

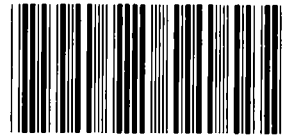
# User's Manual for

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# FAROW:

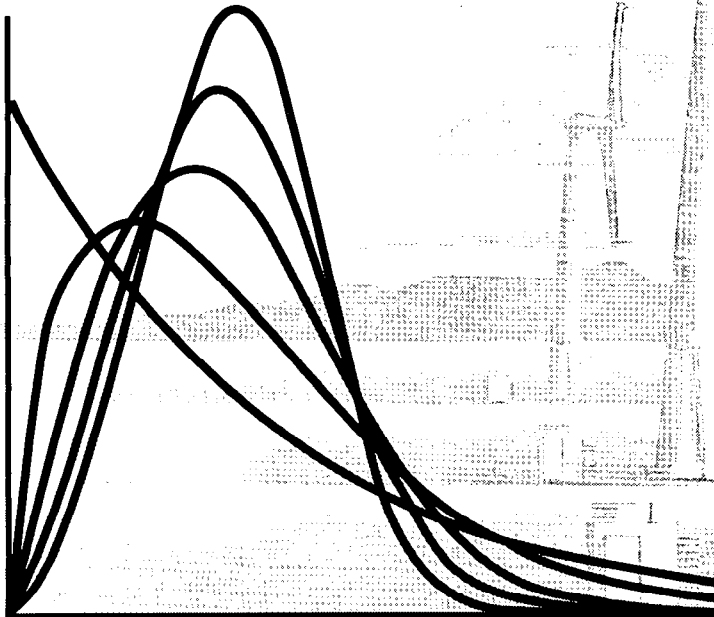
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## Fatigue and Reliability of Wind Turbine Components



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**User's Manual for FAROW:  
Fatigue and Reliability of Wind Turbine  
Components**

Version 1.1

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## ***Abstract***

FAROW is a computer program that assists in the probabilistic analysis of the Fatigue and Reliability of Wind turbines. The fatigue lifetime of wind turbine components is calculated using functional forms for important input quantities. Parameters of these functions are defined in an input file as either constants or random variables. The user can select from a library of random variable distribution functions. FAROW uses structural reliability techniques to calculate the mean time to failure, probability of failure before a target lifetime, relative importance of each of the random inputs, and the sensitivity of the reliability to all input parameters. Monte Carlo simulation is also available.

This user's manual is intended to provide sufficient information to knowledgeably run the program and meaningfully interpret the results. The first chapter provides an overview of the approach and the results. Chapter 2 describes the formulation and assumptions used in the fatigue life calculations. Each of the input parameters is described in detail in Chapter 3 along with hints and warnings on usage. An explanation of the outputs is provided in Chapter 4. Two example problems are described and solved in Chapter 5, one for the case where extensive data are available and the other with limited data where the uncertainty is higher. A typical input file and the output files for the example problems are included in the appendices.

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Please include the operating system on which the program is to be executed.

## ***Acknowledgments***

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# **1 Introduction**

Fatigue is an insidious problem in structures of all types, but especially in wind turbines where severe environmental loadings combine with stringent cost requirements to produce an inevitable conflict between expense and durability. The best weapon for avoiding fatigue problems is an accurate estimate of the fatigue life for candidate or prototype designs. The LIFE2 code (Sutherland, 1989), for example, is one of a few useful tools for achieving that end. These methods share the characteristic of requiring specific values for all governing parameters and producing deterministic predictions of time to failure. FAROW builds on that foundation and provides additional, valuable information for designers by using structural reliability methods.

## **1.1 Why Reliability Methods?**

Every designer of fatigue sensitive structures would like to know the lifetime of the design with perfect accuracy. The design could then be fine tuned to eliminate needless costs while maintaining acceptable durability. Unfortunately, designers are often disappointed with fatigue life predictions. Not only are the techniques difficult to apply, requiring a daunting level of detail of the machine and its environment, but the results are highly sensitive to changes in the inputs (Ashwill et al., 1990). Ranges of plausible answers from two months to ten years erode the value of the results and make the process frustrating. The knowledge that this sensitivity is inherent to the fatigue problem is of little comfort. This sensitivity suggests that an appropriate range of uncertainty be reported, reflecting both natural variability and professional ignorance of precise structural behavior, mechanical fatigue laws, and so forth. A good designer will therefore put appropriate safety factors on all the uncertain quantities that affect fatigue life. It would be beneficial, however, to provide a more quantitative measure of the design conservatism. This in turn suggests that the proper question may not be "what is the actual fatigue life of this component?" but rather "with what probability will the component meet its target design life?" Such questions are naturally addressed by the theory of structural reliability.

Applying *structural reliability methods* to the wind turbine fatigue problem is one way to make sense of life estimates that can jump from years to centuries with the

adjustment of a single parameter. A reliability approach describes controlling parameters as random variables that reflect both inherent randomness, and an imperfect state of knowledge. Deterministic analyses are conducted to determine the fatigue lifetime with selected combinations of possible values of the random variables. The deterministic fatigue lives are compared to an objective criterion called the *failure state function*. In this case the failure state function is simply the computed life minus the target life. A negative value of this function implies *failure* in the reliability sense. The failure state function can be directly analyzed through any of the various FORM/SORM (First/Second Order Reliability Methods) computer codes that are currently available. The development of FORM/SORM methods in the past two decades has made it possible to analyze problems with relatively large sets of random variables. In this way, the fatigue lifetime of wind turbine components can be set in a probabilistic context rather than attempting to determine the exact lifetime of a component.

The main result of a reliability analysis is the probability of failing to meet a specified target lifetime. This result alone provides a more accurate sense of the quality of a component design than a deterministic time to failure based on either qualitative safety factors or ad hoc measures such as maximum strain. But structural reliability methods provide much more information than just probability of failure. *Importance factors*, which indicate how much each random variable contributes to the total probability of failure, are also calculated. By focusing on the most *important* of the random variables in prototype testing and design refinement, the developers can efficiently work toward a more reliable design. The FAROW code also estimates the *sensitivity* of the reliability to each of the controlling parameters, both random and deterministic. Again, the wind turbine developer is provided direction as to which of the parameters have the greatest overall impact on fatigue durability. This kind of information is a natural byproduct of using structural reliability methods in the fatigue analysis of wind turbine components.

While using this tool won't solve all turbine designers' fatigue problems, it will provide important information about the state of the design and about the value of additional data. The type of information it provides about the design can also feed into the broader, corporate decision-making process.

## 1.2 Uncertainty Modeling in FAROW

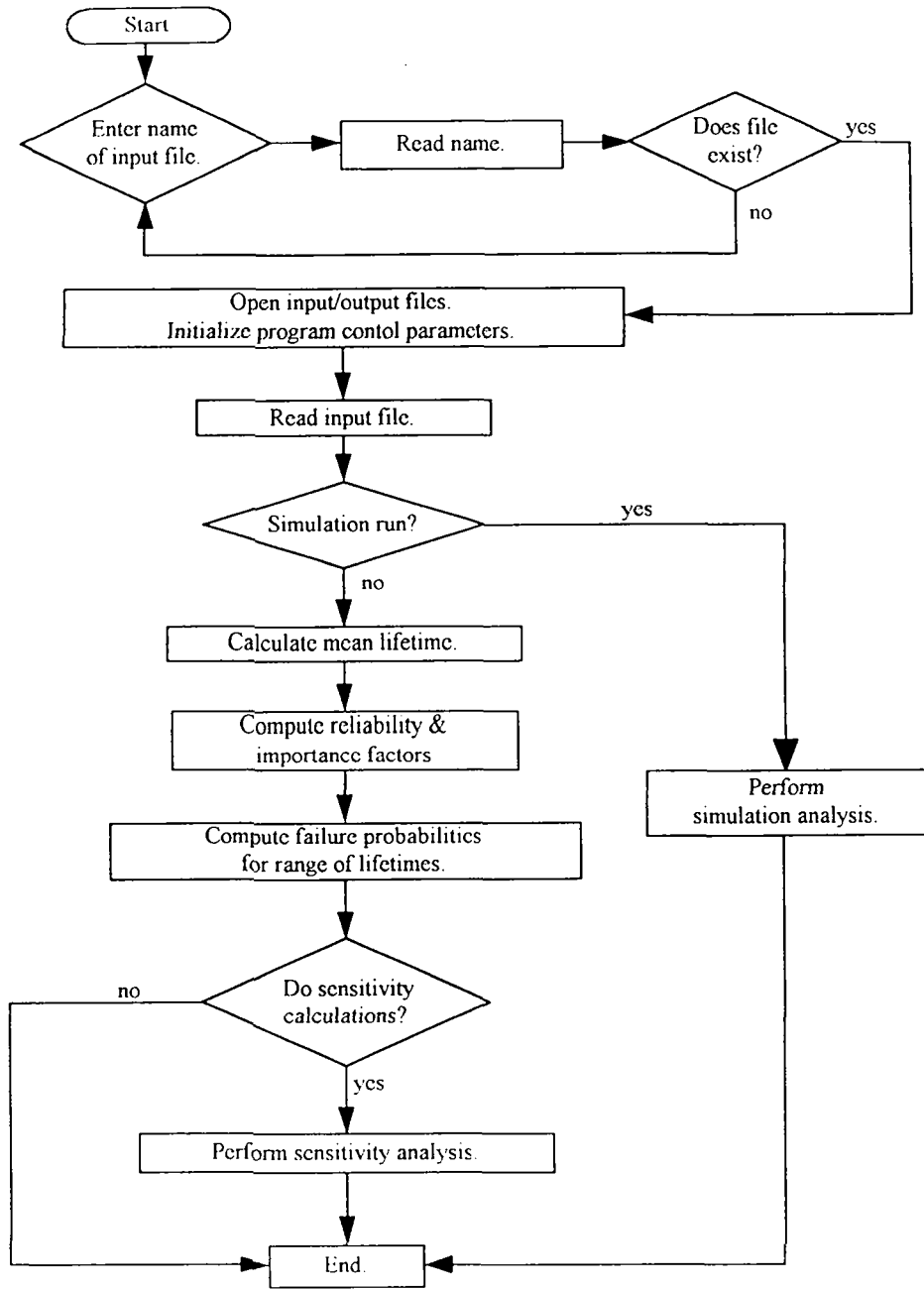
The FAROW code has been named to describe its function, calculating the Fatigue And Reliability Of Wind Turbines. A deterministic fatigue life calculation has been derived for the specific case of wind turbine components loaded by continuous operation in a typical (user-specified) wind environment. This formulation is used by a reliability analysis engine to produce the desired probabilistic results.

The fatigue formulation is intended to capture uncertainty in environmental loading, gross structural response and local fatigue properties. Fatigue damage is modeled probabilistically using Miner's Rule and the effects of variable loads, mean stress effects, and stress concentration factors. Uncertainty in the fatigue properties themselves is included. A critical distinction here is between continuously varying quantities such as an environmental parameter (e.g., instantaneous wind speed  $V$ , applied stress amplitude  $S$  versus time, etc.) and fixed parameters which may be uncertain (e.g., fatigue law coefficients, wind speed distribution parameters, RMS stress at a given wind speed, etc.). Continuously varying quantities are reflected here implicitly, through their average effect on fatigue damage. In contrast, parameter uncertainty doesn't "average out" over fatigue life, and is modeled here explicitly.

FAROW uses assumed functional forms for the controlling quantities of fatigue life. The functions are defined by parameters such as those describing the material S-N curve, RMS stress level at a characteristic wind speed, average wind speed, etc. The trade-off is in the level of generality; the restrictive assumptions catalogued in Chapter 2 permit the user to define the entire problem with a condensed data set. The emphasis has been on keeping the input simple and easy to use. Chapter 3 goes into detail describing the nature of the input parameters and their implications on fatigue life calculations.

The probability of failure is calculated using the general purpose structural reliability package produced by Rackwitz (Gollwitzer et al., 1988). Enhancements to the way the basic algorithm treats correlation between random variables have been added (Winterstein et al., 1989). Importance factors and sensitivities are calculated as well. The analysis is made specific to the wind turbine problem with an appropriate failure state function and by adding the necessary input and output coding. A flowchart of program execution is shown in Figure 1.1.

Figure 1.1 FAROW Flowchart



## 1.3 FAROW Capabilities

As previously stated, calculating probabilities of failure is only one of the many results provided by FAROW that aid in understanding the fatigue reliability of a component and indicate how to improve it. The many capabilities alluded to above are listed here.

- Mean time to failure is estimated using median parameter values.\*
- The probability of failing to meet a lifetime target is determined.
- The evolution of the probability of failure is determined as a function of time.
- The relative importance of each source of uncertainty is calculated.
- The sensitivity of the reliability to each of the input quantities, both constant inputs and the parameters of the distributions of random variables, is calculated.
- Monte Carlo simulation for brute force estimates of the probability of premature failure is included as an option. This approach may work well in high probability of failure cases.
- The inputs are taken from a set of descriptive parameters in a user edited file.
- A library of random variable distribution functions is provided.

## 1.4 FAROW Usage

### 1.4.1 General Usage

Inputs are defined in a user edited file with comments included throughout. The intent is for the user to copy and edit the file for each new case to be analyzed. The name of the input file and file title are the only interactive responses requested by the code. An extension of ".IN" is assumed on the input file. Chapter 3 goes into considerable detail describing the inputs.

---

\* This is the procedure for uncorrelated inputs. When inputs are correlated, the medians of conditional distributions are used.

There are two output files described in Chapter 4. One, given an ".OUT" extension, contains all the results of the computations, as well as an echo of the inputs. The other is given a ".LOG" extension and contains ancillary output intended mostly for assistance if things go wrong. Some of the more esoteric results of the SORM analysis not generally of interest to the casual user are also printed in the ".LOG" file. Example input and output files are included in the appendices.

The program has been tested on IBM compatible 286 and 486 machines, Macintosh, and UNIX based work stations. Compiled versions are available in either DOS or UNIX forms. Upon special request, other forms may also be generated (e.g., Apple). Run times without sensitivity analysis are on the order of seconds. With sensitivity analysis, the 486 run times will be on the order of tens of seconds. Different inputs will affect run times by creating situations of greater or lesser difficulty in calculating the results. There are many possible input sets that can cause numerical problems and even program termination, usually by producing either very short or extremely long fatigue lifetimes. In either of these cases, the actual probability of failure within an economic target lifetime is of little interest, being either very large or vanishingly small. The next section provides some guidance in dealing with numerical problems.

### **1.4.2 What to do If the Program Bombs**

Don't panic. The first try at creating a FAROW input for a specific application may result in unexpected program termination or output results that appear to be nonsense. This possibility exists because fatigue lifetime calculations are highly sensitive to the input parameters. A few simple checks can be very useful in the event FAROW does bomb.

The first step the user should always take is to verify that the input contains the desired values for all parameters *with a consistent set of units*. FAROW uses no prescribed units except time, which assumes cycle rates are in Hertz and lifetimes are in years. It is easy to specify units on material properties and stress levels that are inconsistent. Read Section 3.8 for a brief description of the input quantities that must have matching dimensions.

The second place to look for assistance is the **Warning!** sections following the description of each input parameter in Section 3.2. It is possible that one of the warnings will identify a difficulty in your particular problem set-up.

It is also usually helpful to check the value of the mean lifetime printed in the output file. A very short mean lifetime will produce a very high probability of failure (which may be hard for FORM/SORM techniques to estimate). Better results may be obtained in this case with the Monte Carlo option. An extremely long lifetime indicates that numerical overflow problems could occur during two operations: first when FAROW exercises the random variables searching for the design point, and second during the sensitivity calculations when even the input constants are varied slightly to estimate partial derivatives. Both calculations may produce fatigue lives greater than the numerical capacity of the computer. As discussed in Section 4.2, unrealistically small or negative mean lifetimes indicate problems. One may want to compute the mean lifetime by hand to check if some of the intermediate values in the computation have excessively large or small values. Units may need to be adjusted to alleviate this difficulty. The hand calculated mean lifetime can then be compared with the FAROW result. Recall that the mean lifetime is obtained by substituting the median values of all variables into Equation 2.6. Section 4.7 also describes some of the messages sent to the ".LOG" file created by FAROW, messages that are routinely of little interest but may help sort out a computational problem, such as printouts at each iteration, which could indicate convergence problems.

If difficulties persist, it may be necessary to attempt simpler versions of the problem statement and then work up to the desired problem statement in steps. For example, one or two random variables could be retained while all the other inputs are set to constants. Then random variables can be added one-by-one until the complete problem description is achieved. This procedure will identify which of the random variables is proving to be troublesome. And, because FAROW does not take a lot of execution time with the sensitivity calculations turned off, the process is relatively quick and painless.

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## 2 Fatigue Analysis Assumptions

There is a tradeoff between accuracy, complete generality, versatility, and simplicity in cumulative damage assessment for wind turbines. Accuracy would demand that not only the numbers and amplitudes of the loads be analyzed, but that load sequences be accounted for as well. The most general and versatile approach would supply a multitude of approaches to cover each specific case of material and loading combination. Simplicity, however, requires that many simplifying assumptions be applied to make the problem tractable while retaining the essential, dominant features of the fatigue analysis. FAROW is heavily tilted in the direction of simplicity. This chapter lays out the assumptions made in the fatigue analysis procedure, and enumerates the resulting uncertain parameters required for input by FAROW.

### 2.1 Formulation

A Miner's Rule approach is used to predict the fatigue life of the turbine component. This formulation generalizes a model first suggested by Veers [1990]. It permits direct modeling of uncertainty from various sources, including the wind environment, local stresses for specified wind speed, and fatigue behavior under specified loads.

The assumptions and parameters are as follows:

1. The wind speed,  $V$ , is assumed to have a relative frequency of occurrence described by a Weibull probability density,  $f(V)$ . This distribution shape is completely described by two parameters, the mean value and shape factor,  $\bar{V}, \alpha_V$ . Figure 2.1 illustrates how the shape factor affects the Weibull shape; a large  $\alpha_V$  produces a narrower distribution more concentrated about the mean.

**Resulting uncertain parameters:**  $\bar{V}, \alpha_V$  = mean wind speed, Weibull shape factor.

2. Stresses are described in terms of the root mean square (RMS) of the instantaneous stress variations about the mean value. It is important to avoid

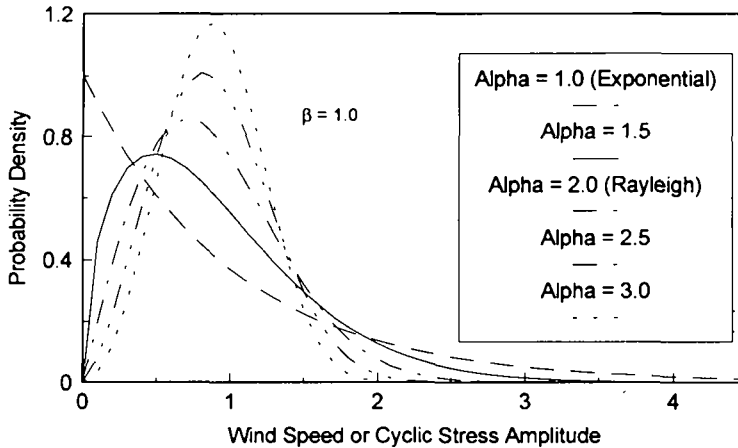


Figure 2.1: Family of Weibull distributions for various Alpha ( $\alpha$ ) values.

confusing the instantaneous stress time series from the cyclic stress descriptions. The instantaneous stresses include all the fluctuations about the mean value, while the cyclic stress amplitudes (obtained from rainflow counting) are positive quantities. Instantaneous stresses are often nearly Gaussian processes, but the stress cycles are often well described by some sort of a Weibull distribution, at least in the high amplitude tail of the distribution. Keep in mind that the RMS stresses talked about here are always measures of the variation of the instantaneous stresses about the mean stress. There is a relationship between stress cycle amplitudes and instantaneous stress RMS from random vibration theory, which is used in FAROW and described in the FAROW theory manual (Veers et al., 1994).

The RMS of the instantaneous (global) stress,  $\sigma_g$ , is assumed to be of the form shown in Eq. 2.1, i.e., increasing in power law fashion with the wind speed  $V$ . Figure 2.2 shows the typical relationships between stress levels and wind speed modeled by different values of  $p$ . The local stress at the fatigue-sensitive detail is further scaled by a stress concentration factor  $K$ . The resulting RMS at a point,  $\sigma$ , is then

$$\sigma = K\sigma_g ; \sigma_g = \sigma_{char} \left( \frac{V}{V_{char}} \right)^p \quad (2.1)$$

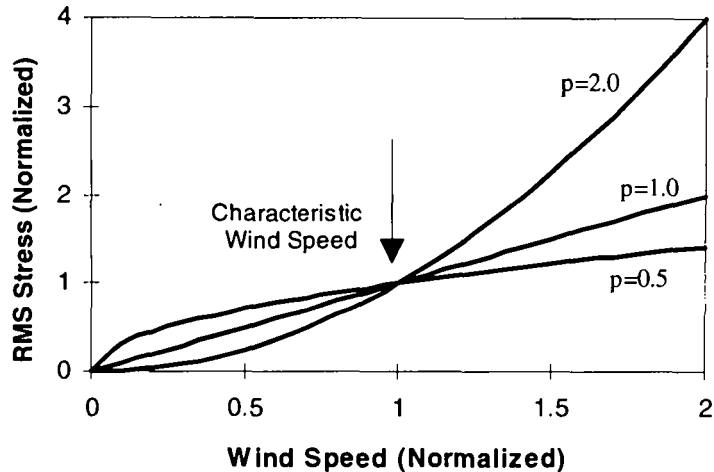


Figure 2.2: Normalized RMS stress ( $\sigma$ ) versus normalized wind speed as modeled by FAROW. The characteristic wind speed and RMS level are user inputs, as are  $p$ , the exponent, and  $K$ , the stress concentration factor.

**Resulting uncertain parameters:**  $V_{char}, \sigma_{char}, p, K$  = characteristic wind speed, the RMS stress level at the characteristic wind speed, power-law exponent, and stress concentration factor. Again, remember that  $\sigma_{char}$  is the RMS of the instantaneous time varying stress, not the root mean square of the stress cycle distribution (discussed below).

3. The probability density of cyclic stress amplitude  $S$  for a given wind speed  $V$ ,  $f(S|V)$ , is also assumed to have Weibull distribution.

**Resulting uncertain parameter:**  $\alpha_s$  is the Weibull shape parameter of stress distribution  $f(S|V)$ . Typical range: between  $\alpha_s=1$  (exponential distribution) and  $\alpha_s=2$  (Rayleigh distribution). Note that the other parameter of the Weibull model of  $f(S|V)$  is determined by the RMS of the instantaneous stress from random vibration theory, assuming the mean square of the stress amplitudes is  $2\sigma^2$ , with  $\sigma$  from Eq. 2.1.

4. The S-N curve is taken here as a straight line on log-log scale, with an effective stress intercept  $C_0$  that includes the Goodman correction for mean stress effects:

$$N_f(S) = C \left( \frac{S}{1 - K |S_m| / S_u} \right)^{-b} = C_0 S^{-b} ; C_0 = C (1 - K |S_m| / S_u)^b \quad (2.2)$$

The straight line S-N curve is shown in Figure 2.3 and the Goodman correction for mean stress is illustrated in Figure 2.4. Many constant amplitude S-N curves have a "knee" or "fatigue limit" for which the lives are considerably extended for low stress amplitude. This effect is not included here and should not be included in any cumulative damage assessment for which larger stresses are occasionally applied, as is certainly the case for wind turbines where high winds and turbulent events are a must. The higher stress peaks alter the way most materials respond and result in greater rates of fatigue damage than would be concluded based solely on constant amplitude results (Mitchell, 1979; Veers, 1989). The Goodman correction is limited to straight line interpolations between zero mean and ultimate stress points and is assumed to be symmetric for tensile and compressive means.

**Resulting uncertain parameters:**  $C$ ,  $b$  = S-N curve parameters;  $S_m$ ,  $S_u$  = mean stress and ultimate strength levels

5. The mean damage rate per unit time,  $\bar{D}$ , is estimated from Miner's rule, where the summation over stress cycles is replaced by an integration first over all stresses at a given wind speed and then by an integration over all wind speeds. Individual stress amplitudes are modeled by the Weibull probability densities described above,  $f(S|V)$ , as is the wind speed distribution,  $f(V)$ .

$$\bar{D} = \int_{V=0}^{V_c} \int_{S=0}^{\infty} F(V) \frac{f(S|V)f(V)}{N_f(S)} dS dV \quad (2.3)$$

The upper cutoff wind speed,  $V_c$ , is the highest wind speed for which the turbine is assumed to operate. Damage rate is in units of time because of the inclusion of the cycle rate,  $F$ . Cycle rate has been modeled as a power series in wind speed defined by constant, linear, and quadratic coefficients,  $f_0$ ,  $f_1$ , and  $f_2$ .

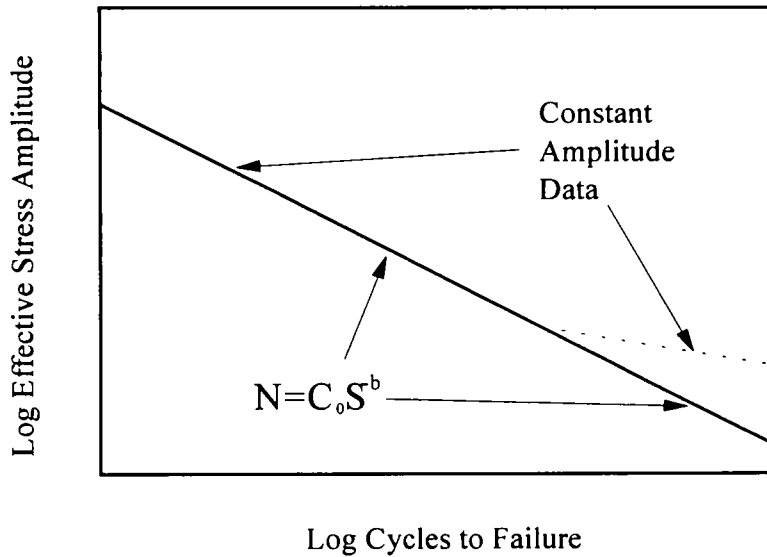


Figure 2.3: The solid line is the S-N curve as modeled in FAROW (without the knee often apparent in constant amplitude data).

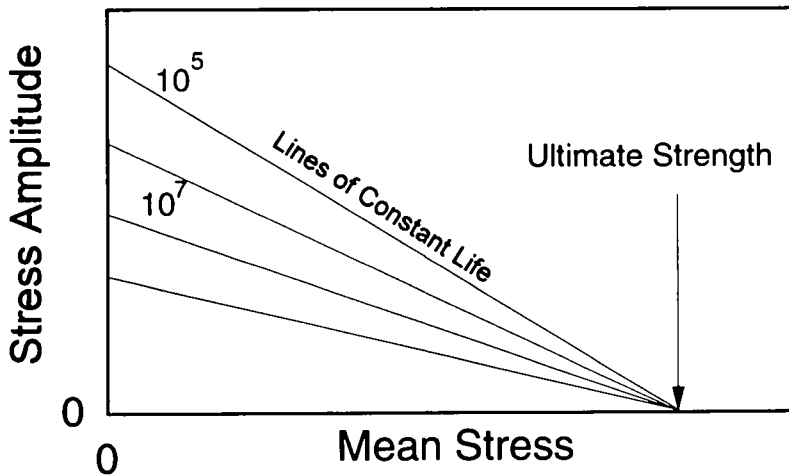


Figure 2.4: Goodman diagram for assessing the effects of mean stress on fatigue lifetime. The *effective stress* is the equivalent amplitude with zero mean.



$$F = f_0 + f_1 \left( \frac{V}{V_{char}} \right) + f_2 \left( \frac{V}{V_{char}} \right)^2 \quad (2.4)$$

After the many cycles that contribute to high-cycle fatigue, the actual damage varies negligibly from its average rate of  $\bar{D}$  multiplied by the total time.

We introduce two additional factors:  $\Delta$  = the actual level of Miner's damage at which failure occurs, and  $A$  = the fraction of time for which the turbine is available ( $A \leq 1$ ). The failure time is then

$$T_f = \frac{\Delta}{AD} \quad (2.5)$$

If Miner's rule is correct we would assign  $\Delta = 1$ . More generally, variability in  $\Delta$  would reflect uncertainty in Miner's rule; e.g., due to load sequence effects.

**Resulting uncertain parameters:**  $V_c, f_0, f_1, f_2, \Delta, A$ .

From the foregoing five assumptions, the fatigue life  $T_f$  is given in terms of a total of  $2+4+1+4+6=17$  uncertain parameters. The target lifetime  $T_t$  is the last parameter in the reliability analysis (making a total of 18) and is treated the same as the other governing parameters even though it may not be used as an uncertain input in most cases. Practical aspects regarding their specification are discussed further in Chapter 3 and in the examples of Chapter 5. We merely note here that problems involving such a relatively large number of random variables have only recently become numerically tractable, with the development of first- and second-order reliability methods (FORM and SORM) over the last two decades. These are the methods used within the FAROW program.

## 2.2 Results

From the foregoing assumptions, Eqs. 2.3 and 2.5 yield an analytical expression for fatigue life  $T_f$  (see FAROW theory Manual [Veers et al., 1994]). Consider first the case when there is no upper-bound cutoff wind speed and cycle frequency is constant; i.e.,  $V_c \rightarrow \infty$  and  $F = f_0$  in Eq. 2.3. In this case,

$$T_f = \frac{C}{f_0 A} \left\{ \left( \frac{2}{(2/\alpha_S)!} \right)^{b/2} \left( \frac{K\sigma_{char}}{(1-K)S_m/S_u} \right)^b \left( \frac{\bar{V}}{V_{char}(1/\alpha_V)!} \right)^{bp} \left( \frac{b}{\alpha_S} \right)! \left( \frac{bp}{\alpha_V} \right)! \right\}^{-1} \quad (2.6)$$

The factorial  $(k)!$  is interpreted here as the gamma function,  $\Gamma(1+k)$ , for non-integer  $k$ .

For finite  $V_c$ , the last factorial  $(bp/\alpha_V)!$  in this result is replaced by the incomplete Gamma function:

$$\gamma \left( 1 + \left( \frac{bp}{\alpha_V} \right), x_c \right) = \int_{x=0}^{x_c} x^{bp/\alpha_V} \exp(-x) dx \quad (2.7)$$

The upper limit in this integral is given by

$$x_c = \left( \frac{V_c(1/\alpha_V)!}{V_{char}} \right)^{\alpha_V} \quad (2.8)$$

Note that parameters directly scaling stress, such as  $\sigma_{char}$  and the stress concentration factor  $K$ , are raised to the power  $b$  arising from the S-N curve. In contrast, parameters scaling the wind speed  $V$ , such as its mean  $\bar{V}$ , are raised to the composite power  $bp$ , reflecting the combined nonlinear effect of Eqs. 2.1 and 2.2. Note that if  $p > 1$ , the uncertainty in these environmental parameters may have significant effect on fatigue life.

Finally, it is also of interest to consider what level of wind speed produces the most fatigue damage. At low winds the stresses are so low that there is little damage. High winds may have high stresses but are relatively uncommon enough to again produce little cumulative damage. The most damaging wind speed is one that combines relatively high stresses and common occurrence. This value corresponds to the maximum of the inner integral in Eq. 2.3. For infinite  $V_c$  (no cut-out) and constant  $F$ , this leads to the following most damaging wind speed:

$$V_{MD} = \frac{\bar{V}}{(1/\alpha_v)!} \left( \frac{bp + \alpha_v - 1}{\alpha_v} \right)^{1/\alpha_v} \quad (2.9)$$

For finite  $V_c$ , the smaller of  $V_{MD}$  and  $V_c$  will give the most damage.

For example, if  $V$  has exponential distribution  $\alpha_v = 1$ , so that  $V_{MD} = bp\bar{V}$ . Thus, the most damaging wind speed depends not only on its average value,  $\bar{V}$ , but also on the exponents  $b$  and  $p$  of the S-N curve and RMS stress relation. Note that  $V_{MD}$  may far exceed the mean  $\bar{V}$ ; e.g.,  $V_{MD} = 20\bar{V}$  when  $b = 10$  and  $p = 2$ . This is a rather extreme case, however. We may typically expect somewhat higher  $\alpha_v$  values, and often lower values of  $p$  and/or  $b$ . For example, common values of  $\alpha_v = 2$  (Rayleigh wind speed distribution) and  $p = 1$  (linear increase in stresses with wind speed) would result in  $V_{MD}$  between 2 and 3 times  $\bar{V}$  for  $b$  values within a realistic range ( $4 < b < 13$ ).



### **3 Input Details**

The inputs are communicated to FAROW through a user-edited input file. Appendix A lists a complete example input file. There are 18 parameters to be specified and a number of analysis options to be defined. All of these details are described below.

This chapter describes the specific input parameters in detail. There has been no attempt to provide an elegant user interface. However, there is a certain amount of simplicity and ease of control in the use of an ASCII file to specify a list of input quantities, some of which change from run to run, but most of which remain the same. It is intended that a template (or generic) file, like Appendix A, be used as a starting point and that specific parameters will be modified using a familiar text editor. All of the inputs are echoed with the output to provide documentation on the calculations. The only inputs required from the keyboard are the name of the input file and an optional title line (up to 72 characters), which is echoed in the output file.

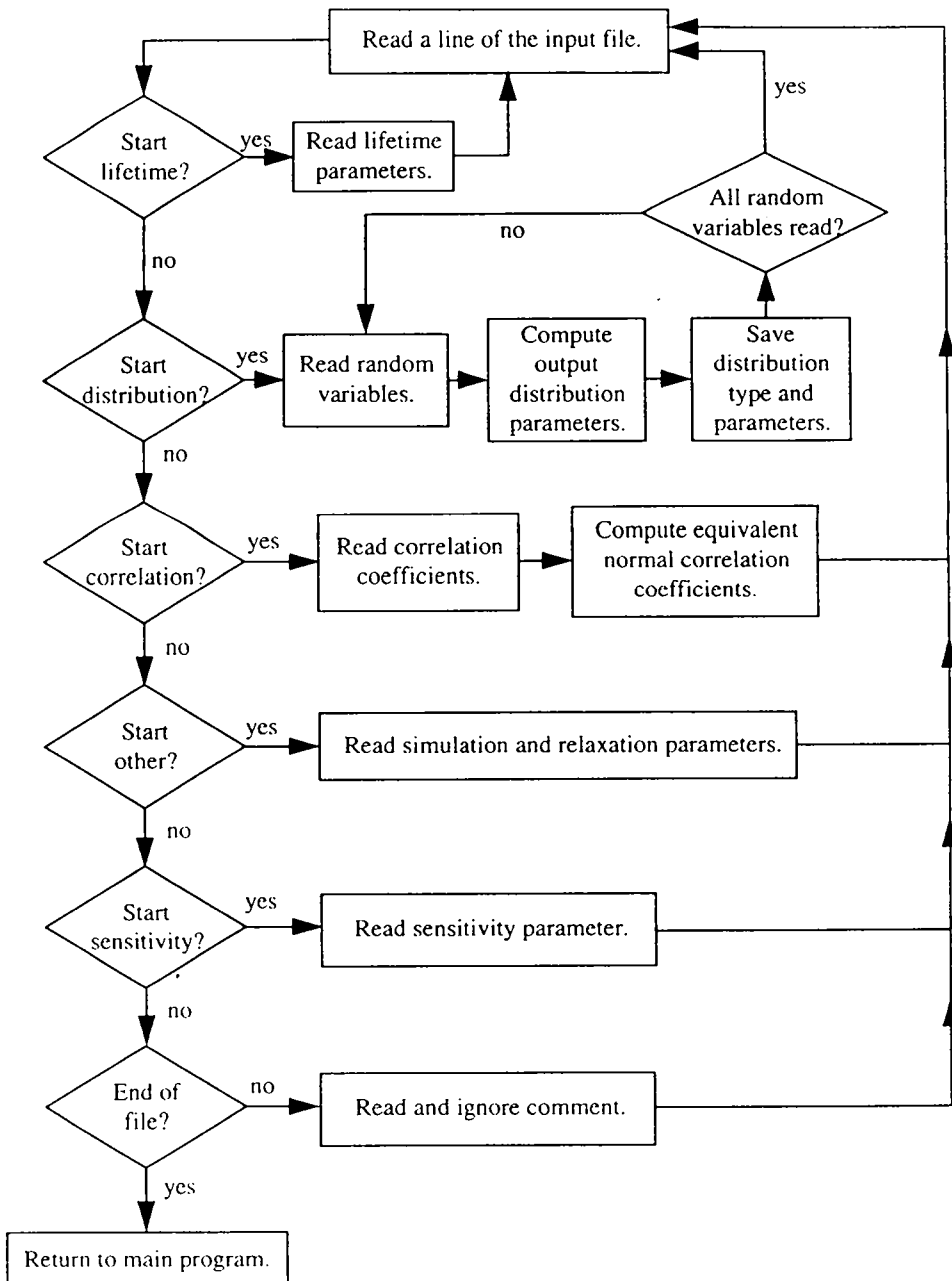
#### **3.1 The Input File**

FAROW's first action upon execution is to prompt the user for an input file name. All subsequent communication with the executing program is through this file. The input file name must have the extension ".IN". When FAROW asks for the input filename, you may enter the name without the extension. FAROW will use this name to create an output file of the same name whose extension is ".OUT". For example, if the input file is TEST.IN, enter TEST at the ENTER NAME OF INPUT FILE: prompt. The output files will be named TEST.OUT and TEST.LOG automatically. An existing file of the same name will be overwritten. It is up to the user to create unique file names for each new run.

The input file for FAROW consists of five blocks of data. The block names are: DIST, CORRELATION, LIFETIME, OTHER, and SENSITIVITY. The blocks are started with \*START\_<name> and ended with \*END\_<name>. The flow of input file reading is shown in Figure 3.1. Anything outside of a block



Figure 3.1 READ INPUT Flowchart



is considered a comment and will be ignored. Within each of these blocks there are key words followed by the input values of the parameters identified by the key words. Do not put comments inside of a \*START\_<name>, \*END\_<name> block. The LIFETIME, SENSITIVITY and OTHER blocks may be in any order and may appear at any location in the file, but the DIST block must come before the CORRELATION block. Anything following the \*END\_OF\_FILE line will also be ignored. All of the inputs are read using free format with a space, comma, equals sign, and tab all interpreted as delimiters between input quantities.

## 3.2 Distribution Block

This section lists each of the input parameters required by FAROW to calculate the fatigue lifetime of the component, as described in Chapter 2. Each parameter can be defined as either a constant or random variable. The parameter is identified by a key word. The parameters are listed below; each subsection heading includes the key word and its definition, both of which are echoed in the output file. The section heading format is: **KEY WORD: Definition: Symbol**. Comments on usage are included, as are warnings of usages to be avoided for either physical or numerical reasons.

### 3.2.1 c: S-N Coefficient: C

The fatigue life (S-N) behavior of the material is assumed to be a straight line on a log-log plot, which is described by the function

$$N_f = CS_{eff}^{-B} \quad (3.1)$$

where  $N_f$  is the total number of cycles to failure,  $S_{eff}$  is the effective stress amplitude (see Eq. 3.2 below) and C and B are the material properties, S-N coefficient and exponent, respectively.

#### Comments

The coefficient C controls the level of the S-N curve. Changing the coefficient causes the S-N curve to shift without changing slope. Variability in C while holding B constant is often sufficient to fully represent the random nature of the material fatigue properties.

### **Warning!**

Although FAROW permits any consistent set of units, the use of small stress units may result in a value for C large enough to cause numerical problems (overflows) in the evaluation of the failure state function. It is recommended that stress units be selected to keep C well below machine overflow limits (e.g., *ksi* is better than *psi* and *GPa* may have to replace *MPa*, etc).

**Units:** Cycles\*(Stress)<sup>B</sup>, where stress units are User Specified

### **3.2.2 B: S-N Exponent: *b***

Equation 3.1 for the S-N curve defines the S-N exponent as B. The effective stress amplitude (a combination of cyclic stress amplitude and mean stress defined by Goodman's Rule shown in Section 3.2.3) is raised to the -B power.

#### **Comments**

A change in B will rotate the S-N curve about the point where the effective stress has unity value. In systems of units where unity stress is small compared to nominal loadings, variation in the exponent B will result in large shifts in the S-N curve over the entire range of interest. Therefore, it is usually not a good representation of physical variability to allow B to vary independent of C. As stated above, it is often sufficient to vary C while holding B constant. Alternatively, both parameters can be varied simultaneously to model variation in both location and slope of the S-N curve, but a high level of positive correlation will be required to maintain realistic variation of the material properties.

### **Warning!**

Values of the S-N exponent are often in the range of 5 to 12, and occasionally even higher values are reported. Remember that this implies taking stress levels to very high powers in the evaluation of the failure state function, and will yield results that are very sensitive to small fluctuations in the inputs. This reflects a physical sensitivity, but can also give numerical problems with overflows while evaluating possible values of the input variables.

**Units:** Dimensionless

### **3.2.3 ULTST: Ultimate Strength: $S_u$**

The ultimate strength is a static strength material property that affects the fatigue life results through mean stress effects. The Goodman Rule for combining stress

amplitudes with the mean stress relies on the ultimate strength in the following way:

$$S_{eff} = S_a \left( 1 - \frac{SCF|MEANST|}{ULTST} \right)^{-1} \quad (3.2)$$

where the  $a$  subscript refers to the stress amplitude and the SCF, MEANST, and ULTST refer to the parameter keywords.

#### **Comments**

The ultimate strength is often used as a point of reference for the S-N curve at one (or sometimes 1/4) cycle. In this case there should be a functional relationship between ULTST and S-N coefficient  $C$ . A high positive correlation between these parameters can be used to model this effect.

**Units:** User Specified (stress)

#### **3.2.4 MEANST: Mean Stress: $S_m$**

The mean stress is the average over time of the applied stresses at the point of interest. It is assumed that the mean stress is constant.

#### **Comments**

The ratio of the absolute value of the mean stress to the ultimate strength is used to increase the effective stress through the Goodman Rule as shown in Section 3.2.3. Therefore, variations in mean stress should be compared with the ultimate strength when checking the validity of the constant-mean restriction.

#### **Warning!**

When the product of mean stress and stress concentration factor has a significant probability of exceeding the ultimate strength (in either tension or compression) a numerical divide by zero or nonsense answers can result. A static failure, or negligibly small fatigue lifetime, is the actual result, neither of which is within the scope of this code. High mean values must be avoided through adequate static design.

**Units:** User Specified (stress)

#### **3.2.5 SCF: Stress Concentration Factor: $K$**

The RMS stress levels defined in the above relationships are assumed to be nominal stresses at some location on the component. The stress concentration



factor is applied separately to permit the user to separate the effect of uncertainty in the amplification of the nominal stress by geometric details in the region of greatest fatigue concern. The stress concentration factor is applied to both cyclic and mean stresses.

### Comments

If there is any one area that has plagued wind turbine manufacturers (and hence operators) in the past, it is the possibility of grossly underestimating stress concentrations. A designer can allow for this uncertainty by using FAROW with a high variability on SCF, but there is no substitute for a good understanding of the stress states within a geometric detail. A misunderstanding of the stress concentrations will be reflected in inappropriate inputs to FAROW, and no computer program is any better than its input.

**Units:** Dimensionless

### 3.2.6 VCHAR: Characteristic Wind Speed: $V_{char}$

The RMS stress level,  $\sigma$ , is defined as a function of wind speed by the following relationship

$$\sigma = \text{RMSC} * \left( \frac{V}{\text{VCHAR}} \right)^{\text{RMSEXP}} \quad (3.3)$$

where  $V$  is the wind speed and other variables are as described in this chapter. VCHAR is used to nondimensionalize the base of the exponent. It is also used in the equation (3.4) that defines the cycle frequency as a function of wind speed.

### Comments

VCHAR should be set to some value at which the stresses are relatively well defined, such as at the maximum wind speed for which linear aerodynamics apply. It is an anchor point in wind speed where the RMS level is unaffected by the exponent, RMSEXP, and is only affected by changes in the coefficient, RMSC (see Figure 5.4 of Section 5.2.2 for an example).

### Warning!

If the characteristic wind speed is set too low, variations in RMSEXP will cause large changes in stress levels at high winds, which may be unintended. Even if the exponent is a constant, numerical problems could

still result during the evaluation of sensitivities, where even constants are varied slightly to compute the derivatives.

**Units:** User Specified (wind speed)

### **3.2.7 RMSC: RMS Coefficient: $\sigma_{char}$**

The RMS coefficient is the rate of increase of RMS stress level with wind speed as shown in Eq. 3.3.

#### **Comments**

The value of this coefficient is equal to the RMS stress level at the characteristic wind speed,  $V=VCHAR$ .

**Units:** User Specified (stress)

### **3.2.8 RMSEXP: RMS Exponent: $p$**

The RMS stress level,  $\sigma$ , is assumed to be a monotonically increasing function of wind speed as shown in Eq. 3.3. An RMS exponent of unity gives a linear relationship. An exponent of less than one makes the curve concave downward while an exponent greater than one has the opposite effect, making the stresses increase more rapidly with wind speed above the characteristic wind speed.

#### **Comments**

A large RMS exponent can cause extremely high stress levels at high wind speeds, which may be greater than intended. Make sure to check the curve fit over the entire range of wind speeds from zero to cut-out.

**Units:** Dimensionless

### **3.2.9 ALPHAS: Stress Cycle Distribution Shape: $\alpha_s$**

Stress cycle amplitudes are assumed to be Weibull distributed with shape factor "alpha" given by ALPHAS. The " $\beta$ " parameter of the Weibull distribution is defined by the RMS and ALPHAS as described in the FAROW theory manual (Veers et al., 1994).

#### **Comments**

The Weibull family of distributions includes two of the more popular distributions, exponential and Rayleigh, as special cases. Exponential and Rayleigh distributions can be selected by setting ALPHAS to either 1 or 2, respectively. In general, the smaller ALPHAS, the fatter the high stress-amplitude tail of the distribution.

**Units:** Dimensionless



### 3.2.10 **F0: Cyclic Rate Constant: $f_0$**

The rate at which stress cycles are applied to the component is specified through the three cycle rate parameters, F0, F1, and F2, which specify constant, linear and quadratic dependencies on wind speed.

$$F = F0 + F1\left(\frac{V}{VCHAR}\right) + F2\left(\frac{V}{VCHAR}\right)^2 \quad (3.4)$$

F0 is therefore the constant coefficient defining the frequency of cyclic load application.

#### **Comments**

Each of the three frequency coefficients can have any value. However the user should insure that nonsense values of  $F$  do not result, such as negative or unintended high frequency, over the entire range of wind speeds. The sum of the three coefficients is the frequency at the characteristic wind speed.

**Units:** Hertz

### 3.2.11 **F1: Cyclic Rate Linear Coefficient: $f_1$**

The rate of stress cycles can be allowed to vary in a linear fashion with wind speed by using this parameter. The relationship between cycle rate and wind speed is shown in Eq. 3.4.

**Units:** Hertz

### 3.2.12 **F2: Cyclic Rate Quadratic Coefficient; $f_2$**

The rate of stress cycles can be allowed to vary quadratically with wind speed by using this parameter. The relationship between cycle rate and wind speed is shown in Eq. 3.4.

**Units:** Hertz

### 3.2.13 **VBAR: Average Wind Speed: $\bar{V}$**

VBAR is the average annual wind speed at the turbine site. It is used to define the Weibull wind speed distribution.

#### **Comments**

The annual average wind speed, and the Weibull distribution that it helps to define, are very important factors in the fatigue lifetime calculation.



Fatigue damage is calculated by integrating the distribution of stress cycles at each wind speed over the wind speed distribution from zero to cut-out.

**Units:** User Specified (wind speed)

### **3.2.14 ALPHAV: Wind Speed Distribution Shape: $\alpha_V$**

A Weibull distribution is used to define the long term distribution of wind speeds. ALPHAV is the "alpha" shape parameter for this distribution.

#### **Comments**

A Rayleigh distribution is often used as a generic, wide-open-spaces distribution, which can be obtained by setting  $ALPHAV = 2$ . Smaller values of ALPHAV will lead to distributions with greater amounts of time spent in the high wind tail of the distribution.

**Units:** Dimensionless

### **3.2.15 VMAX: Cut-Out Wind Speed: $V_C$**

The cut-out wind speed is the maximum wind speed for which the wind turbine is assumed to operate. The integration over wind speed for fatigue damage accumulation is truncated at VMAX.

#### **Comments**

The cut-out wind speed is a fixed truncation for the integration of fatigue damage. FAROW uses the approximation that there is no damage at higher wind speeds. Also, the turbine is assumed to always operate at wind speeds below cut-out. (The error due to machine shut-down in low winds is negligible for any case where there are significant increases in RMS stress response with wind speed.) Allowing VMAX to be a random variable does not model the case of cut-outs that vary over time, but rather models the case where there is a fixed, but uncertain cut-out wind speed.

**Units:** User Specified (wind speed)

### **3.2.16 DELTA: Miner's Damage Summation at Failure: $\Delta$**

DELTA is the value of the Miner's rule summation at which failure is assumed to occur. Unity is traditionally used. It can also be interpreted as the ratio of the actual time to failure divided by the predicted time to failure to reflect bias in the cumulative damage analysis.

#### **Comments**

Miner's rule works by summing the damage (reciprocal of the constant amplitude number of cycles to failure) from each stress cycle until the total

equals one, at which time failure is assumed. There have been numerous cases in the literature where Miner's rule is consistently biased, predicting lifetimes either too long or too short. Setting DELTA to a value other than unity is a means of accounting for this bias. Also, allowing DELTA to be a random variable is a good way to model the uncertainty in the accuracy of the fatigue analysis.

**Units:** Dimensionless

### **3.2.17 AVAIL: Availability: A**

Availability is the ratio of the amount of time a turbine is available to run divided by the total time. No turbine is ready to run at all times. Typical values of availability for the best turbines will be in the mid-ninety percentiles. AVAIL is a factor applied to the damage summation that gives credit for the down time during which damage will not be accumulated. AVAIL should be a number less than or equal to one.

#### **Comments**

Because of the restricted range of realistic values for AVAIL, it is not expected to play an important role in the component fatigue reliability calculations. It is only included for completeness.

#### **Warning!**

Permitting very low values for AVAIL may give more credit for down time than is prudent, resulting in overly optimistic reliability estimates.

**Units:** Dimensionless

### **3.2.18 TARLIF: Target Lifetime: $T_t$**

The target lifetime sets the goal against which the calculated lifetimes (using possible values of the parameters defined as random variables) are compared. A calculated lifetime less than the target is defined as "failure" in the reliability sense. The results of the reliability calculation include the probability that the actual lifetime will be less than TARLIF.

#### **Comments**

Although TARLIF, like all the input parameters, is permitted to be defined as a random variable, it is expected that TARLIF will find its greatest use and simplest interpretation as a constant. It is feasible, however, that a user may wish to make it a random variable, perhaps to reflect an uncertain time to economic replacement of the component of interest.

**Units:** Years

### 3.3 Distribution Function Library

The user must select the probability distribution type for each of the parameters in the distribution block from a small library of distribution functions. The pdf's include Normal (or Gaussian), Log-normal, Weibull, 4-moment Hermite, Uniform and Triangular. The first three distributions cover a wide range of distribution types, with the Weibull including the exponential and Rayleigh as special cases.

Table 3.1 shows the distribution types, input codes and coefficients needed to specify each type. There are a maximum of four coefficients for each distribution although most make use of only two. The distribution number is used to specify the distribution type in the input file.

3

Table 3.1: Library of distributions supported by FAROW.

<u>Code</u> <u>Number</u>	<u>Type</u>	<u>Coeff 1</u>	<u>Coeff 2</u>	<u>Coeff 3</u>	<u>Coeff 4</u>
0	Constant	Value			
1	Normal	Mean	Std Dev*		
2	Log Normal	Mean	Std Dev		
3	Weibull	Mean	Std Dev		
4	Hermite	Mean	Std Dev	Skewness	Kurtosis
5	Normal	Mean	COV**		
6	Log Normal	Mean	COV		
7	Weibull	Mean	COV		
8	Uniform	Min	Max		
9	Triangular	Min	Max	Most Likely	

\*Std Dev is standard deviation.  
\*\*COV is coefficient of variation.

Each of the 18 user-specified parameters is associated with a key word in the input file. The code numbers shown in Table 3.1 allow the user to specify each parameter as either a constant quantity or as a random variable. Each line of input starts with the key word and distribution code followed by the coefficient values needed to specify the selected distribution (or constant). Table 3.2 shows one example. The key words can be entered in any order, permitting the users to organize the input in any way that makes sense to them. The output mirrors the input ordering. No key words can be omitted.

Table 3.2:  
Example input of distribution types from the FAROW input file.

*START_DIST				
SCF	2	3.5	.35	
ALPHAS	2	2	.1	
VCHAR	0	10		
VMAX	0	25		
F0	7	1.5	.2	
F1	1	0	.1	
F2	1	0	.1	
MEANST	1	1	3.0	
ULTST	6	245	.1	
VBAR	7	6.3	.05	
ALPHAV	7	2	.1	
C	5	4.946E21	.6	
B	0	7.3		
RMSC	7	4.5	.05	
RMSEXP	6	1	.05	
DELTA	9	0.5	2.0	1.0
AVAIL	8	.9	1.0	
TARLIF	0	20		
*END_DIST				

### 3.4 Correlation Block

Correlation between random variables is defined in the \*START\_CORRELATION, \*END\_CORRELATION block. Initially, all variables are uncorrelated. Do not correlate a parameter defined to be constant (or with a standard deviation of zero) to anything. Do not correlate a variable to itself. To correlate two random variables, use their key words. It does not matter which is listed first. The value of the correlation coefficient must be between -1.0 and 1.0.

If there are no correlated variables, the block markers must be entered as follows:

```
*START_CORRELATION
*END_CORRELATION
```

Table 3.3: Example input for correlations given the above distribution parameters:

```
*START_CORRELATION
F1      F2      -.3213
C       ULTST   .8
ALPHAV  VBAR    -.5556
F2      RMSEXP  .3
MEANST  RMSC    .1
F0      RMSEXP  .25
SCF     RMSC    -.15
RMSC    ALPHAS  .5
*END_CORRELATION
```

The DIST block must precede the CORRELATION block in the input file because FAROW transforms the physical correlation, given as input, to a correlation that exists between standard normal representations of the correlated variables. Since the distribution types of the correlated variables dictate the degree of correlation in this standard normal space, the distribution types must be known a priori.

### 3.5 Target Lifetime Block

The range of target lifetimes is used by the program to compute the failure probabilities as a function of time. The user enters the minimum lifetime, the maximum lifetime and the step size.

Table 3.4: Example input for target lifetime:

```
*START_LIFETIME
MIN      5
MAX     30
STEP     5
*END_LIFETIME
```

### 3.6 Other Input Block

Table 3.5: Example of OTHER input section.

```
*START_OTHER
RELAX
0.
NSIM
0
SEED      1310717421
*END_OTHER
```

The block \*START\_OTHER, \*END\_OTHER has three parameters. They are RELAX, NSIM and SEED. The RELAX parameter controls the steps in the first order reliability method and must be between 0.0 and 1.0. A larger relaxation gives smaller steps. Zero is suggested unless there are convergence problems. If the simulation parameter NSIM is set to any number other than zero, Monte Carlo simulations are performed until NSIM

number of failures have occurred. The user can change SEED in order to generate different random numbers. SEED must be an integer between 0 and 2,147,483,648 (which is  $2^{31}$ ). The seed is only used if  $NSIM > 0$ .

For the OTHER block of input, the value of the parameter may be entered either on the same line or on the line below the key word.

### 3.7 Sensitivity Block

The final input block is for sensitivity. Its only function is to turn sensitivity calculations on or off. If anything other than YES is entered in this block, or if the entire block is omitted, sensitivity calculations will not be performed.

Table 3.6: Example of SENSITIVITY input section.

```
*START_SENSITIVITY
YES
*END_SENSITIVITY
```

### 3.8 A Note on Units

The only hardwired units in the FAROW code are the input quantities of frequency, which are assumed to be in units of cycles per second (Hertz), and target lifetime, which is assumed to be in units of years. The output quantity of mean time to failure has the dimension of years as well. All the other user-

specified inputs can be in any consistent set of units. Table 3.7 summarizes the units defined by FAROW and left to the user.

Table 3.7 Units associated with FAROW key words.

Specified By	Units	Key word
	Dimensionless	B, SCF, RMSEXP ALPHAS, ALPHAV DELTA, AVAIL
User	<i>Stress</i>	C, RMSC, MEANST, ULTST
	<i>Wind Speed</i>	VCHAR, VBAR, VMAX
FAROW	Hertz	F0, F1, F2
	Years	TARLIF

3

It is important that the user carefully check for consistency, especially between material properties and applied stresses. Also, the fatigue properties of the material need to be specified in terms of stress *amplitudes* (half of the difference between maximum peak and minimum valley), not stress *ranges* (full difference between peak and valley). The internal Weibull stress cycle distribution based on the RMS level of the instantaneous stress gives stress amplitudes. If the material properties are obtained in terms of ranges, you can convert to amplitudes by dividing the S-N coefficient, C, by  $2^B$  (see Eq. 3.1) and leaving the exponent unchanged.

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## **4 Output Details**

While the meaning of most of the results of a FAROW analysis is obvious, additional background is useful for the correct interpretation of some output. While a “probability of failure” before a target lifetime has a certain intrinsic meaning, it may be less obvious what the “reliability index” means or how you might use the sensitivity of this index to an input COV. These and other issues of this kind are addressed in this chapter.

Particular users will find different sections of the output more useful than others. Many of the initial users of the program found that simply getting a quick mean lifetime calculation from the average values of the input parameters was very useful (mostly because of the ease of input and speed of response). Others may use the sensitivity estimates to quantify the changes in specific inputs needed to achieve a reliability objective. Both users will find what they need in the output file.

### **4.1 Mean Lifetime**

The first result printed out by FAROW is the mean lifetime. This value is obtained by selecting the median values for all the random variables and calculating the resulting lifetime. (When the inputs are correlated, the medians of the conditional distributions are used.) This representative life, reported in units of years, can be very useful when the FAROW program is first applied to a specific fatigue problem. It provides an estimate of roughly where the design stands in a mean sense. If the mean life is anywhere near the target life (including less than the target) there is little need to proceed with a detailed probabilistic analysis; the design is most likely inadequate. On the other hand, an extremely large mean lifetime could result in numerical problems in evaluating the vanishingly small ( $<10^{-12}$ ) probability of premature failure. Evaluating this small probability of failure exactly is also of little interest because the important result is that the design for fatigue is overly conservative. However, applications with mean lifetimes of thousands of years may still have significant probabilities of failure in a relatively short time if the uncertainties are large enough.

## 4.2 Probability of Failure and Reliability Index

Failure is defined in this context to be not just fatigue failure, but a fatigue failure in less than the specified target lifetime. Because of the common usage of the term in fatigue applications to mean simply the point at which the component has broken, we sometimes use the term premature failure to describe failure in the reliability sense. The probability of failure in the reliability sense is just as it seems. It is the probability, given the random variable definition of the input parameters, that the component will break in less than the target lifetime.

FAROW calculates the probability of premature failure with an integration over the combination of possible values that can combine to produce this premature failure. That integration is first done using a first order (flat) approximation to the shape of the failure surface. Then the calculation is repeated using a second order (curved) approximation as well. These estimates are called the FORM (first order reliability method) and SORM (second order reliability method) results. Since SORM is a more accurate estimate than the FORM result, comparing the two is an excellent way to see roughly how accurate the estimates are. The exact result should be within a distance of the difference between the two from the SORM result. The FORM and SORM probabilities of failure and reliability indices are both calculated and printed by FAROW. FAROW also prints an IMPROVEMENT FACTOR, which is the ratio of the SORM and FORM reliability indices. A ratio of one indicates no improvement, which in turn means that the probability of failure is well estimated even by the first order approximation. The deviation of the improvement factor from one is a good way to measure the difficulty in estimating the probability of failure and, hence, the accuracy of the estimate.

The reliability index, usually called  $\beta$ , is the one-dimensional equivalent of the number of standard deviations the target lifetime is from the mean lifetime. The probability of failure is calculated first, and the reliability index is just another way of stating the same result; it comes from a normal probability table. Probability of failure can range over several orders of magnitude and goes to zero as the reliability is increasing. The reliability index, on the other hand, always has values in the single digit range and increases as the reliability increases. The index is therefore a useful tool in communicating how the reliability changes with adjustments to the design or operating conditions of a turbine. It also behaves

much better than probability of failure in sensitivity estimates because it does vary over such a wide range.

### 4.3 Importance Factors

The importance factors are the relative contribution of each random variable to the failure probability. To understand them, it helps to be acquainted with the concept of the design point. The design point is the most likely combination of values to result in failure exactly at the target lifetime. This is the closest you can get to the median value of each random variable (and produce failure at the target lifetime) without simultaneously moving one or more of the other variables away from their medians by a greater amount.

When a particular random variable has an importance factor near zero, its design point value is near its median. In other words, it didn't matter much that that variable was random, it might just as well have been a constant equal to the median. Variables with large importance factors are associated with design point values far from the median, which have smaller probabilities of occurrence. These are the variables that control the probability of failure and are therefore called the most *important*.

Without getting into needlessly complicated details, importance factors are actually the direction cosines of the vector of all random variables at the design point. The squared values must therefore sum to one and are a good way to represent relative fractions (or percentages) of each random variable's contribution to the failure probability.

The design point portion of the FAROW output includes the importance factors and a few other useful quantities in a table (see Appendices B and C). The first column contains the key word that identifies the random variable. Importance factors are listed in the fourth column accompanied by a bar graph to provide a visual highlight. The fifth column is the squares of the importance factors, which represent the percentages of the probability of failure attributed to each random variable. The second and third columns can be useful too. The second column is the physical value of each random variable at the design point. This set of values will produce a lifetime exactly equal to the target lifetime. It may be instructive to compare this combination of values to what might have been selected using



conservative engineering judgment in a deterministic fatigue life estimate. The GAUSSIAN VALUE column shows the number of standard deviations each physical value is from the median of the distribution. (It is called “GAUSSIAN” because the calculations are done in a standard Gaussian space where one unit is one standard deviation.) Here again, it is often instructive to see how far from the median each random variable is to achieve the result. It may be surprising to see how a little deviation in each input can lead to a relatively small probability of failure.

A note should be made here with regard to the effect of correlation. As indicated previously, the user can request either uncorrelated or correlated random variables. While this choice affects internal computations within FAROW, the interpretation of most output is unchanged. One exception to this, however, regards the reported importance factors. If correlation is present, FAROW models it sequentially: the second variable is modeled conditionally on the first, the third on the first two, and so forth. In this case, it is most meaningful to consider the sum of importance factors over all correlated variables. The reported importance factors are in addition to all previous correlated variables; this will depend on the ordering of the correlated variables within FAROW.

#### **4.4 Sensitivities**

The final section of the program output contains the results of the sensitivity analyses. These sensitivities are computed by varying each input parameter by 10% ( $\pm 5\%$ ), computing the FORM reliability index, and dividing the change in reliability by the change in the parameter. Normalized sensitivities, obtained by multiplying the calculated sensitivity by the original value, are also computed. Zero valued parameters are also varied by  $\pm .05$  in absolute value to arrive at sensitivity estimates, although the normalized sensitivities will always be zero.

The sensitivities can be used to estimate how much a parameter needs to be changed to produce a desired movement of the reliability index. For example, multiplying the normalized values by the percentage change in the parameter gives the linear estimate of the absolute change in the reliability index. Of course, because the sensitivity is evaluated at the design point, such an estimate is only valid for small changes in the parameters.

The user is cautioned that sensitivities of the mean depend on the definition of the distribution for the random variable. For example, a random variable whose probability distribution is defined by the mean and standard deviation will have a slightly different sensitivity to the mean than the same random variable whose distribution is defined by the mean and coefficient of variation (COV). The difference arises because a change in the mean induces a change in the coefficient of variation when the standard deviation is specified. On the other hand, if the COV is fixed, a change in the mean produces a change in the standard deviation. Either representation can be implemented through FAROW depending upon the user's choice to characterize a distribution by its mean and COV, mean and standard deviation, etc. (See Table 3.1). Care should be taken to ensure that the sensitivity estimates computed by FAROW are consistent with the user's needs. In practice, the differences are usually small.

#### **4.5 Simulation**

The FAROW program has the additional capability to perform a Monte Carlo simulation to estimate the probability of fatigue failure before the target lifetime. This capability can serve as a check on the probability of failure produced by the FORM/SORM analysis. Because the accuracy of FORM/SORM estimates is best when the probability of failure is small, applications with probabilities of failure approaching (or exceeding) one-half should be checked using the Monte Carlo option. This option is invoked whenever the variable NSIM is set to any integer greater than zero. FAROW then performs a Monte Carlo simulation until NSIM premature failures have occurred. The probability of failure is the ratio of the number of failures to the total number of simulations needed to produce those failures. Be aware that when the simulation option is invoked only the failure probability is computed and printed. The other outputs described here in Chapter 4 are not calculated.

#### **4.6 The .LOG File**

The ".LOG" file contains information that is generally of little interest, unless something goes wrong. All the messages that come to the screen during program execution are echoed to the ".LOG" file. It also includes warnings and error messages if the program is having trouble converging on a solution. In this case, the output to the ".LOG" file includes some cryptic information called "FU",

which indicates the error at each solution step and is therefore a measure of the rate of convergence. The user can determine how much difficulty FAROW is having converging by how many times "FU" is printed out. The GAUSSIAN VALUE of each random variable is also printed; the user may determine which random variables are having difficulty in converging by examining the history of changes.

## **5 Examples**

It may be simplest to get started by working through a couple of examples that show how a fatigue reliability problem might be approached. Two specific examples are included here, one of a real system and another of a hypothetical situation. These examples should not restrict the user's creativity in applying this rather powerful tool for probabilistic analysis, but are intended to give some initial guidance. In each example a parameter is varied to illustrate a point.

The first example is the kind of analysis one might encounter in the final design stages of a machine where there has already been extensive testing and data analysis so that the uncertainty in many of the inputs is fairly small. Data are taken from the 34-m Test Bed in Bushland Texas, a machine designed and tested by Sandia National Laboratories. In this example the distribution type used to describe the S-N curve is varied to illustrate the possible effects due to this choice.

The second, hypothetical example represents an attempt to deal with the uncertainty in fatigue analysis of a typical fiberglass HAWT blade early in the design stages, before any test data are available, and while detailed analysis may be in progress. Many more parameters are uncertain than in the first example, and levels of uncertainty are generally higher. We also examine the effect of changing the stress amplitude distribution type between two ends of the range of typical Weibull distribution shapes: the exponential and Rayleigh special cases.

As stated in the explanation of the fatigue analysis assumptions in Chapter 2, there are five specific areas of information required to conduct a fatigue analysis of a component:

1. wind-speed distribution,
2. RMS of the instantaneous stress at the point,
3. distribution of stress amplitudes,
4. S-N curve, and
5. average damage rate per time.

The input parameters that define each of these areas are described for the examples below.



## 5.1 Example 1: Extensive Test Data

The 34-m Test Bed VAWT in Bushland, Texas has been operated since 1988 with extensive instrumentation to collect wind-speed and operational-stress data. The aluminum material of which the blades are extruded has also been well characterized. A reliability analysis of the fatigue of blade joints on this turbine therefore has many inputs that are relatively well nailed down. However, there has been no component testing to establish fatigue properties of the joints, or even stress concentration factors. There remain some inputs with high uncertainty. The specific inputs to a reliability analysis follow.

### 5.1.1 Wind Speed Distribution

Extensive measurements have been made at the Bushland site. Historical data are also available from the Amarillo Airport about 30 miles away across flat terrain. The distributions measured at these two sites are plotted in Figure 5.1 along with a

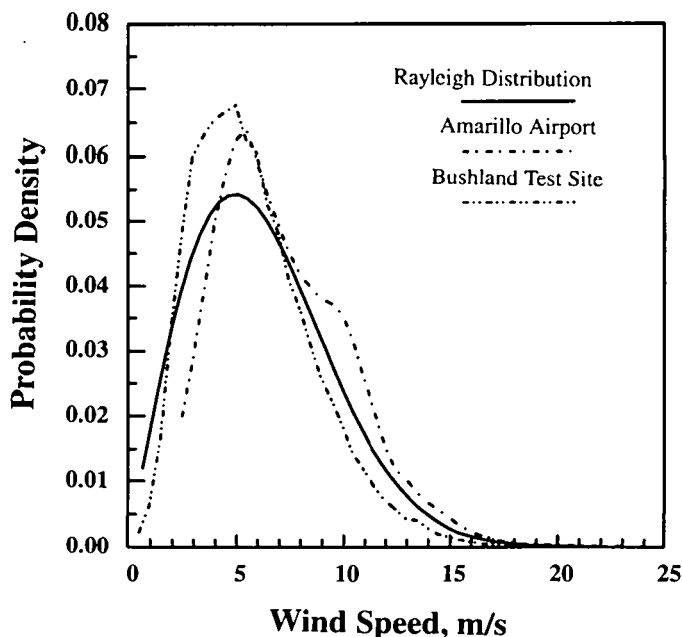


Figure 5.1: Wind speed distributions from Amarillo and Bushland, Texas, as well as the theoretical Rayleigh distribution with a 6.3 m/s mean.



Rayleigh distribution. The mean wind speeds  $\bar{V}$  for Bushland and Amarillo are 6.2 and 6.6 m/s respectively, and the high wind tails of the distributions are quite different. To model this uncertainty in the local distribution, the FAROW parameters of  $\bar{V}$  and  $\alpha_V$  are defined as random variables with means of 6.3 and 2.0, respectively. The mean wind speed is assumed to have a COV of 0.05 while the shape parameter,  $\alpha_V$ , is given a larger COV of 0.1. The result is an uncertain wind speed distribution that is a perturbation about a Rayleigh distribution (implied by the mean  $\alpha_V$  of 2.0) with mean of 6.3 m/s. Both parameters are assumed to be normally distributed by selecting distribution code 5.

### 5.1.2 RMS of the Instantaneous Stress

After viewing copious data sets reduced in the form of RMS stress vs. wind speed, it was clear that the RMS stress increases linearly with wind speed, even up to the highest wind speeds for which data are available. The value of the nominal RMS stress at the highest stressed location (an upper blade to tower joint) has a value of 4.5 MPa at 10 m/s. This relationship is specified by setting  $RMSC = 4.5$ ,  $RMSEXP = 1$ , and  $VCHAR = 10$ , with only  $RMSC$  treated as a random variable while the exponent and characteristic wind speed are defined as constants. Because there is a great deal of data available, a relatively small variation,  $COV = 0.05$ , was chosen for the RMS constant, which is also assumed to be normally distributed.

The stress concentration factor has not been predicted or measured with accuracy. The best guess for this heavily bolted joint is that  $SCF$  has a mean of 3.5 and a  $COV$  of 0.10.

### 5.1.3 Distribution of Stress Amplitudes

Stress time series were rainflow counted and the histograms of the amplitudes were plotted, indicating a very good fit to a Rayleigh distribution. (The distribution of stress amplitudes is expected to vary for different machine types, as some HAWT data have shown, e.g., Jackson, 1992). FAROW's Weibull form of the stress amplitude distribution is fixed at a Rayleigh distribution by setting  $\alpha_S$  to a constant value of 2.0.

### 5.1.4 S-N Curve

The blades and joints are made of 6063-T6 aluminum extrusions for which extensive fatigue test data are available. The test data are shown in Figure 5.2, normalized to an effective stress amplitude as used by FAROW (see Section 2.1). Notice that there are two distinct straight line portions of the fit to the data. We choose here to use the low cycle portion and extrapolate to higher cycles for two reasons (Mitchell, 1979). First, it is a conservative approach. Second, there has been evidence that fatigue limits and kinks in the constant amplitude S-N curve are washed out by variable amplitude loadings. That is, constant amplitude loadings at low level do not exceed certain material constraints and cause little damage, while in variable amplitude loadings the large loads eliminate those constraints and enable more damage from the smaller cycles. The least squares fit

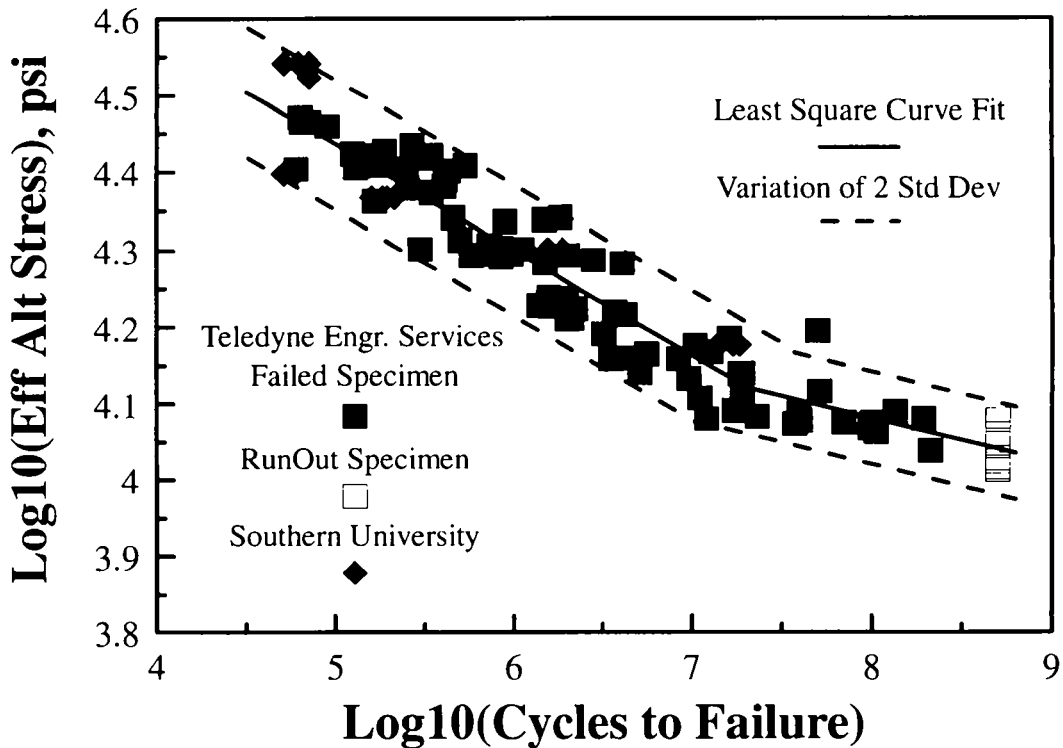


Figure 5.2: Effective stress amplitude versus cycles to failure (S-N) for 6063 aluminum alloy.

to the data gives an exponent, B, of 7.3 with a coefficient, C, of  $5 \times 10^{-21}$  (based on stress units of MPa). The distribution of the data about the least squares line fits a Weibull distribution with a COV of 0.613.

The mean stress and ultimate strength are needed to define the effective stress amplitudes using a Goodman rule. The mean stresses have been measured near the joint, but vary substantially along the blade span, resulting in a high uncertainty for the actual local mean. The mean stress is defined to be normally distributed with mean of 7.0 MPa with a COV of 0.20. The ultimate strength of the extruded aluminum material has been measured and is set to a constant value of  $ULTST = 285$  MPa.

### 5.1.5 Average Damage Rate

The parameters needed to complete the calculation for the average damage rate include VMAX, F0, F1, F2, DELTA, and AVAIL. VMAX is set to a very high value of 50 m/s to produce a situation where the turbine is always operated. The frequency of cycles has been measured and found to be relatively independent of wind speed, but it does vary from data sample to data sample. F0 is set to a normally distributed random variable with mean 2.0 and COV of 0.20. F1 and F2 are both fixed at zero. DELTA and AVAIL are both set to unity with no variation for this example.

### 5.1.6 Discussion of Results

The entire output file from FAROW is printed in Appendix B. It shows both an echo of the input data and the results of the analyses. Specific results are discussed below.

**Mean Lifetime and Probability of Failure:** The mean time to failure in this example is 327 years, which may seem like a huge buffer for a 20-year design life. Actually, it is not so large as it seems, but might be enough, depending on what is an acceptable risk on the investment. The calculated probability of failure in less than 20 years is about 3%. Given the first order (FORM) estimate of 2.5% and the second order (SORM) estimate of 3.1%, the exact probability of failure can be safely estimated in the range of 2.5 - 3.5%. The calculations over a 10- to 30-year span of target lifetimes (shown in Appendix B) indicate that the probability of failure in less than 10 years is only 1%, and in less than 30 years is about 5%.

**Reliability Index:** The reliability index, which is a notional "distance from the mean" of the target lifetime in units of standard deviations, is 1.87 in this example. This indicates that of all possible values of the calculated lifetime, the target lifetime of 20 years is roughly two standard deviations from the mean value of 327 years. In fact, the reliability index is calculated directly from the probability of failure from standard normal probability tables (or subroutines in the case of FAROW). This index is important because sensitivities (see below) will indicate how much changes in the inputs affect the index. The effect of input changes on the probability of failure must be calculated by the reverse process: estimate the change in reliability index and then calculate probabilities from tabulated values of the standard normal distribution function.

**Importance Factors:** Figure 5.3 illustrates the relative size of the importance factors by plotting their squares in a pie chart. (The squared importance factors must sum to 1.0.) The importance factors are dominated by the variance in the S-N coefficient,  $C$ , which accounts for about half of the total variability. The stress concentration factor and wind speed distribution shape factor come in second and third with about 24% and 14% respectively. The rest of the random variables contribute negligibly. This situation is what might be expected at the stage of product development when the substantial prototype testing has reduced the uncertainty in stress response quantities. It also makes it clear that component testing and analysis to determine the stress concentration due to geometric details is very important in increasing rotor reliability.

**Sensitivity Estimates:** The reliability is most sensitive to changes in the S-N exponent. This should come as no surprise after an inspection of Equation 2.6 for calculated lifetime. The exponent applies to most elements of the fatigue life expression, as well as appearing in factorials within the expressions. However, the exponent is usually treated as a constant, as in this example, and does not contribute to the probability of failure; the uncertainty has been absorbed into the S-N coefficient.

Normalized sensitivities to the mean values of a number of input quantities are nearly equal: SCF, VCHAR, VBAR, RMSC. The sensitivities are somewhat lower, but by less than a factor of two for ALPHAV, ALPHAS, and RMSEXP. All of the normalized sensitivities to the standard deviations (or COVs) of the random

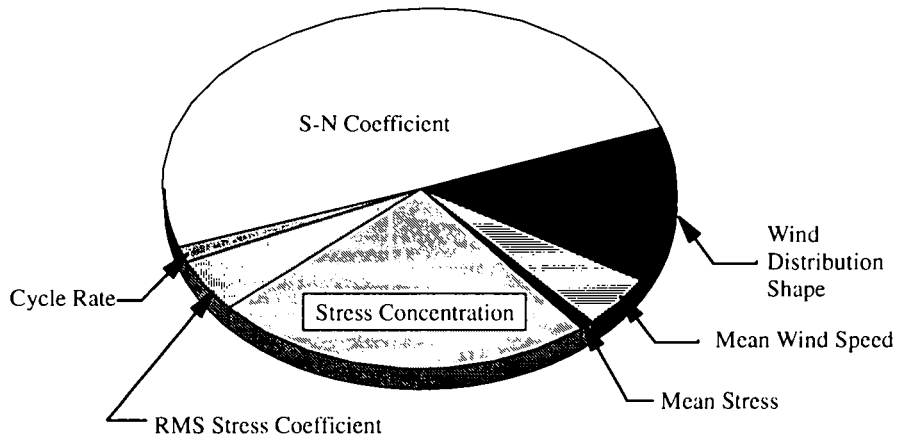


Figure 5.3: Relative importance factors as fractions of the total influence on probability of failure.

variables are substantially lower. This mitigates the importance of specifying the precise value of the variance for each of the random variables, indicating that the estimated reliability is much more sensitive to the mean values of the inputs. However, it may be much more likely for a large error to be made in specifying the variance of a random variable than in specifying the mean.

Sensitivities can be used to numerically estimate how much any single input would need to be changed to achieve a desired increase (or decrease) in the reliability. For example, suppose a target reliability index of 2.0 is desired, an increase of about 10% above the FAROW estimate of 1.87. This can be achieved by reducing the uncertainty in the stress concentration factor by about 24% (10% divided by 0.4232), which means the input COV of 0.10 would have to be decreased to 0.075. But to achieve the same result by decreasing the uncertainty in the RMS stress levels, RMSC, would require a 106% reduction in the input COV (10% divided by 0.0937), which is well beyond the extent of the linear sensitivity estimate and may be impossible to achieve. Thus, use of the sensitivities can establish what reliability improvements are possible, and how such improvement might be achieved. This is useful information for determining where additional investment in testing and analysis to reduce uncertainty can have the greatest pay-off in reliability improvement.

5

## 5.2 Example 2: Limited Test Data

This example represents an earlier point in the design/development process, the design stages before any hardware has been built, but perhaps while analyses of the parts and loadings are in progress. The number of uncertain parameters is therefore greater, and some of the levels of uncertainty may be higher.

This example is for a HAWT blade built of a mostly unidirectional fiberglass composite material. Material testing has not been done on the specific blade material, but published data from similar materials are available. Stress levels have been predicted with relatively high confidence, at least in wind speeds below stall. We assume a stall-controlled machine operating at variable speed in low winds (fixed pitch) to optimize efficiency. The objective is to have a very low probability of failure in the first five years of operation.

### 5.2.1 Wind-Speed Distribution

The prospective sites are varied, but are generally assumed to have average wind speeds in the neighborhood of 7.5 m/s with uncertainty in the high wind-speed distribution content. Therefore, both  $\bar{V}$  and  $\alpha_V$  are defined as random variables.  $\bar{V}$  is normally distributed with a mean of 7.5 and a standard deviation of 0.5.  $\alpha_V$  is taken to be Weibull distributed with a mean of 1.8 and a COV of 0.1. The Weibull is chosen because it has a relatively "fatter tail" on the low side, which is the more damaging value for wind-speed distribution shape factors (i.e., smaller shape factors result in wind-speed distributions with greater frequency of high winds).

The mean wind speed has been correlated to the shape factor in this example. A positive correlation of 0.5 models a tendency toward a smaller tail (due to a larger shape factor) whenever the mean value is higher than average. The result is a wind-speed distribution where the tail region tends to stay the same while the middle region shifts. Of course this is only a tendency; concurrent increases in both the mean and tail are still possible.

### 5.2.2 Instantaneous Stress at the Point

The nominal flapwise-bending stresses are represented by a mean stress of 3.5 ksi with an RMS variation about the mean of 0.4 ksi in the blade root region for steady state operation at the characteristic wind speed of 10 m/s. The nominal

uncertainty in stress predictions leads to assessment of a 10% COV on RMSC, which is taken to be normally distributed about the 0.4 ksi mean value. Let's assume stresses have been predicted to increase linearly with wind speed. Because of the uncertainty of the stress predictions above stall, the parameter RMSEXP is defined as a normally distributed random variable with mean 1.0 and 20% COV. Variations in this exponent have the effect of "wagging the tail" of the RMS stress vs. wind-speed curve at high wind speeds as illustrated in Figure 5.4. The mean stress is assumed to have a normal distribution with a COV of 20%.

The highly uncertain stress concentration factor,  $K$ , is taken to be log-normally distributed with mean 1.5 and COV = 0.2. The log-normal is chosen because it has a fatter tail on the high end, which is the most dangerous for stress concentrations.

### 5.2.3 Distribution of Stress Amplitudes

The rainflow counted stress amplitudes from flapwise loads on HAWT blade roots have at times been shown to be exponentially distributed. We assume that the analysis in this example supports this evidence. The parameter  $\alpha_S$  is therefore taken to be narrowly distributed (COV of 0.05) about a mean value of 1.0.

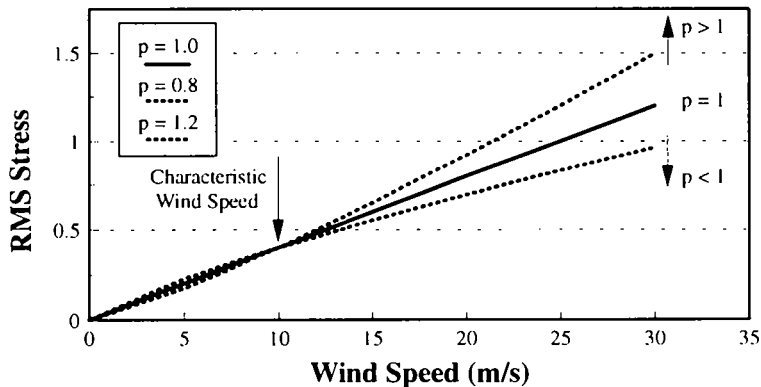


Figure 5.4: Illustration of the FAROW model for RMS stress level versus wind speed. The variable  $p$  has the effect of "wagging the tail" of the RMS stress at high winds.

### 5.2.4 S-N Curve

Materials data on mostly unidirectional fiberglass composites can be found in Mandell et al. (1992), Figure 5.5. The S-N data in this report, however, are reported in the form of peak stress divided by ultimate strength, at a stress ratio (maximum divided by minimum) of 0.10, versus cycles to failure. Cumulative damage assessment in FAROW and elsewhere is typically done using stress mean and amplitude. The data do not convert simply from one form to the other; a straight line log-log plot in one form will be curved in the other form. Mandell's data have been converted to mean and amplitude using Goodman's rule in the same way it is applied in the FAROW fatigue formulation. The two curves are shown along with the data in Figure 5.5. The resulting expression for fatigue life as a function of effective stress is

$$N_f = CS_{eff}^{-b} ; C = \frac{S_u^{10}}{10} , b = 10 . \quad (5.1)$$

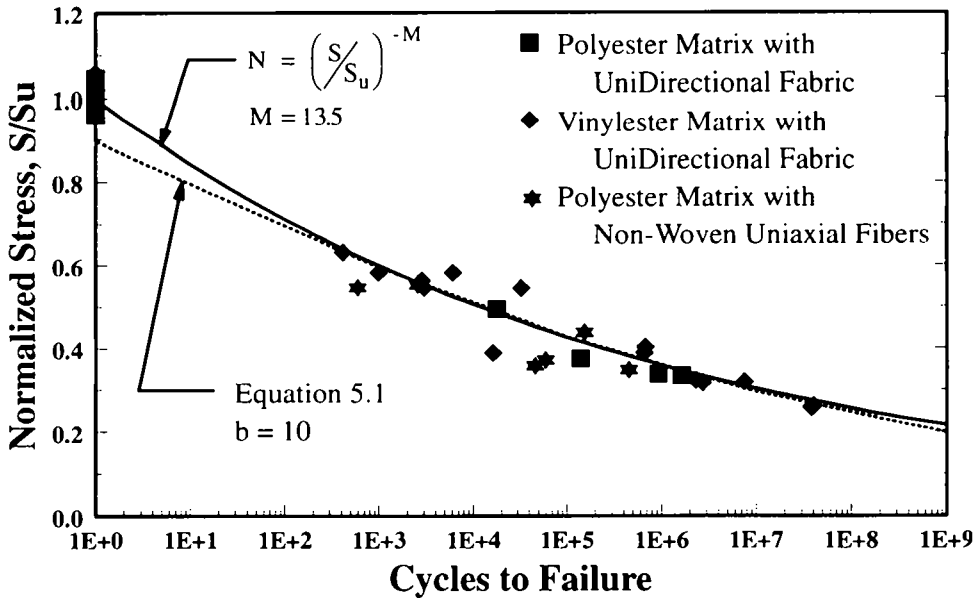


Figure 5.5: S-N data and curves for uniaxial fiberglass composite (from Mandell, et al., 1992).



As shown in the figure, this fit is almost indistinguishable from the original in the range of the test data, between  $10^3$  and  $10^7$  cycles to failure. It falls slightly below the Mandell fit at higher and lower cycles to failure. Notice that the change from peak stress to effective stress amplitude results in a slight reduction in the S-N exponent,  $B$ , from Mandell's  $M = 13.5$  to  $b = 10$ .

The S-N coefficient,  $C$ , in this formulation is functionally related to the ultimate strength,  $ULTST$ , through Eq. 5.1. Given an ultimate strength of 85 ksi, the S-N coefficient will be  $2 \times 10^{18}$ , with the obscure units of: (ksi)<sup>10</sup> cycles.  $C$  and  $ULTST$  are assigned a correlation of 0.9 to simulate the functional dependence. The variance in  $C$  is used to represent not only the variation in material properties, which alone usually result in COVs > 0.5, but also must reflect the fact that the referenced S-N data used to estimate the material parameters are not based on the actual material to be used in the blade. The S-N coefficient is here chosen to be Weibull distributed with the above mean and a 0.7 COV. The exponent is fixed at  $B = 10$ .  $ULTST$  has been given a normal distribution with a mean of 85 ksi and a COV of 0.1.

### 5.2.5 Average Damage Rate

All of the remaining parameters except those controlling the cycle rate are chosen to be constants. The cut-out wind speed is selected to be 25 m/s. The Miner's rule constant  $\Delta$  is fixed at unity (although it might be good practice to assign some healthy uncertainty to this parameter when dealing with composite materials). The availability is also set to one.

The frequency here is modeled in some more detail to treat loading on this variable speed rotor. To achieve a cycle rate of one Hz at zero wind speed, 2 Hz at 10 m/s, and a maximum of 2.5 Hz in high winds, the cycle rate coefficients are given mean values of  $F0 = 1.0$ ,  $F1 = 1.25$ , and  $F2 = -0.25$ . The resulting mean curve for cycle rate versus wind speed is shown in Figure 5.6. All three coefficients are assumed to be uncertain:  $F0$  is assigned a log-normal distribution with a COV of 0.20, while the others are assigned normal distributions with COVs of 0.10. The log-normal is used because it has a "fatter tail" on the high side, which is the worst case for cycle rate. To keep the sum of the coefficients from wandering too far from the stated value of 2.0 Hz at the characteristic wind speed of 10 m/s, some negative correlation is assigned between  $F1$  and  $F2$ . That

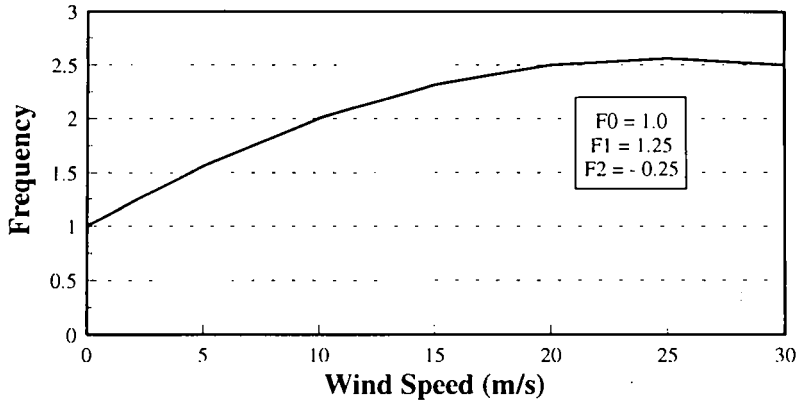


Figure 5.6: Example stress cycle rate versus wind speed model.

way, a higher realization of one will more likely be coupled with a lower realization of the other, keeping the sum more stable. The constant coefficient is allowed to vary more freely to reflect the possibility of a poor over-all prediction of the average cycle rate.

### 5.2.6 Discussion of Results

The entire output file for this example is printed in Appendix C. It shows both an echo of the input data and the results of the analyses. Specific results are discussed here.

**Mean Lifetime and Probability of Failure:** By substituting the median values for all the random variables defined above, and using the constant values for all the other input parameters, a mean lifetime of 600 years is calculated. The probability of failing in less than the five-year target, however, is estimated at 7.6%, illustrating both the uncertainty in the fatigue life calculation given reasonable uncertainty in the inputs and the sensitivity of fatigue life to parameter variation. In addition, FAROW prints out the probability of premature failure for a user-specified range of target lifetimes, plotted in Figure 5.7.

**Reliability Index:** Because probabilities of failure can range over orders of magnitude as reliability increases and probability of failure approaches zero, a more well-behaved reliability index is usually defined. The reliability index is the distance from the mean, measured in standard deviations, of the design point (the

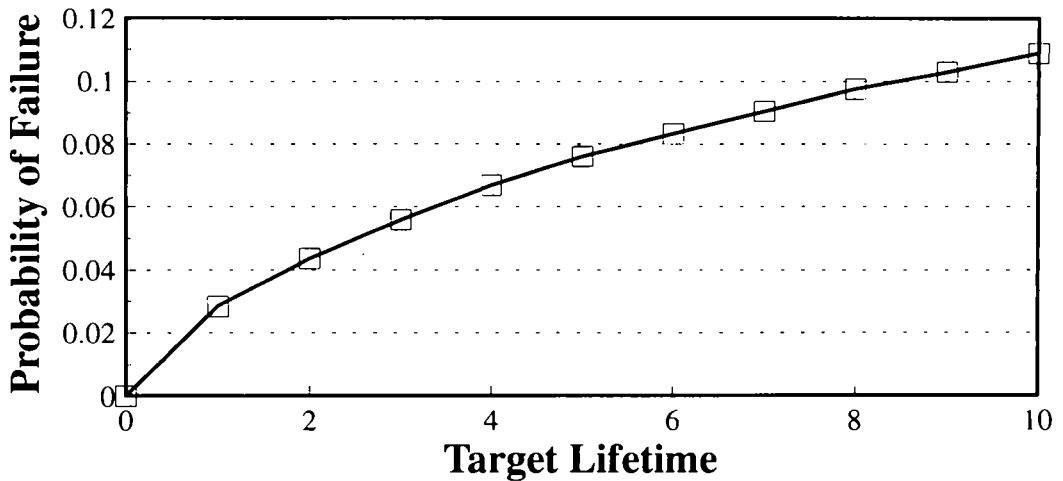


Figure 5.7: Example FAROW results for probability of premature failure as a function of target lifetime.

most likely combination of values that, when substituted into the deterministic analysis, produce failure at the target lifetime). For example, a "three sigma" probability of failure of 0.0013 would be associated with an index of 3.0. This keeps the index limited to small values and produces a measure that increases as reliability improves. The reliability index in this example is 1.43.

**Importance Factors:** FAROW also determines how much each of the uncertain inputs contributes to the probability of failure. Appendix C shows the FAROW output file segment that contains these importance factors. Notice that importance factors only apply to inputs with non-zero variance, and not to parameters defined as constants. The values of the random variables at the design point are listed under the PHYSICAL column. Also printed are GAUSSIAN values, which are the number of standard deviations from the mean. A GAUSSIAN value near zero is associated with a low importance factor and indicates that the variable contributes negligibly to the probability of failure. It is interesting that the value of each random variable that combines to produce a five-year lifetime (120 times less than the mean lifetime) deviates less than one standard deviation from its mean.

The random variable with the greatest importance in Appendix C is the stress concentration factor ( $K = SCF$ ), with the RMS exponent ( $p = RMSEXP$ ) and stress

amplitude distribution shape factor ( $\alpha_s = \text{ALPHAS}$ ) next in line. Although the S-N coefficient ( $C = C$ ) was assigned a large uncertainty ( $\text{COV} = 0.7$ ), it is only tied for fourth in importance among the random variables in this example. Recall that in the first example of Section 5.1, where there were more data from stress measurements, S-N properties dominated the uncertainty.

**Sensitivity Estimates:** FAROW determines the sensitivity of the reliability to all input quantities, first to constants and mean values, and then to the variance of the random variables. The sensitivities are derivatives of the reliability index with respect to the input parameters. Thus linear estimates of how much the reliability can be increased by changes in the parameters are available. The entire table of sensitivity calculations are included in the output file in Appendix C. A few of the sensitivities in this example bear examining.

The greatest sensitivity to a mean value or constant is to the S-N exponent,  $b$ . But the stress amplitude distribution shape factor,  $\alpha_s$ , is a close second. While the normalized sensitivity to  $b$  is 10 (meaning a 10% change in  $b$  will change in the reliability index by 10 times 10%, or 1.0), the sensitivity to  $\alpha_s$  is 7.5. Several sensitivities are in the 2 to 3.5 range. Also, if the  $\alpha_s = 1.0$  assumption in this example is changed to the opposite extreme of  $\alpha_s = 2.0$  (a Rayleigh distribution) and the analysis is run again, the resulting mean time to failure becomes 18 million years (!) and the probability of failure in less than 5 years is  $3 \times 10^{-6}$ . This change is of course well beyond the linear approximation that can be obtained using the sensitivities.

Sensitivity to the assumed variance (standard deviation or COV) in the uncertain parameters is less than sensitivity to the mean values or constants. Sensitivity to the variance indicates how much is to be gained by reducing the uncertainty in each input. The general trends follow that of the importance factors, but not exactly. In this example, the greatest increase in reliability can be gained by reducing the variance in stress concentration factor and RMS exponent, just as might be surmised by the importance factors. But reducing the uncertainty in the S-N coefficient is a close third, higher than its importance ranking. Sensitivities to these three variances are 0.53, 0.31 and 0.27, respectively.

The sensitivities can therefore be used to estimate the value of obtaining more information. Conducting additional testing or analysis to reduce the uncertainty in

the stress concentration factor by half, from  $COV = 0.2$  to  $0.1$ , would increase the reliability index by about a quarter [the relative change in the  $COV$  ( $0.5$ ) times the normalized sensitivity ( $0.53$ ) equals  $0.27$ ]. The reduction in probability of failure associated with an increase in reliability index from  $1.43$  to  $1.70$  is obtained from a table of normal probabilities. The one-sided normal probability of being greater than  $1.7$  standard deviations from the mean is  $4.5\%$ . Thus reducing by half the uncertainty in this one parameter alone decreases the probability of premature failure by  $40\%$  (from  $0.076$  to  $0.045$ ). By contrast, reducing the uncertainty in the average cycle rate by any amount does not affect the reliability at all.



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## **6** References

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## Appendix A: Sample Input File

The entire text of an input file is listed below. It does not correspond to any example in this manual but merely illustrates the form of the input file. It could be used as a template and modified with any convenient text editor. All of the text not appearing between \*START\_name and \*END\_name lines are treated as user comments and are ignored by FAROW. Everything between the start and end statements are read and interpreted by FAROW and used to formulate the reliability analysis and control program execution. The comments can be completely deleted or can be added to without bound for clearer documentation of the intent of parameter settings. Comments are not echoed in the output file. Inputs are described in detail in Chapter 3.

This is an input file for FAROW. Comments can be placed anywhere outside of a \*START\_name and \*END\_name block. DO NOT put any comments between \*START\_name and \*END\_name. The order of each block of data between \*START\_name and \*END\_name is irrelevant, except the DIST block must precede the CORRELATION block. Within a block, the keywords may be in any order. For example, STEP could be before MIN in the LIFETIME block. The distribution library and keyword descriptions included below (FYI) may be deleted or moved if they become unnecessary.

### --- DISTRIBUTION LIBRARY ---

Code#	Distr Type	Coeff 1	Coeff 2	Coeff 3	Coeff 4
1	Normal	Mean	Std Dev*		
2	Log Normal	Mean	Std Dev		
3	Weibull	Mean	Std Dev		
4	Hermite	Mean	Std Dev	Skewness	Kurtosis
5	Normal	Mean	COV**		
6	Log Normal	Mean	COV		
7	Weibull	Mean	COV		
8	Uniform	Min	Max		
9	Triangular	Min	Max	Most Likely	

\*Std Dev is the standard deviation.

\*\*COV is the coefficient of variation.

-----  
\*START\_LIFETIME

MIN=2

MAX=20  
 STEP=2  
 \*END\_LIFETIME

```

-----
KEYWORD  DESCRIPTION
-----
C        S-N COEFFICIENT
B        S-N EXPONENT
ULTST    ULTIMATE STRENGTH
MEANST   MEAN STRESS
RMSC     RMS COEFFICIENT (RMS level at VCHAR)
RMSEXP   RMS EXPONENT
VCHAR    CHARACTERISTIC WIND SPEED
ALPHAS   STRESS CYCLE DISTRIBUTION SHAPE (Weibull shape factor)
SCF      STRESS CONCENTRATION FACTOR
F0       CYCLE RATE CONSTANT COEFFICIENT
F1       CYCLE RATE LINEAR COEFFICIENT
F2       CYCLE RATE QUADRATIC COEFFICIENT
VBAR     MEAN WIND SPEED
ALPHAV   WIND SPEED SHAPE (Weibull shape factor)
VMAX     CUT-OUT WIND SPEED
DELTA    MINER'S DAMAGE
AVAIL    AVAILABILITY
TARLIF   TARGET LIFE
  
```

Enter the keyword, the distribution type and the coefficients that define the distribution.

```

-----
*START_DIST
VBAR      6      14.      0.1
ALPHAV    6      2       0.05
C         7      3.5e15  .6
B         0      8.3
ULTST     5      35.4   .1
MEANST    5      2.174  0.2
F0        6      1.13   0.2
F1        1      0       0
F2        1      0       0
SCF       5      3.0    .1
ALPHAS    2      2       0
VCHAR     5      25     0
VMAX      5      45     0
RMSC      5      .765   .05
RMSEXP    5      1.00   .1
DELTA,1,1.0,.1
AVAIL,1,0.95,.05
TARLIFE,0,10
*END_DIST
-----
  
```



-----  
\*START\_CORRELATION  
C       ULTST 0.75  
\*END\_CORRELATION  
-----

RELAX must be between 0. and 1. inclusive. A larger relaxation  
gives smaller steps in FORM.  
For NSIM > 0, Monte Carlo simulations are performed until NSIM  
failures have occurred.  
Enter a large SEED number if NSIM > 0. (SEED < 2\*\*31)

-----  
\*START\_OTHER  
RELAX=0  
NSIM=0  
SEED  
131071  
\*END\_OTHER  
-----

If you want sensitivity calculations, enter YES. Otherwise,  
enter NO.

-----  
\*START\_SENSITIVITY  
YES  
\*END\_SENSITIVITY  
-----

\*END\_OF\_FILE

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## Appendix B: Example 1 Output File

The entire output file from Section 5.1 is listed here. The output file contains an echo of the inputs, a summary of internal variables used by FAROW to complete the calculations, the probability of failure and reliability index, the importance factors, and the sensitivities. A discussion of the results is included in Section 5.1.6.

FAROW Version 1.1 9/94  
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DATE: 09/26/94  
 TIME: 14:29:41  
 TITLE: Example from Section 5.1: Extensive Test Data

===== INPUT SUMMARY =====

\* \* I N P U T P A R A M E T E R S \* \*

KEYWORD	DESCRIPTION OF KEYWORD	DISTRIBUTION NUMBER/TYPE	INPUT PARAMETERS	
-----	-----	-----	-----	-----
C	S-N COEFFICIENT	7/WEIBULL	MEAN .5000E+22	COV .6130
F0	CYCLE RATE CONSTANT COEFFICIENT	5/NORMAL	MEAN 2.000	COV .2000
RMSC	RMS COEFFICIENT	5/NORMAL	MEAN 4.500	COV .5000E-01
SCF	STRESS CONCENTRATION FACTOR	6/LOG NORMAL	MEAN 3.500	COV .1000
MEANST	MEAN STRESS	5/NORMAL	MEAN 7.000	COV .2000
VBAR	MEAN WIND SPEED	5/NORMAL	MEAN 6.300	COV .5000E-01
ALPHAV	WIND SPEED SHAPE	5/NORMAL	MEAN 2.000	COV .1000
TARLIF	TARGET LIFETIME	1/NORMAL	MEAN 20.00	STD DEV .0000
B	S-N EXPONENT	1/NORMAL	MEAN 7.300	STD DEV .0000
ULTST	ULTIMATE STRENGTH	5/NORMAL	MEAN 285.0	COV .0000
VCHAR	CHARACTERISTIC WIND SPEED	5/NORMAL	MEAN 10.00	COV .0000
RMSEXP	RMS EXPONENT	5/NORMAL	MEAN 1.000	COV .0000
ALPHAS	STRESS CYCLE DISTRIBUTION SHAPE	5/NORMAL	MEAN 2.000	COV .0000



F1	CYCLE RATE LINEAR COEFFICIENT	5/NORMAL	MEAN	COV
			.0000	.0000
F2	CYCLE RATE QUADRATIC COEFFICIENT	5/NORMAL	MEAN	COV
			.0000	.0000
VMAX	CUT-OUT WIND SPEED	1/NORMAL	MEAN	STD DEV
			50.00	.0000
DELTA	MINERS DAMAGE	1/NORMAL	MEAN	STD DEV
			1.000	.0000
AVAIL	AVAILABILITY	1/NORMAL	MEAN	STD DEV
			1.000	.0000

\* \* I N T E R N A L   P A R A M E T E R S \* \*

C	MEAN =	.5000E+22	STD DEV =	.3065E+22
	BETA =	.5598E+22	ALPHA =	.5963
F0	MEAN =	2.000	STD DEV =	.4000
RMSC	MEAN =	4.500	STD DEV =	.2250
SCF	MEAN =	3.500	STD DEV =	.3500
MEANST	MEAN =	7.000	STD DEV =	1.400
VBAR	MEAN =	6.300	STD DEV =	.3150
ALPHAV	MEAN =	2.000	STD DEV =	.2000
TARLIF	CONSTANT =	20.00		
B	CONSTANT =	7.300		
ULTST	CONSTANT =	285.0		
VCHAR	CONSTANT =	10.00		
RMSEXP	CONSTANT =	1.000		
ALPHAS	CONSTANT =	2.000		
F1	CONSTANT =	.0000		
F2	CONSTANT =	.0000		
VMAX	CONSTANT =	50.00		
DELTA	CONSTANT =	1.000		
AVAIL	CONSTANT =	1.000		

\* \* C O R R E L A T E D   V A R I A B L E S \* \*

CORRELATION BETWEEN	PHYSICAL	GAUSSIAN
-----	-----	-----
NONE		

RELAXATION PARAMETER: RELAX = .0000

RUN FORM/SORM SOLUTION. NO SIMULATION DONE.

=====END OF INPUT SUMMARY =====

===== RESULTS =====

CALCULATED MEAN LIFETIME: .3267E+03 YEARS

TARGET LIFETIME: .2000E+02 YEARS

\* \* F O R M / S O R M C A L C U L A T I O N S \* \*

SECOND ORDER (SORM) IMPROVEMENT FACTOR = 1.230

	RELIABILITY INDEX	FAILURE PROBABILITY
	-----	-----
FORM:	1.956	.2525E-01
SORM:	1.866	.3105E-01

\* \* D E S I G N P O I N T \* \*

KEYWORD	PHYSICAL VALUE	GAUSSIAN VALUE	IMPORTANCE		IMPORTANCE BY FRACTION OF TOTAL VARIATION
			FACTOR	GRAPH	
	-----	-----	-----	-----	-----
C	1.312E+21	-1.378E+00	.705	*****	.497
F0	2.092E+00	2.297E-01	-.117	*	.014
RMSC	4.597E+00	4.293E-01	-.220	**	.048
SCF	3.835E+00	9.669E-01	-.494	*****	.244
MEANST	7.257E+00	1.838E-01	-.094	*	.009
VBAR	6.435E+00	4.293E-01	-.220	**	.048
ALPHAV	1.854E+00	-7.311E-01	.374	****	.140

\* \* L I F E T I M E C A L C U L A T I O N S \* \*

MINIMUM LIFETIME = 10 MAXIMUM LIFETIME = 30 STEP SIZE = 1

TARGET LIFETIME	FAILURE PROBABILITY
-----	-----
10	.1138E-01
11	.1325E-01
12	.1497E-01
13	.1697E-01
14	.1842E-01
15	.2072E-01

16	.2250E-01
17	.2467E-01
18	.2690E-01
19	.2881E-01
20	.3095E-01
21	.3284E-01
22	.3515E-01
23	.3753E-01
24	.4008E-01
25	.4187E-01
26	.4451E-01
27	.4646E-01
28	.4863E-01
29	.5101E-01
30	.5339E-01

\* \* S E N S I T I V I T Y   E S T I M A T E S \* \*

KEYWORD	MEAN (INPUT VALUE)	dBETA/dMEAN	dBETA/dMEAN (Normalized)
-----	-----	-----	-----
C	.5000E+22	.1233E-21	.6163
F0	2.000	-.3128	-.6255
RMSC	4.500	-.9994	-4.497
SCF	3.500	-1.425	-4.988
MEANST	7.000	-.7164E-01	-.5014
VBAR	6.300	-.7139	-4.497
ALPHAV	2.000	1.732	3.463
TARLIF	20.00	-.3082E-01	-.6164
B	7.300	-2.744	-20.03
ULTST	285.0	.1652E-02	.4709
VCHAR	10.00	.4522	4.522
RMSEXP	1.000	-2.169	-2.169
ALPHAS	2.000	1.623	3.245
F1	.0000	-.5080	.0000
F2	.0000	-.8695	.0000
VMAX	50.00	.0000	.0000
DELTA	1.000	.5942	.5942
AVAIL	1.000	-.5963	-.5963

KEYWORD	STD DEV COV (INPUT VALUE)	dBETA/dSTD COV	dBETA/dSTD COV (Normalized)
-----	-----	-----	-----
C	.6130	-1.723	-1.056
F0	.2000	.1854E-02	.3707E-03
RMSC	.5000E-01	-1.874	-.9370E-01



SCF	.1000E+00	-4.232	-.4232
MEANST	.2000	-.6354E-01	-.1271E-01
VBAR	.5000E-01	-1.875	-.9374E-01
ALPHAV	.1000E+00	-2.664	-.2664

Normal termination of FAROW.



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## Appendix C: Example 2 Output File

The entire output file from Section 5.2 is listed here. The output file contains an echo of the inputs, a summary of internal variables used by FAROW to complete the calculations, the probability of failure and reliability index, the importance factors, and the sensitivities. A discussion of the results is included in Section 5.2.6.

FAROW Version 1.1 9/94

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DATE: 09/26/94

TIME: 14:35:50

TITLE: Example from Section 5.2: Limited Test Data

```

===== INPUT SUMMARY =====
* * I N P U T   P A R A M E T E R S   * *
KEYWORD  DESCRIPTION OF KEYWORD          DISTRIBUTION  INPUT PARAMETERS
-----  -
C        S-N COEFFICIENT                7/WEIBULL    MEAN          COV
                                     .2000E+19    .7000
B        S-N EXPONENT                   1/NORMAL    MEAN          STD DEV
                                     10.00       .0000
ULTST    ULTIMATE STRENGTH              5/NORMAL    MEAN          COV
                                     85.00      .1000
MEANST   MEAN STRESS                    5/NORMAL    MEAN          COV
                                     3.500      .2000
SCF      STRESS CONCENTRATION FACTOR    6/LOG NORMAL MEAN          COV
                                     1.500      .2000
VCHAR    CHARACTERISTIC WIND SPEED      5/NORMAL    MEAN          COV
                                     10.00      .0000
RMSC     RMS COEFFICIENT                 5/NORMAL    MEAN          COV
                                     .4000      .1000
RMSEXP   RMS EXPONENT                   5/NORMAL    MEAN          COV
                                     1.000      .2000
ALPHAS   STRESS CYCLE DISTRIBUTION SHAPE 5/NORMAL    MEAN          COV
                                     1.000      .5000E-01
F0       CYCLE RATE CONSTANT COEFFICIENT 6/LOG NORMAL MEAN          COV
                                     1.000      .2000
F1       CYCLE RATE LINEAR COEFFICIENT   5/NORMAL    MEAN          COV
                                     1.250      .1000
F2       CYCLE RATE QUADRATIC COEFFICIENT 5/NORMAL    MEAN          COV
                                     -.2500     .1000
VBAR     MEAN WIND SPEED                 1/NORMAL    MEAN          STD DEV
                                     7.500      .5000

```

ALPHAV	WIND SPEED SHAPE	7/WEIBULL	MEAN	COV
			1.800	.1000
VMAX	CUT-OUT WIND SPEED	1/NORMAL	MEAN	STD DEV
			25.00	.0000
DELTA	MINERS DAMAGE	1/NORMAL	MEAN	STD DEV
			1.000	.0000
AVAIL	AVAILABILITY	1/NORMAL	MEAN	STD DEV
			1.000	.0000
TARLIF	TARGET LIFETIME	1/NORMAL	MEAN	STD DEV
			5.000	.0000

\* \* I N T E R N A L   P A R A M E T E R S \* \*

C	MEAN = .2000E+19	STD DEV = .1400E+19
	BETA = .2206E+19	ALPHA = .6891
B	CONSTANT = 10.00	
ULTST	MEAN = 85.00	STD DEV = 8.500
MEANST	MEAN = 3.500	STD DEV = .7000
SCF	MEAN = 1.500	STD DEV = .3000
VCHAR	CONSTANT = 10.00	
RMSC	MEAN = .4000	STD DEV = .4000E-01
RMSEXP	MEAN = 1.000	STD DEV = .2000
ALPHAS	MEAN = 1.000	STD DEV = .5000E-01
F0	MEAN = 1.000	STD DEV = .2000
F1	MEAN = 1.250	STD DEV = .1250
F2	MEAN = -.2500	STD DEV = -.2500E-01
VBAR	MEAN = 7.500	STD DEV = .5000
ALPHAV	MEAN = 1.800	STD DEV = .1800
	BETA = 1.877	ALPHA = .8228E-01
VMAX	CONSTANT = 25.00	
DELTA	CONSTANT = 1.000	
AVAIL	CONSTANT = 1.000	
TARLIF	CONSTANT = 5.000	

\* \* C O R R E L A T E D   V A R I A B L E S \* \*

CORRELATION BETWEEN		PHYSICAL	GAUSSIAN
-----		-----	-----
F1	F2	-.8000	.8004
C	ULTST	.9000	.9368
ALPHAV	VBAR	.5000	.5074

RELAXATION PARAMETER: RELAX = .0000

RUN FORM/SORM SOLUTION. NO SIMULATION DONE.

=====END OF INPUT SUMMARY =====

===== RESULTS =====

CALCULATED MEAN LIFETIME: .6004E+03 YEARS  
 TARGET LIFETIME: .5000E+01 YEARS

\* \* F O R M / S O R M C A L C U L A T I O N S \* \*

SECOND ORDER (SORM) IMPROVEMENT FACTOR = 1.122

	RELIABILITY INDEX	FAILURE PROBABILITY
	-----	-----
FORM:	1.498	.6711E-01
SORM:	1.438	.7528E-01

\* \* D E S I G N P O I N T \* \*

KEYWORD	PHYSICAL VALUE	GAUSSIAN VALUE	IMPORTANCE		IMPORTANCE BY FRACTION OF TOTAL VARIATION
			FACTOR	GRAPH	
	-----	-----	-----	-----	-----
C	1.137E+18	-4.741E-01	.317	.***	.100
ULTST	8.118E+01	-1.427E-02	.010	.	.000
MEANST	3.554E+00	7.677E-02	-.051	*	.003
SCF	1.784E+00	9.758E-01	-.652	*****	.425
RMSC	4.176E-01	4.390E-01	-.293	***	.086
RMSEXP	1.135E+00	6.755E-01	-.451	*****	.203
ALPHAS	9.706E-01	-5.884E-01	.393	****	.154
F0	9.876E-01	3.619E-02	-.024	.	.001
F1	1.254E+00	3.195E-02	-.021	.	.000
F2	-2.505E-01	-1.253E-02	.008	.	.000
VBAR	7.548E+00	9.692E-02	-.065	*	.004
ALPHAV	1.796E+00	-2.298E-01	.153	.**	.024

\* \* L I F E T I M E C A L C U L A T I O N S \* \*

MINIMUM LIFETIME = 1 MAXIMUM LIFETIME = 10 STEP SIZE = 1

TARGET LIFETIME      FAILURE PROBABILITY

TARGET LIFETIME	FAILURE PROBABILITY
1	.2751E-01
2	.4370E-01
3	.5632E-01
4	.6747E-01
5	.7564E-01
6	.8411E-01
7	.9068E-01
8	.9878E-01
9	.1037
10	.1106

\* \* S E N S I T I V I T Y   E S T I M A T E S \* \*

KEYWORD	MEAN (INPUT VALUE)	dBETA/dMEAN	dBETA/dMEAN (Normalized)
C	.2000E+19	.1632E-18	.3264
B	10.00	-1.038	-10.38
ULTST	85.00	.3775E-02	.3209
MEANST	3.500	-.7108E-01	-.2488
SCF	1.500	-2.262	-3.393
VCHAR	10.00	.3510	3.510
RMSC	.4000	-7.772	-3.109
RMSEXP	1.000	-2.448	-2.448
ALPHAS	1.000	7.475	7.475
F0	1.000	.0000	.0000
F1	1.250	-.2680	-.3349
F2	-.2500	-.9578	.2394
VBAR	7.500	-.3076	-2.307
ALPHAV	1.800	.9692	1.744
VMAX	25.00	-.4836E-01	-1.209
DELTA	1.000	.3127	.3127
AVAIL	1.000	-.2999	-.2999
TARLIF	5.000	-.6182E-01	-.3091

KEYWORD	STD DEV COV (INPUT VALUE)	dBETA/dSTD COV	dBETA/dSTD COV (Normalized)
C	.7000	-.3821	-.2675
ULTST	.1000E+00	.0000	.0000
MEANST	.2000	.0000	.0000
SCF	.2000	-2.660	-.5319
RMSC	.1000E+00	-1.130	-.1130
RMSEXP	.2000	-1.574	-.3147

ALPHAS	.5000E-01	-4.544	-.2272
F0	.2000	.0000	.0000
F1	.1000E+00	.0000	.0000
F2	.1000E+00	.0000	.0000
VBAR	.5000	.0000	.0000
ALPHAV	.1000E+00	.0000	.0000

Normal termination of FAROW.

