isolation also look correct at all frequencies as they have the correct spectral properties; only the high-frequency coherence detail is incorrect. This may seem quite subtle, but in some situations, unfortunately, the effect upon the simulated turbine loads can be significant, as demonstrated in the next section.

We can also observe from these figures that the measured coherence curve from Bladed 4.6 fits very well with the theoretical curve. This means that these wind files do model the effects of wind gusts ‘correctly’ and that the wind generation algorithm is now working correctly, i.e. since version 4.4. (To be precise, ‘correctly’ in this context means as defined by the chosen coherence model; note that all these models are partly empirical, and although widely accepted as realistic they do not actually represent the physics of the flow correctly in all particulars.)

Note that the above description is for the longitudinal component of turbulence, but the issue also applies to the lateral and vertical components (the spectra and coherence functions are different for each component, but the principle is the same). In the Veers method, all three components of turbulence are generated independently of one another (this is just one of the non-physical aspects of the method), and so the frequency above which the coherences erroneously fall to zero in Bladed 4.3 would be different for each of the three components.

5 LOADS COMPARISON

To investigate the differences in loads that might be expected due to the change in coherence algorithm, a number of studies have been carried out over a range of turbine ratings and diameters. Firstly, damage equivalent loads were compared as described in Section 5.1 and also load spectra were examined as described in Section 5.2. Finally a study was conducted in Bladed 4.6 to check how the grid definition may affect the loads observed, descibed in Section 5.3.

5.1 Comparison of damage equivalent loads

5.1.1 Kaimal model comparison

Damage equivalent loads were calculated for a number of turbines (ratings between 2MW and 7MW and a range of wind classes from IA to IVB) using “non-symmetrical” (i.e. $\Delta y \neq \Delta z$ in this case) Kaimal wind files created in Bladed 4.3 and these simulations were then repeated using “symmetrical” ($\Delta y = \Delta z$) Kaimal wind files created in Bladed 4.4. The results were postprocessed and the percentage difference in the damage equivalent loads were calculated. Maximum and minimum values for each load component over the range of turbines were plotted in Figure 5-1. A positive percentage difference indicates that the DEL created using the wind file which includes the coherence correction result from Bladed 4.4 is larger.

From this figure the effects of the change in the coherence can be seen especially in side-side fatigue loads (typically non-driving components) such as tower base Mx, tower top Fy and tower base Fy. This effect is also very dependent on the rotor size and wind class and both of these factors contribute to the different magnitudes of differences in damage equivalent loads observed. In general, it is not possible to predict exactly how the DELs may be affected for a particular turbine model without specific investigation.

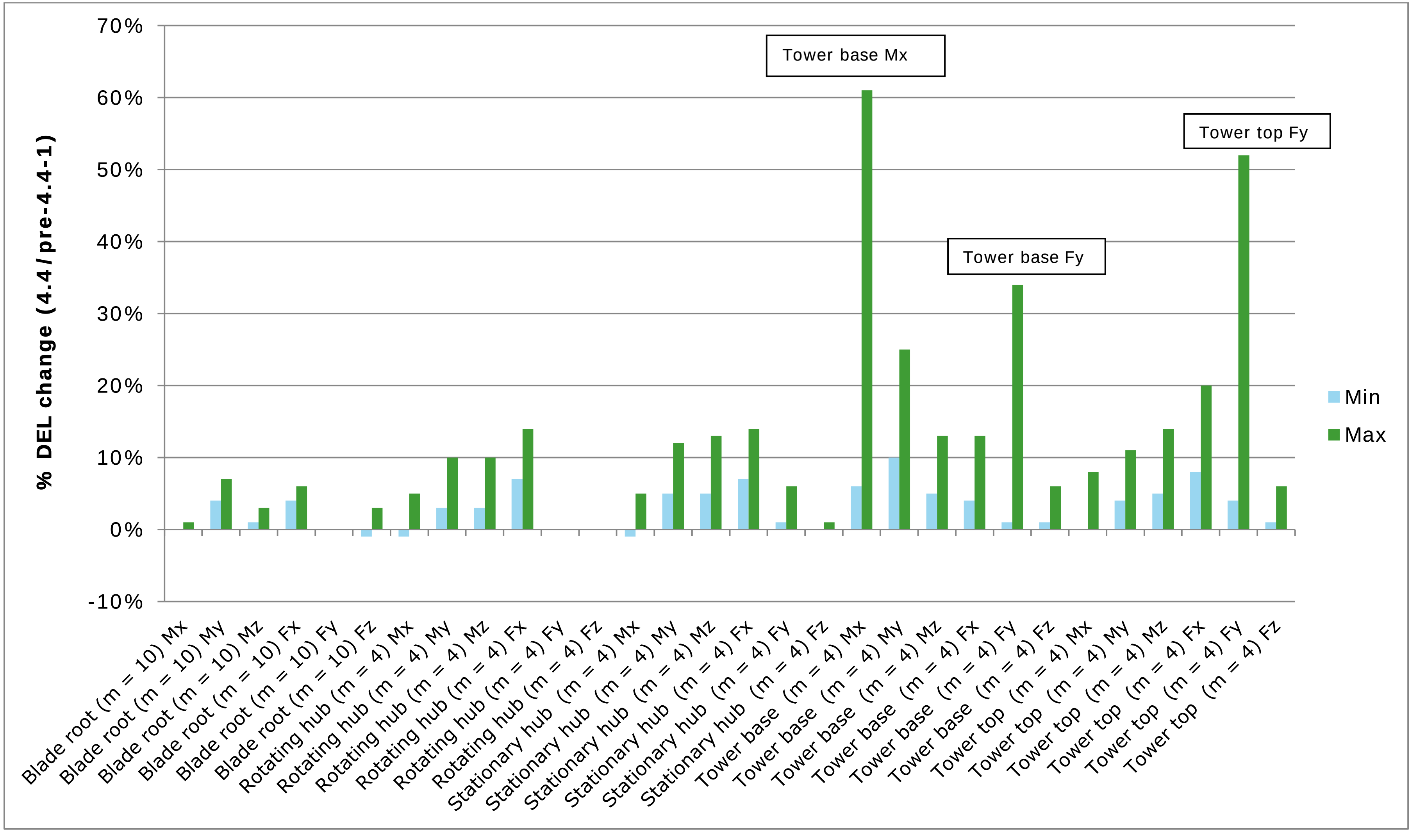

Figure 5-1 Kaimal model comparison – Maximum and minimum percentage change in damage equivalent loads from a range of turbine sizes (2MW - 7MW) and a range of wind classes (IA – IVB).

5.1.2 Von Karman model comparison

A similar study over a range of wind turbine ratings and wind classes was conducted using the Von Karman model. The following wind files were created and used:

- Improved Von Karman wind files created in Bladed 4.3 with even grid spacing ($\Delta y = \Delta z$)
- Improved Von Karman wind files created in Bladed 4.3 with unequal grid spacing ($\Delta y \neq \Delta z$)
- Improved Von Karman wind files created in Bladed 4.6 with even grid spacing ($\Delta y = \Delta z$)

It should be noted that all of these cases have length scales which are unequal in the y and z directions (i.e. each of these files is "unsymmetrical").

The results were postprocessed and the percentage difference in the damage equivalent loads were calculated. Figure 5-2 shows a plot of percentage comparison of DELs i.e. (IVK Bladed 4.6 even spacing/IVK Bladed 4.3 unequal spacing)-1. Figure 5-3 shows a plot of percentage comparison of DELs i.e (IVK Bladed 4.6 even spacing/IVK Bladed 4.3 even spacing)-1.

From these plots it is evident that there are similar trends to those observed in the Kaimal comparison where the load components which are most affected are those in the side-side direction i.e. tower base Mx, tower base Fy and tower top Fy. It is also evident that in the case of the Improved Von Karman model, the percentage load differences are smaller than those observed with the Kaimal model. It can also be seen that the percentage load differences are generally larger in Figure 5-3: this confirms the prediction made in Section 3.3 where least coherence would be calculated for the case where NY = NZ and the length scales are not equal in the y and z directions.

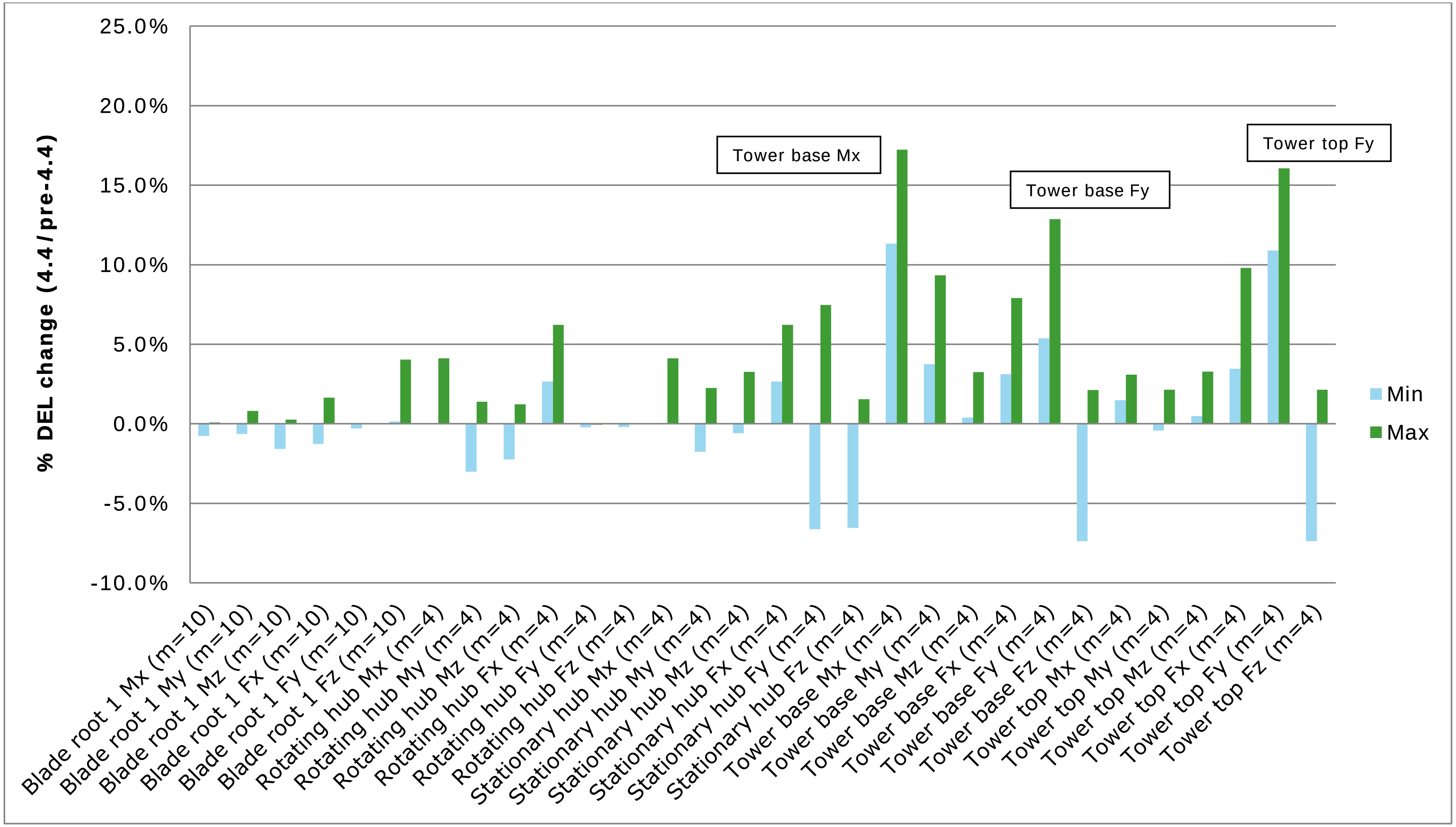

Figure 5-2 – Percentage change in damage equivalent loads for the Von Karman model. (IVK Bladed 4.6 even spacing / IVK Bladed 4.3 unequal spacing)-1

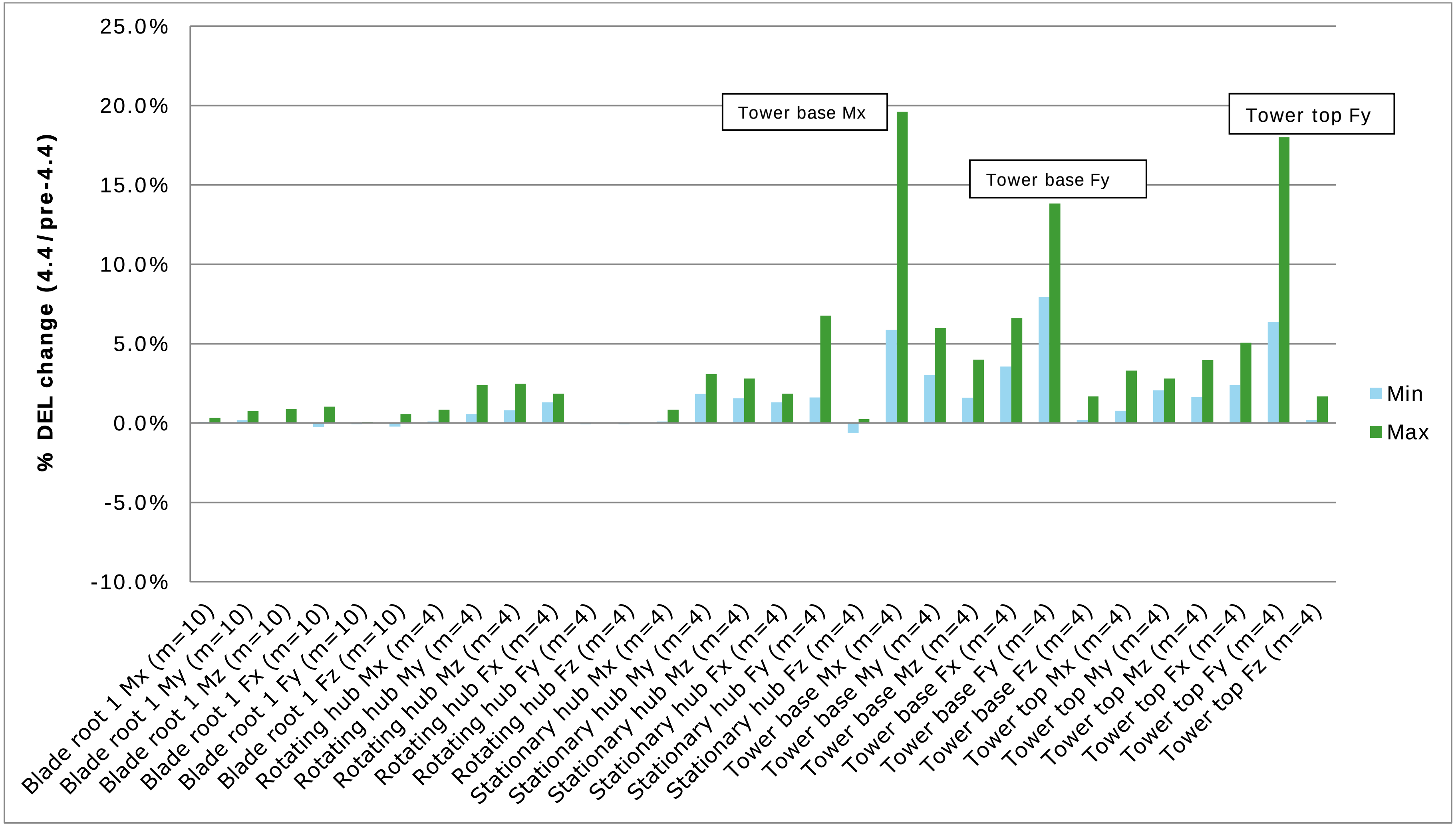

Figure 5-3 Percentage change in damage equivalent loads for the Von Karman model. (IVK Bladed 4.6 even spacing / IVK Bladed 4.3 even spacing)-1

5.1.3 Comparison of contributing load cases to the DEL

Examples of normalised DELs contributions across a typical set of fatigue load cases are shown in Figure 5-4 to Figure 5-5 for one of the turbines investigated. The load components shown are percentage changes in tower base Mx and tower base My, comparing identical sets of simulations run with the same Bladed version, but using input wind files created both in 4.6 and 4.3, both with a ‘square’ grid, i.e. $\Delta y = \Delta z$, although the cases are still “unsymmetrical” because of the Improved von Karman length scales. It can be seen that in the case of the tower base Mx, the load cases which are most affected are the DLC 1.2 (i.e. power production using the normal turbulence model) between rated wind speed and cut out wind speeds.

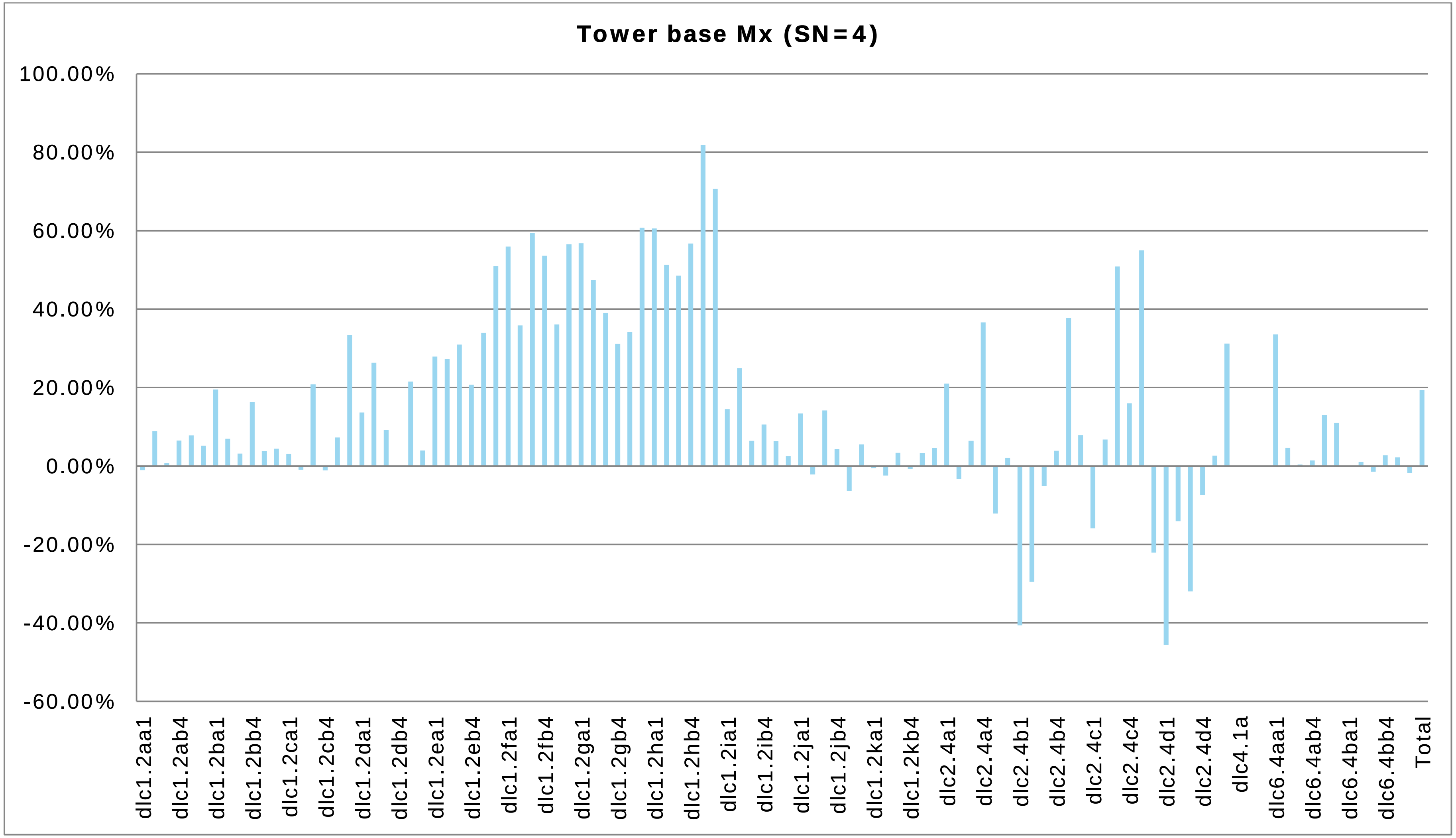

Figure 5-4 Example comparison of contributing damage equivalent loads ((VK_new_sq/VK_old_sq)-1)

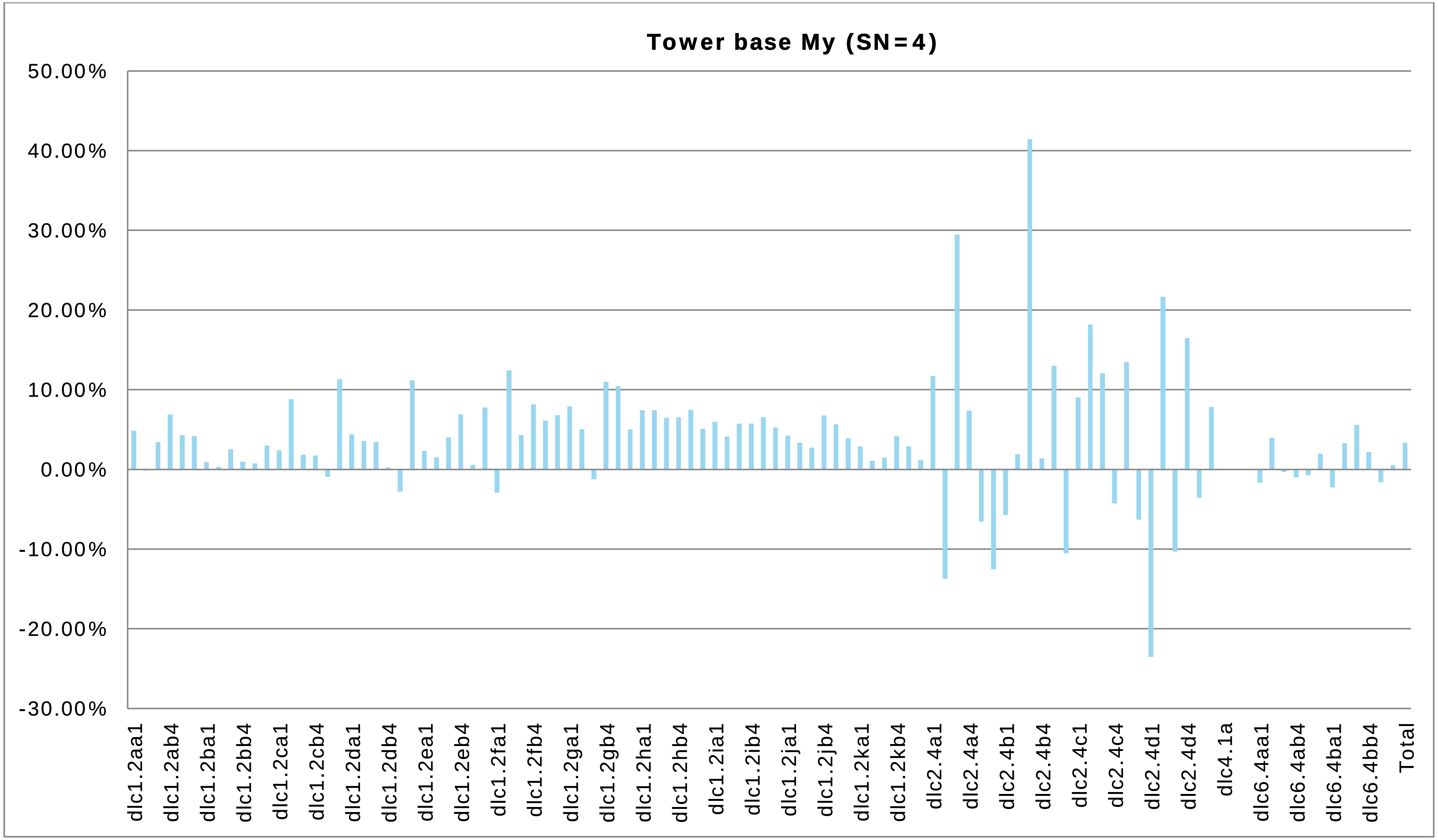

Figure 5-5 Example comparison of contributing damage equivalent loads ((VK_new_sq / VK_old_sq)-1)

5.2 Load spectra

The differences in loading which occur due to using wind files before and after the coherence modification can also be observed in the load spectra. Figure 5-6 shows an example autospectrum for tower base Mx for one of the turbines investigated, where the black line is for a simulation which uses Kaimal wind files from Bladed 4.4. The red line is for the equivalent simulation which uses a “non-symmetrical” Kaimal wind file from Bladed 4.3.

From the spectra we can see a reasonable match for the spectral peaks that relate to rotor harmonics. These peaks include contributions from rotor imbalance, wind shear and tower shadow which are not affected by the wind file modification. However it’s also apparent that there are large differences in the troughs of the spectra where the black line (wind files from Bladed 4.3) falls significantly below the spectra created with Bladed 4.4 which includes the coherence modification. The frequency content in the loading at the troughs is typically driven by wind turbulence and it can be deduced that the difference in these troughs is due to the lack of coherency between spatial points for the case which uses the wind file from Bladed 4.3.

A similar plot which shows the comparison for the Improved Von Karman model is shown in Figure 5-7. The black line is for a simulation which uses Improved Von Karman wind files from Bladed 4.4. The red line is for the equivalent simulation which uses a non-square ($\Delta y \neq \Delta z$) Improved Von Karman wind file from Bladed 4.3. The green line is for the equivalent simulation which uses a square ($\Delta y = \Delta z$) Improved Von Karman wind file from Bladed 4.3. This plot shows similar trends to those discussed above i.e. the peaks match well with disagreement in the troughs.

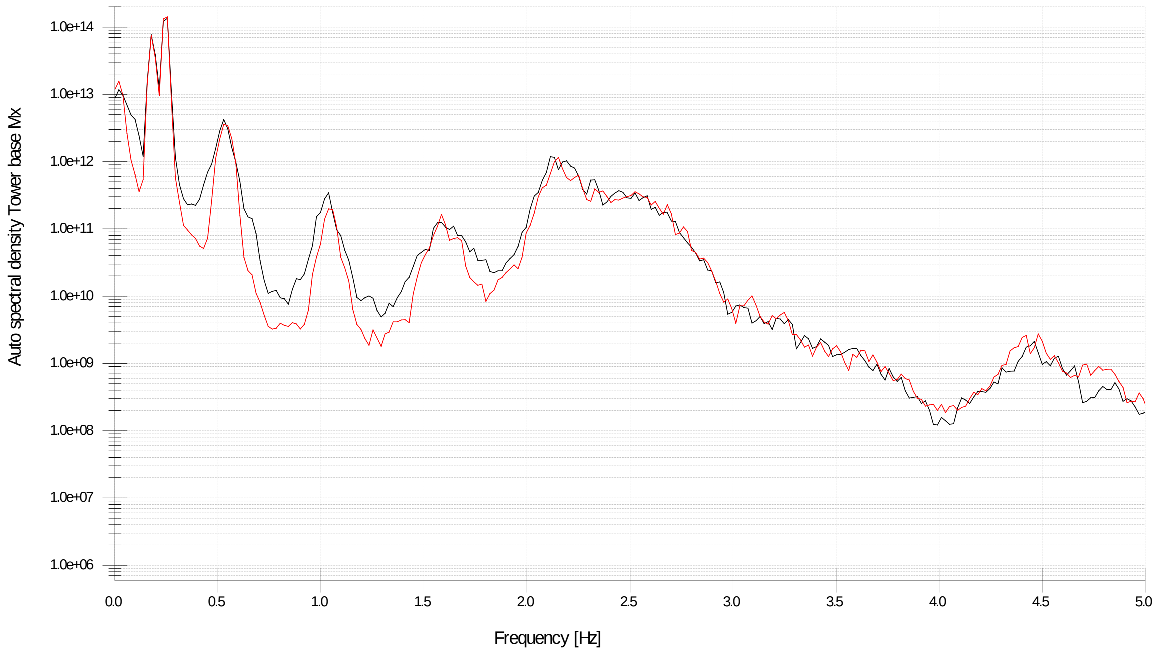

Figure 5-6 – Kaimal model comparison spectra for Tower base Mx for an example large turbine. Black: wind files from Bladed 4.4, red: "non-symmetrical" (Δy ≠ Δz) wind files from Bladed 4.3.

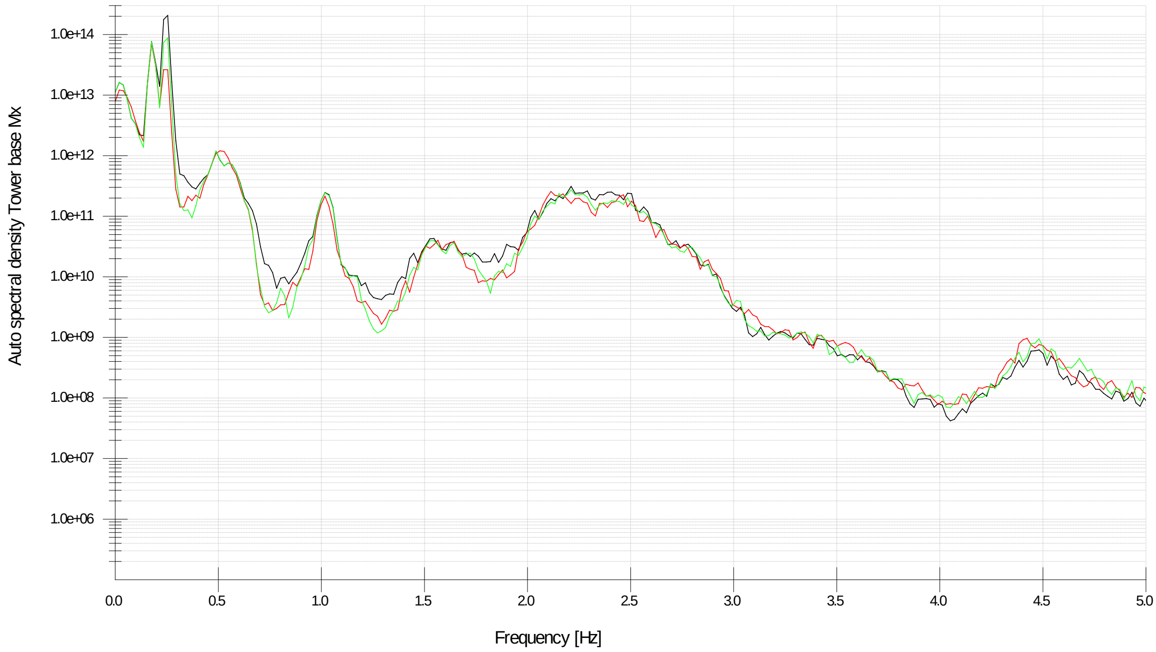

Figure 5-7 – Von Karman model comparison spectra for Tower base Mx for an example large turbine, Black: Bladed 4.4 square (Δy = Δz), red: non-square (Δy ≠ Δz) Bladed 4.3, green: square (Δy = Δz) Bladed 4.3.

5.3 Von Karman spacing in Bladed 4.6

As an additional topic studied here, it has been observed that changing the grid spacing for Improved Von Karman wind files, even after the correction in the coherency calculations, can result in differences in the time series and therefore an increase in loading for a particular simulation. In order to understand this effect better two simulations were run at rated wind speed in Bladed 4.6: one using a 5x5 improved Von Karman wind file, the other using the same wind file with the grid spacing modified to 5x7.5m. The percentage changes in the DEL are shown below.

Inverse SN slope [.]	Tower base Mx	Tower base My
3	1%	10%
4	2%	13%
5	2%	15%
6	2%	17%
7	2%	19%
8	1%	20%
9	0%	21%
10	-1%	22%
11	-2%	23%
12	-2%	24%

Table 5-1 – Percentage change in DEL (one simulation)

Changing the spacing in a Von Karman wind file, and hence the number of grid points, results in a different random number sequence and is therefore analogous to changing the turbulence seed, so finding a difference in load is not unexpected when examining one simulation in isolation. By repeating this test using a complete set of DLC 1.2 simulations (power production with the normal turbulence model) then the results will converge to within limits as one might expect from seed variability. To prove this, the above study has been extended to a full dlc1.2 load case and the results are shown in the table below.

Inverse SN slope [.]	Tower base Mx	Tower base My
3	-1%	-1%
4	-1%	-2%
5	0%	-2%
6	0%	-2%
7	1%	-2%
8	1%	-2%
9	2%	-2%
10	2%	-2%
11	2%	-2%
12	2%	-2%

Table 5-2 – Percentage change in DEL (set of DLC 1.2 simulations)

6 CONCLUSIONS

This report gives an overview of the coherence modification in Bladed 4.4 including in depth discussion of the changes made to the code, a verification that the coherence now conforms to the coherence as defined in the standards and also an overview of how this change affects the turbine fatigue loading.

A summary of the important points to note:

- **Kaimal model:** coherence was not modelled fully when creating wind files using a non-square grid (i.e. $\Delta y \neq \Delta z$) in Bladed versions prior to version 4.4
- **Improved Von Karman:** coherence was not modelled fully in Bladed versions prior to 4.4 in either symmetric or non-summetric grid cases. The effect is most pronounced when the spatial grid has an equal number of points laterally and vertically (i.e. Ny = Nz)
- Effects in the loading are predominantly seen in side-side fatigue loads (which are typically non-design-driving)
- The load effects are very turbine-dependent (rotor size, wind class, ...)

It is recommended that future turbine load and performance calculations are carried out using the latest Bladed version available. Specifically, wind files created with Bladed 4.4 or later should be used even if an older version of Bladed (“dtbladed.exe”) is used to run the turbine simulations. This is possible because the format of the wind files has not changed, and there are no other inconsistencies.

7 REFERENCES

/1/ "Wind energy handbook", T. Burton, N. Jenkins, D. Sharpe and E. Bossanyi, 2nd edition, 2011 (John Wiley & Sons).

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/3/ Veers P S, "Three dimensional wind simulation", SAND88 - 0152, Sandia National Laboratories, March 1988.

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