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MLife Theory Manual for Version 1.00

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Nomenclature

A	availability factor of the wind turbine
c_j	number of occurrences of the j[th] time-series when the time-series is classified as a discrete design load case (DLC)
D	lifetime fatigue damage
D^{Life}	binned lifetime fatigue damage without using Goodman correction
D^{LifeF}	binned lifetime fatigue damage with Goodman-corrected load ranges about a fixed-mean
D^{Life0}	binned lifetime fatigue damage with Goodman-corrected load ranges about a zero fixed-mean
D_j^{Life}	fatigue damage over the design lifetime caused by time-series j with uncorrected load ranges
D_j^{LifeF}	fatigue damage over the design lifetime caused by time-series j with Goodman-corrected load ranges about a fixed-mean
D_j^{Life0}	fatigue damage over the design lifetime caused by time-series j with Goodman-corrected load ranges about a zero fixed-mean
D_j^{ST}	fatigue damage caused by time-series j based cycles with uncorrected load ranges
D_j^{STF}	fatigue damage caused by time-series j based cycles with Goodman corrected load ranges about a fixed-mean
D_j^{ST0}	fatigue damage caused by time-series j based cycles with Goodman corrected load ranges about a zero fixed-mean
DEL^{Life}	lifetime damage equivalent load without Goodman correction
DEL^{LifeF}	lifetime damage equivalent load with Goodman-corrected load ranges about a fixed-mean
DEL^{Life0}	lifetime damage equivalent load with Goodman-corrected load ranges about a zero fixed-mean
DEL_j^{ST}	short-term damage equivalent load for time-series j without Goodman correction
DEL_j^{STF}	short-term damage equivalent load for time-series j with Goodman-corrected load ranges about a fixed-mean
DEL_j^{ST0}	short-term damage equivalent load for time-series j with Goodman-corrected load ranges about a zero fixed-mean
DR_{agg}^{ST}	short-term aggregate damage-rate without Goodman correction
DR_j^{ST}	short-term damage-rate without Goodman correction
DR_j^{STF}	short-term damage-rate with Goodman-corrected load ranges about a fixed-mean
DR_j^{ST0}	short-term damage-rate with Goodman-corrected load ranges about a zero fixed-mean
f^{eq}	equivalent frequency of damage equivalent load
f_j^{Life}	lifetime damage count extrapolation factor for time-series j
i	fatigue cycle index
j	time-series index
k	binned-cycle index
l	wind speed bin index
L_i^M	mean load of cycle i
L_{ji}^M	mean load ith cycle of the jth time-series
L^{MF}	fixed-mean load
L_i^R	load range for cycle i
L_k^R	midpoint of the k[th] load range bin
L_i^{RF}	Goodman-corrected load range about a fixed-mean for cycle i
L_{ji}^R	load range for cycle i and time-series j
L_{ji}^{RF}	Goodman-corrected load range about a fixed-mean for cycle i time-series j
L_{ji}^{R0}	Goodman-corrected load range about a zero fixed-mean for cycle i time-series j
L_{max}^R	the maximum load range across all time series
L^{ult}	ultimate load
m	Whöler Exponent
n_i	damage count for cycle i
n_{ji}	damage count for cycle i and time-series j
n_{jk}	damage count for load range bin k and time-series j
n_{jk}^F	damage count for Goodman-corrected load ranges about a fixed-mean for load range bin k and time-series j
n_{jk}^0	damage count for Goodman-corrected load ranges about a zero fixed-mean for load range bin k and time-series j
n_{ji}^{Life}	extrapolated damage count for cycle i and time-series j across the design lifetime
n_{jk}^{Life}	extrapolated damage count for load range bin k and time-series j
n_{jk}^{LifeF}	extrapolated damage count for Goodman-corrected load ranges about a fixed-mean for load range bin k and time-series j
n_{jk}^{Life0}	extrapolated damage count for Goodman-corrected load ranges about a zero fixed-mean for load range bin k and time-series j
$n^{Life,eq}$	lifetime equivalent counts
n^R	number of load range bins
n_j^{STeq}	equivalent counts for time-series j
n^{V1}	number of wind speed bins in the range $[0 - V_{in}]$
n^{V2}	number of wind speed bins in the range $(V_{in} - V_{out}]$
n^{V3}	number of wind speed bins in the range $(V_{out} - V_{max}]$
N^{eq}	number of equivalent cycles to failure
N_i	number of cycles until failure for the load range of cycle i
N_{ji}	number of cycles until failure for the load range of cycle i and time-series j

N_k	number of cycles to failure for load-range bin k
N_j^{eq}	number of equivalent cycles to failure for time-series j
p_l^v	probability factor for wind speed bin l
T_j	elapsed time of time-series j
T_l	total time spent in windspeed bin l
T^{Fail}	time until failure
T^{Life}	design lifetime (seconds)
V_{ave}	median wind speed of the Weibull distribution
V_{in}	turbine cut-in wind speed
V_l	midpoint wind speed of wind speed bin l
V_{max}	maximum wind speed in the binned distribution
V_{out}	turbine cut-out wind speed
V_j^{ave}	average wind speed of time-series j
β	Weibull distribution shape parameter
Γ	gamma function
Δ^R	load range bin width
Δ_{max}^R	maximum load range bin width
Δ^{V1}	wind speed bin width for wind speeds in the range
Δ^{V2}	wind speed bin width for wind speeds in the range
Δ^{V3}	wind speed bin width for wind speeds in the range
Δ^{Vmax}	maximum width of an wind speed bin
Δ_l^V	width of wind speed bin l
λ	Weibull distribution scale parameter
σ^V	standard deviation of the wind speed distribution

Introduction

MLife is a MATLAB-based tool created to post-process results from wind turbine tests, and aero-elastic, dynamic simulations. MLife computes statistical information and fatigue estimates for one or more time-series. We specifically designed MLife to handle hundreds of time-series. The program reads a text-based settings file in conjunction with one or more time-series data files. Alternatively, the program can read parameter variables which were created using MATLAB, outside of MLife.

The program generates results in the form of MATLAB variables, text output files, and/or Excel formatted files. This allows you to make other calculations or present the data in ways MLife cannot.

The fatigue calculations include short-term damage-equivalent loads (DELs) and damage rates, which are based on single time-series, lifetime DEL results based on the entire set of time-series data, and the accumulated lifetime damage and the time until failure.

Lifetime Damage

MLife follows the techniques outlined in Annex G of IEC 61400-1 edition 3. The program accumulates fatigue damage due to fluctuating loads over the design life of the wind turbine. These fluctuating loads are broken down into individual hysteresis cycles by matching local minima with local maxima in the time-series, e.g., rainflow counting. The cycles are characterized by a load-mean and range. We assume damage accumulates linearly with each of these cycles according to Miner's Rule (Palmgren and Miner). In this case the total damage from all cycles will be given by,

$$D = \sum_i \frac{n_i}{N_i(L_i^{RF})} \tag{1}$$

where $N_i(\cdot)$ denotes the number of cycles to failure, n_i the cycle count, and L_i^{RF} is the cycle's load range about a fixed load-mean value. The relationship between load range and cycles to failure (S-N curve) is modeled by

$$N_i = \left(\frac{L^{ult} - |L^{MF}|}{\left(\frac{1}{2} L_i^{RF}\right)} \right)^m \tag{2}$$

where L^{ult} is the ultimate design load of the component, L^{MF} is the fixed load-mean, and the Whöler exponent, m, is specific to the component under consideration.

The above formulations assume the fatigue cycles occur over a constant, or fixed, load-mean. However, the actual load cycles will occur over a spectrum of load means. Therefore, a correction must be made to the fatigue cycles' load ranges to analyze the data as if each cycle occurred about a fixed mean load. This is the Goodman correction for a Goodman exponent equal to one.

$$L_i^{RF} = L_i^{R} \left(\frac{L^{ult} - |L^{MF}|}{L^{ult} - |L_i^{M}|} \right) \tag{3}$$

where L_i^R is the ith cycle's range about a load mean of L_i^M.

From a practical standpoint, the lifetime damage of a wind turbine is estimated using a collection of time-series data which covers a much shorter time period than the design lifetime. To correctly estimate the total lifetime damage from these short input time-series, we must extrapolate the time-series damage-cycle counts over the design lifetime. Equations 1-3 are rewritten such that they now account for the accumulation of damage using one or more input time-series.

$$D_j^{Life} = \sum_i \frac{n_{ji}^{Life}}{N_{ji}} \tag{4}$$

$$D^{Life} = \sum_j D_j^{Life} \tag{5}$$

$$N_{ji} = \left(\frac{L^{ult} - |L^{MF}|}{\left(\frac{1}{2} L_{ji}^{RF}\right)} \right)^m \tag{6}$$

$$L_{ji}^{RF} = L_{ji}^{R} \left(\frac{L^{ult} - |L^{MF}|}{L^{ult} - |L_{ji}^{M}|} \right) \tag{7}$$

where D_j^{Life} is the extrapolated damage over the design lifetime due to the jth time-series, n_{ji}^{Life} is the extrapolated cycle counts, N_{ji} is the cycles to failure, and L_{ji}^R is range about a load mean of L_{ji}^M for the ith cycle in the jth time-series.

MLife also enables fatigue calculations to be performed without the Goodman correction. In this case, we simply set $L_{ji}^{RF} = L_{ji}^{R}$, and $L^{MF} = 0$ in equation 7. Using this option, the user must still specify the value of L^{ult}.

MLife extrapolates the damage cycle counts differently depending on the design load case (DLC) classification of the time-series data. MLife includes three generalized DLC classifications, which are intended to encompass the required fatigue-related DLCs of IEC 61400-1 edition 3. These are:

- Power Production (IEC DLC 1.2)
- Parked (IEC DLC 6.4)
- Discrete Events (IEC DLCs 2.4, 3.1, and 4.1)

Wind Speed Distribution and Binning

The power production and parked DLCs rely on the local wind speed distribution at the wind turbine site to extrapolate the damage-cycle counts. MLife models the wind with a Weibull distribution. This distribution is divided up into wind speed bins.

p_l^v is the probability of the wind speed falling into bin l and is given by differencing the cumulative distribution function at the bin edges,

$$p_l^v = e^{-\left(\frac{V_l - \frac{\Delta_l^V}{2}}{\lambda}\right)^{\beta}} - e^{-\left(\frac{V_l + \frac{\Delta_l^V}{2}}{\lambda}\right)^{\beta}} \tag{4}$$

where V_l is the wind speed at the midpoint of bin l, Δ_l^V is the width of bin l, β is the shape factor of the Weibull distribution (if $\beta = 2$ we have a Rayleigh distribution).

The shape factor is a function of the mean wind speed and standard deviation of the wind, such that,

$$\beta = \left(\frac{\sigma^V}{V_{ave}}\right)^{-1.086} \tag{5}$$

where V_{ave} is the median wind speed of the Weibull distribution, and σ^V is the standard deviation of the wind.

λ is the scale parameter and is set to,

$$\lambda = \frac{V_{ave}}{\Gamma\left(1 + \frac{1}{\beta}\right)} \tag{6}$$

where $\Gamma(*)$ is the gamma function.

To determine the wind speed binning in MLife, the user specifies the maximum width, Δ^{Vmax}, of any single wind speed bin. The binning is split into three separate sub-ranges, $[0 - V_{in}], (V_{in} - V_{out}], (V_{out} - V_{max}]$, where V_{in} is the turbine's cut-in wind speed, V_{out} is the turbine's cut-out wind speed, and V_{max} is the maximum wind speed to be included in the binned distribution. The bin width of each sub-range is computed by first determining the smallest number of bins which creates a bin width less than or equal to Δ^{Vmax}.

$$n^{V1} = ceil\left(\frac{V_{in}}{\Delta^{Vmax}}\right) \tag{7}$$

$$n^{V2} = ceil\left(\frac{V_{out} - V_{in}}{\Delta^{Vmax}}\right) \tag{8}$$

$$n^{V3} = ceil\left(\frac{V_{max} - V_{out}}{\Delta^{Vmax}}\right) \tag{9}$$

where n^{V1}, n^{V2}, and n^{V3} are the number of bins in the three sub-ranges, and $ceil(\cdot)$ is a ceiling function which returns the next largest integer value.

Once the number of bins in each sub-range is determined, the actual wind speed bin width of each sub-range is computed by dividing the sub-range's wind speed span by the number of bins,

$$\Delta^{V1} = \frac{V_{in}}{n^{V1}} \tag{10}$$

$$\Delta^{V2} = \frac{V_{out} - V_{in}}{n^{V2}} \tag{11}$$

$$\Delta^{V3} = \frac{V_{max} - V_{out}}{n^{V3}} \tag{12}$$

where Δ^{V1}, Δ^{V2}, and Δ^{V3} are the wind speed bin widths for the three sub-ranges.

In total, there are $n^{V1} + n^{V2} + n^{V3}$ wind speed bins across the range $[0, V_{max}]$. The data from a time-series is assigned a specific wind speed bin, l, based on its median wind speed, V_j^{ave} such that,

$$l = \begin{cases} ceil\left(\frac{V_j^{ave}}{\Delta^{V1}}\right), \left(0 \le V_j^{ave} \le V_{in}\right) \\ n^{V1} + ceil\left(\frac{V_j^{ave} - V_{in}}{\Delta^{V2}}\right), \left(V_{in} < V_j^{ave} \le V_{out}\right) \\ n^{V1} + n^{V2} + ceil\left(\frac{V_j^{ave} - V_{out}}{\Delta^{V3}}\right), \left(V_{out} < V_j^{ave} \le V_{max}\right) \end{cases} \tag{13}$$

Once the wind speed bin index, l, has been identified for a time-series, the bin's mid-point wind speed and bin width are determined by,

$$V_l = \begin{cases} \left(l - \frac{1}{2}\right)\Delta^{V1}, \left(1 \le l \le n^{V1}\right) \\ V_{in} + \left(l - n^{V1} - \frac{1}{2}\right)\Delta^{V2}, \left(n^{V1} < l \le n^{V2}\right) \\ V_{out} + \left(l - n^{V1} - n_2^V - \frac{1}{2}\right)\Delta^{V3}, \left(n^{V2} < l \le n^{V3}\right) \end{cases} \tag{14}$$

$$\Delta_l^V = \begin{cases} \Delta^{V1}, & \left(1 \le l \le n^{V1}\right) \\ \Delta^{V2}, & \left(n^{V1} < l \le n^{V2}\right) \\ \Delta^{V3}, & \left(n^{V2} < l \le n^{V3}\right) \end{cases} \tag{15}$$

Lifetime Damage Count Extrapolation

In addition to the wind speed distribution, the power production and parked DLC cycle-count extrapolation is affected by the turbine's availability factor, A. An availability of 1 indicates the turbine is always online and producing power when the wind speed is in the range $(V_{in} - V_{out}]$.

The power production DLC damage-cycle counts are scaled such that,

$$f_j^{Life} = \begin{cases} \dfrac{T^{Life} A p_l^v}{T_l}, (V_{in} < V_j^{ave} \le V_{out}) \\ \dfrac{T^{Life} p_l^v}{T_l}, (otherwise) \end{cases} \tag{16}$$

where T^{Life} is the design lifetime period, T_l is the total elapsed time for all power production time-series that have a mean wind speed falling in bin l, and f_j^{Life} is the extrapolation factor for time-series j.

Parked DLC damage-cycle counts are scaled such that,

$$f_j^{Life} = \begin{cases} \dfrac{T^{Life}(1-A) p_l^v}{T_l}, (V_{in} < V_j^{ave} \le V_{out}) \\ \dfrac{T^{Life} p_l^v}{T_l}, (otherwise) \end{cases} \tag{17}$$

where, T_l is the total elapsed time for all idling time-series that have a mean wind speed falling in bin l.

Discrete DLC damage-cycle counts are scaled such that,

$$f_j^{Life} = c_j \tag{18}$$

where c_j corresponds to the number of occurrences of the j[th] time-series over the design lifetime.

The extrapolated cycle counts over the design lifetime, for all DLC classifications, are obtained using,

$$n_{ji}^{Life} = f_j^{Life} n_{ji} \tag{19}$$

where f_j^{Life} corresponds to equations 16, 17, or 18, depending on the DLC classification and n_{ji} is the i[th] cycle count for time-series j,

The lifetime damage is accumulated for all cycles and time-series such that,

$$D^{Life} = \sum_j \sum_i \frac{n_{ji}^{Life}}{N_{ji}} \tag{20}$$

Time until Failure

In addition to calculating the damage over a design lifetime, one can calculate the time until failure. Since failure occurs when D^{Life} equals one, the time until failure, T^{Fail}, is simply the ratio of the design lifetime over the accumulated damage,

$$T^{Fail} = \frac{T^{Life}}{D^{Life}} \tag{21}$$

By examining the equations for n_{ji}^{Life} and N_{ji} , one discovers that both D^{Life} and T^{Fail} are not influenced by the value of L^{MF}. There will be a difference however between the Goodman corrected and uncorrected results. MLife computes both, if requested.

Short-term Damage Rate

The short-term damage and damage-rates are computed by,

$$D_j^{ST} = \sum_i \frac{n_{ji}}{N_{ji}} \tag{22}$$

$$DR_j^{ST} = \frac{D_j^{ST}}{T_j} \tag{23}$$

$$DR_{agg}^{ST} = \frac{\sum_j D_j^{ST}}{\sum_j T_j} \tag{24}$$

where D_j^{ST} is the accumulated damage from time-series j, DR_j^{ST} is the short-term damage-rate for time-series j, and DR_{agg}^{ST} is the aggregate short-term damage-rate for all time-series.

Damage Equivalent Loads

MLife also estimates a short-term damage-equivalent load (DEL) for each input time-series. A DEL is a constant-amplitude fatigue-load that occurs at a fixed load-mean and frequency and produces the equivalent damage as the variable spectrum loads such that,

$$D_j^{ST} = \sum_i \frac{n_{ji}}{N_{ji}} = \frac{n_j^{STeq}}{N_j^{eq}} \tag{25}$$

$$n_j^{STeq} = f^{eq} T_j \tag{26}$$

$$N_j^{eq} = \left(\frac{L^{ult} - |L^{MF}|}{\left(\frac{1}{2} DEL_j^{STF}\right)} \right)^m \tag{27}$$

where f^{eq} is the DEL frequency, T_j is the elapsed time of time-series j, n_j^{STeq} is the total equivalent fatigue counts for time-series j, DEL_j^{STF} is the DEL for time-series j about a fixed mean, and N_j^{eq} is the equivalent number of cycles until failure for time-series j. Solving for DEL_j^{STF} in equation 27 yields,

$$DEL_j^{STF} = \left(\frac{\sum_i \left(n_{ji}\left(L_{ji}^{RF}\right)^m\right)}{n_j^{STeq}}\right)^{\frac{1}{m}} \tag{28}$$

The DEL about a zero mean can also be computed by setting L^{MF} equal to zero.

$$DEL_j^{ST0} = \left(\frac{\sum_i \left(n_{ji}\left(L_{ji}^{R0}\right)^m\right)}{n_j^{STeq}}\right)^{\frac{1}{m}} \tag{29}$$

where L_{ji}^{R0} is the adjusted load ranges about a zero fixed-mean, per equation 3, and DEL_j^{ST0} is the DEL for time-series j about a zero fixed-mean.

MLife also computes a short-term, time-series-based DEL, DEL_j^{ST}, without using the Goodman correction, such that $L_{ji}^{RF} = L_{ji}^{R}$, and where L^{MF} equals zero.

$$DEL_j^{ST} = \left(\frac{\sum_i \left(n_{ji}\left(L_{ji}^{R}\right)^m\right)}{n_j^{STeq}}\right)^{\frac{1}{m}} \tag{30}$$

Aggregate Short-term DELs

MLife also computes a set of short-term DELs based on the aggregate of all cycle counts of the individual time-series.

$$DEL_{agg}^{STF} = \left(\frac{\sum_j \sum_i \left(n_{ji}\left(L_{ji}^{RF}\right)^m\right)}{\sum_j n_j^{STeq}}\right)^{\frac{1}{m}} \tag{31}$$

where DEL_{agg}^{STF}, is the aggregate short-term DEL about a fixed-mean.

$$DEL_{agg}^{ST0} = \left(\frac{\sum_j \sum_i \left(n_{ji}\left(L_{ji}^{R0}\right)^m\right)}{\sum_j n_j^{STeq}}\right)^{\frac{1}{m}} \tag{32}$$

where DEL_{agg}^{ST0}, is the aggregate short-term DEL about a zero fixed-mean.

$$DEL_{agg}^{ST} = \left(\frac{\sum_j \sum_i \left(n_{ji}\left(L_{ji}^{R}\right)^m\right)}{\sum_j n_j^{STeq}}\right)^{\frac{1}{m}} \tag{33}$$

where DEL_{agg}^{STF}, is the aggregate short-term DEL without using the Goodman correction.

Lifetime Damage Equivalent Loads

The program computes a lifetime DEL which includes the fatigue cycles from all time-series. In this case, a lifetime equivalent cycle count is determined using the lifetime count extrapolation factor, f_j^{Life}, and the short-term equivalent count, n_j^{STeq}, such that,

$$n^{Life,eq} = \sum_j f_j^{Life} n_j^{STeq} \tag{34}$$

As with the short-term DEL calculations, we equate the lifetime damage due to variable fatigue cycles to the damage resulting from a repeating equivalent load,

$$D^{Life} = \sum_j \sum_i \frac{n_{ji}^{Life}}{N_{ji}} = \frac{n^{Life,eq}}{N^{eq}}, \tag{35}$$

In the case of an equivalent load about a fixed mean, solving for DEL^{LifeF} yields,

$$DEL^{LifeF} = \left(\frac{\sum_j \sum_i \left(n_{ji}^{Life}\left(L_{ji}^{RF}\right)^m\right)}{n^{Life,eq}}\right)^{\frac{1}{m}} \tag{36}$$

For the lifetime equivalent load about a zero mean we have,

$$DEL^{Life0} = \left(\frac{\sum_j \sum_i \left(n_{ji}^{Life}\left(L_{ji}^{R0}\right)^m\right)}{n^{Life,eq}}\right)^{\frac{1}{m}} \tag{37}$$

For the lifetime equivalent load without using the Goodman correction about a zero mean we have,

$$DEL^{Life} = \left(\frac{\sum_j \sum_i \left(n_{ji}^{Life}\left(L_{ji}^{R}\right)^m\right)}{n^{Life,eq}}\right)^{\frac{1}{m}} \tag{38}$$

Binning the Load Cycles

As an option, MLife will also bin the individual fatigue cycle counts according to load range.

If the user selects the number of range bins, MLife computes the width of each bin using,

$$\Delta^R = \frac{L_{max}^R}{n^R} \tag{39}$$

where, n^R is the number of range bins, Δ^R is the width of each range bin, and L_{max}^R corresponds to the maximum load range present in the rainflow cycles across all input time-series.

If the user selects the maximum width of each range bin, MLife first computes the number of bins using,

$$n^R = ceil\left(\frac{L_{max}^R}{\Delta_{max}^R}\right) \tag{40}$$

then, the actual width of the bins is computed using equation 39.

The load bin, k, associated with load range value L_{ji}^{RF} for the ith cycle in the jth time-series is,

$$k = ceil\left(\frac{L_{ji}^{R}}{\Delta^{R}}\right) \tag{41}$$

and the value of the load range for bin k is,

$$L_{k}^{R} = \left(k - \frac{1}{2}\right)\Delta^{R} \tag{42}$$

The load range type used to compute the L_{max}^{R} quantity depends on the requested result type. The options are to use the uncorrected cycles, L_{ji}^{R}, the Goodman-corrected cycles about a fixed-mean, L_{ji}^{RF}, or the Goodman-corrected cycles about a zero fixed-mean, L_{ji}^{R0}, see Table 1.

Type of Result to Calculate	Cycles used to compute L_{max}^{R}
Fixed-Mean only	L_{ji}^{RF}
Zero Fixed-Mean only	L_{ji}^{R0}
Fixed-Mean and Zero Fixed-Mean	L_{ji}^{R0}
Without Goodman Correction	L_{ji}^{R},
With and Without Goodman Correction	L_{ji}^{R},

Table 1. Which cycles are used to determine L_{max}^{R}

Once the load range bins are determined, the cycle counts, n_{ji}, are collected using the appropriate load range type as shown in Table 2.

Type of Result to Calculate	Cycle Load Ranges	Binned Cycle Counts
Fixed-Mean	L_{ji}^{RF}	n_{jk}^{F}
Zero Fixed-Mean	L_{ji}^{R0}	n_{jk}^{0}
Without Goodman Correction	L_{ji}^{R}	n_{jk}

Table 2. Which cycles are used to determine binned cycle counts

n_{jk} is the total number of cycle counts from times-series j whose uncorrected load ranges fall into bin k, n_{jk}^{F} is the total number of cycle counts from times-series j whose fixed-mean load ranges fall into bin k, and n_{jk}^{0} is the total number of cycle counts from times-series j whose zero fixed-mean load ranges fall into bin k.

The lifetime cycle counts are obtained using,

$$n_{jk}^{Life} = f_{j}^{Life} n_{jk} \tag{43}$$

$$n_{jk}^{LifeF} = f_{j}^{Life} n_{jk}^{F} \tag{44}$$

$$n_{jk}^{Life0} = f_{j}^{Life} n_{jk}^{0} \tag{45}$$

For a given processing session, MLife computes at most a single damage-rate and lifetime damage result when applying the Goodman correction. Table 3 outlines which binned cycle counts are used in the possible cases. In the un-binned case, the damage results are independent of a chosen fixed-mean. In the binned case, these results could vary slightly due to the binning process. MLife will also compute the binned, uncorrected, damage-rate and lifetime damage results, if requested.

Type of Result to Calculate	Binned Cycle Counts	Short-term Damage Rate	Lifetime Damage
Fixed-Mean Only	n_{jk}^{F}	DR_{j}^{STF}	D^{LifeF}
Zero Fixed-Mean Only	n_{jk}^{0}	DR_{j}^{ST0}	D^{Life0}
Fixed-Mean and Zero Fixed-Mean	n_{jk}^{F}	DR_{j}^{STF}	D^{LifeF}
Without Goodman Correction	n_{jk}	DR_{j}^{ST}	D^{Life}

Table 3. Which versions of damage and damage-rate are used when binning

DR_{j}^{ST} is the short-term damage-rate of the j^th time-series using the uncorrected load ranges, DR_{j}^{STF} is the damage-rate of the j^th time-series using the load ranges corrected to a fixed-mean, and DR_{j}^{ST0} is the damage-rate of the j^th time-series using the load ranges corrected to a zero fixed-mean. D^{Life} is the lifetime damage using the uncorrected load ranges, D^{LifeF} is the lifetime damage using the load ranges corrected to a fixed-mean, and D^{Life0} is the lifetime damage using the load ranges corrected to a zero fixed-mean.

The various binned lifetime damage equations are,

$$D_{j}^{Life} = \sum_{k} \frac{n_{jk}^{Life}}{N_{k}} \tag{46}$$

$$D_{j}^{LifeF} = \sum_{k} \frac{n_{jk}^{LifeF}}{N_{k}}, \tag{47}$$

$$D_j^{Life0} = \sum_k \frac{n_{jk}^{Life0}}{N_k} \tag{48}$$

$$D^{Life} = \sum_j D_j^{Life} \tag{49}$$

$$D^{LifeF} = \sum_j D_j^{LifeF} \tag{50}$$

$$D^{Life0} = \sum_j D_j^{Life0} \tag{51}$$

The cycles to failure equation becomes,

$$N_k = \left(\frac{L^{ult} - |L^{MF}|}{\left(\frac{1}{2} L_k^R\right)} \right)^m \tag{52}$$

N_k are the cycles to failure for load bin k. L_k^R is the load range value associated with bin k.

The binned short-term damage and damage-rates are computed by,

$$D_j^{ST} = \sum_k \frac{n_{jk}}{N_k} \tag{53}$$

$$D_j^{STF} = \sum_k \frac{n_{jk}^F}{N_k} \tag{54}$$

$$D_j^{ST0} = \sum_k \frac{n_{jk}^0}{N_k} \tag{55}$$

$$DR_j^{ST} = \frac{D_j^{ST}}{T_j} \tag{56}$$

$$DR_j^{STF} = \frac{D_j^{STF}}{T_j} \tag{57}$$

$$DR_j^{ST0} = \frac{D_j^{ST0}}{T_j} \tag{58}$$

The binned short-term DEL about a fixed mean becomes,

$$DEL_j^{STF} = \left(\frac{\sum_k \left(n_{jk}^F (L_k^R)^m \right)}{n_j^{STeq}} \right)^{\frac{1}{m}} \tag{59}$$

The binned short-term DEL about a zero mean becomes,

$$DEL_j^{ST0} = \left(\frac{\sum_k \left(n_{jk}^0 (L_k^R)^m \right)}{n_j^{STeq}} \right)^{\frac{1}{m}} \tag{60}$$

The binned short-term DEL without the Goodman correction about a zero mean becomes,

$$DEL_j^{ST} = \left(\frac{\sum_k \left(n_{jk} (L_k^R)^m \right)}{n_j^{STeq}} \right)^{\frac{1}{m}} \tag{61}$$

The binned short-term aggregate DEL equations become,

$$DEL_{agg}^{STF} = \left(\frac{\sum_j \sum_k \left(n_{jk}^F (L_k^R)^m \right)}{\sum_j n_j^{STeq}} \right)^{\frac{1}{m}} \tag{62}$$

$$DEL_{agg}^{ST0} = \left(\frac{\sum_j \sum_k \left(n_{jk}^0 (L_k^R)^m \right)}{\sum_j n_j^{STeq}} \right)^{\frac{1}{m}} \tag{63}$$

$$DEL_{agg}^{ST} = \left(\frac{\sum_j \sum_k \left(n_{jk} (L_k^R)^m \right)}{\sum_j n_j^{STeq}} \right)^{\frac{1}{m}} \tag{64}$$

The lifetime DEL equations are,

$$DEL^{LifeF} = \left(\frac{\sum_j \sum_k \left(n_{jk}^{LifeF} (L_k^R)^m \right)}{\sum_j n_j^{STeq}} \right)^{\frac{1}{m}} \tag{65}$$

$$DEL^{Life0} = \left(\frac{\sum_j \sum_k \left(n_{jk}^{Life0} (L_k^R)^m \right)}{\sum_j n_j^{STeq}} \right)^{\frac{1}{m}} \tag{66}$$

$$DEL^{Life} = \left(\frac{\sum_j \sum_k \left(n_{jk}^{Life} (L_k^R)^m \right)}{\sum_j n_j^{STeq}} \right)^{\frac{1}{m}} \tag{67}$$

where n_{jk}^{LifeF}, n_{jk}^{Life0}, and n_{jk}^{Life} are the extrapolated damage counts.

Peak Finding and Filtering

The peak-finding algorithm begins by adding the first time-series data point to the peak list. The entire time-series is then traversed, and a peak is identified by a change in sign of the time-series derivative. If a peak value occurs multiple, consecutive times, only the last point of the group is added to the peaks list. Finally, the last data point in the time-series is added to the peaks list. MLife also incorporates a racetrack filter that is useful for eliminating small amplitude variations in the time-series. The algorithm filters out all potential peak points that vary from their adjacent peak point by amplitudes less than a threshold percentage of the maximum range of the time-series.

Fatigue Cycle Counting

MLife uses the one-pass cycle counting method of Downing and Socie. With this approach, unclosed partial cycles can be generated anywhere in the time-series, if certain criteria are met. The method attaches an unclosed cycle count of uc to these cycles. Complete cycles are assigned a cycle count of one. For typical wind turbine loads data, only a small percentage of cycles tend to be counted as partial cycles. However, we strongly encourage you to set uc equal to 0.5 unless you have a specific reason for choosing a different value.

Program Outline

MLife's analysis follows this general outline:

1. Process all the input data files, one at a time.
    a. Read a time-series file into memory.
    b. Compute the statistics for this time-series.
    c. Extract the local maxima and minima (peaks) from the time-series.
    d. Filter the peaks (optional).
2. Compute the aggregate statistics across all data files.
3. Determine the fatigue cycles for each time-series using rainflow counting. Each cycle is characterized by,
    a. The cycle's mean load and range.
    b. The adjusted load range when using a fixed or zero mean.
    c. The weight of the cycle, which allows partial cycles to be counted as a fraction of a complete cycle. Complete cycles have a count of one.
4. Compute the short-term damage-rates and damage-equivalent load (DEL) of each time-series.
5. Sum the damage contribution of each time-series to determine short-term aggregate damage-rates and DELs.
6. Extrapolate the damage contribution of each time-series across the design lifetime to determine the lifetime damage.
7. Determine the lifetime DEL.
8. Compute the time until failure.

Future Work

MLife currently does not model the load range distribution by a stationary random process (equation G-2 of IEC 61400-1, Annex G). This prevents the extrapolation of load ranges, accounting for loads which may exist over the design lifetime, but are not found in the short-term input time-series.

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Feedback

If you have problems with MLife, please contact Greg Hayman. If he has time to respond to your needs, he will do so, but please do not expect an immediate response. Please send your comments or bug reports to:

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