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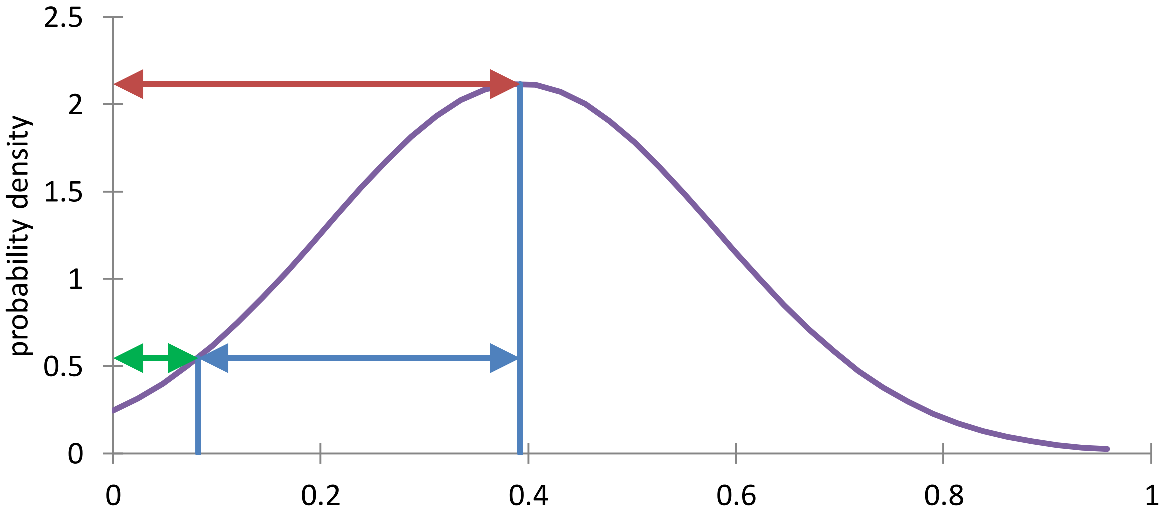

Reliability analysis with VMEA of a rack and pinion mechanism in a wave energy gravity accumulator

Johan Sandström*, Pär Johannesson*, Mikael Sidenmark°

*RISE Research Institutes of Sweden
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Abstract

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The method Variation and Mode Effect Analysis (VMEA) is successfully implemented for the AGMA based gear design of the rack pinion mechanism. The rack and pinion is a feature in Ocean Harvesting Technologies (OHT) gravity accumulator device. The purpose of it is to make the electrical power output to the grid more uniform. This is a novel technology where previous experience in designing is absent. The VMEA method is there for useful for incorporating all known uncertainties to estimate the uncertainty and reliability of the technology. This allows for adequate safety factors to be set so the desired reliability can be achieved.

The uncertainty and reliability analysis is performed for different OHT designs and methods where the reliability is calculated. This calculation can be used as basis for further analysis when more design details are determined and modifications are made, thus allowing for more optimized and reliable design to be made.

Key words: Reliablilty, VMEA, Gears, Marine Energy

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Content

1 Introduction

Ocean Harvesting Technologies (OHT) develops a technology for ocean energy that smooths the power output delivered to electrical grid. This is especially important for wave energy converters since their power output is to a large degree intermittent.

The OHT design is a novel technology where prior knowledge does not exist. Consequently, guidelines for reliable designs are not at hand. For an economical and successful implementation of the OHT concept, the design needs to be cost effective and have an acceptable level of reliability. The level of reliability is set so the risk of failure is balanced to consequence of failure. This balance is also different to traditional marine applications such as offshore and shipping where the consequences of failure are severe with respect to safety of personnel and environmental impacts. While, for ocean energy applications these consequences are limited in severity. Furthermore, cost effectiveness needs to be higher than for e.g. oil and gas.

The method Variation and Mode Effect Analysis (VMEA) is a statistical tool that quantifies the resulting variation of some important property of a system due to the uncertainties that the system depends on. When the property is related to safe operation of the system, the calculated variation can be used to set safe design levels (e.g. safety factors) so a certain reliability is achieved.

2 Ocean Harvesting Technologies Power Smoothing and Electricity Generation

The Ocean Harvesting Technologies (OHT) concept is a gear box together with a gravity energy accumulator in the form of a weight that temporally stores energy to produce an even power output to the electric power grid. The input power comes from buoys or similar devices that take energy of incoming sea waves. As the waves are highly irregular, power input is also uneven.

In principle, the OHT gearbox transmits power to the gravity accumulator when the incoming power from the waves is large. Otherwise, when the incoming wave power is small the gravity accumulator instead transmits power to the gearbox. The effect is that the power output to the generator is smoothed.

The weight in the accumulator compensates for the variable speed input to the gearbox and provides the generator with a close to constant torque and speed. The speed of the generator is slowly tuned to match the generated power output to the average captured power in the current sea state. The OHT concept is further described in (Sahlin, 2013). The weight is put in a housing sealed from the surrounding sea, c.f. **Figure 1**.

In **Figure 2** is the principle of concept given. The weight is lifted with a rack and pinion drive inside a central tower, providing constant pressure in the collection system and constant power output. The central tower collects power from the surrounding buoys in the form of high pressure hydraulic fluid that is pumped from the buoys to the tower through a hydraulic piping system. The flows from all buoys converge in the tower and drive a hydraulic motor. The hydraulic motor is connected to a planetary gearbox and a generator. A floating ring gear of the planetary gearbox is connected to a rack and pinion drive that lifts a large weight. This arrangement provides a constant torque to the drive train in the tower and a constant pressure to the hydraulic collection system. This reduces the cost and increases the efficiency of components in the complete power take-off.

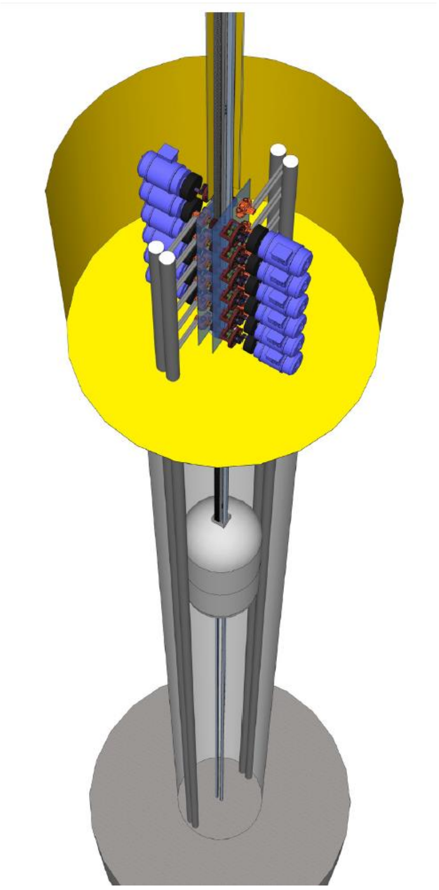

Figure 1 Assembly of tower with gravity accumulator, rack and OHT drive train.

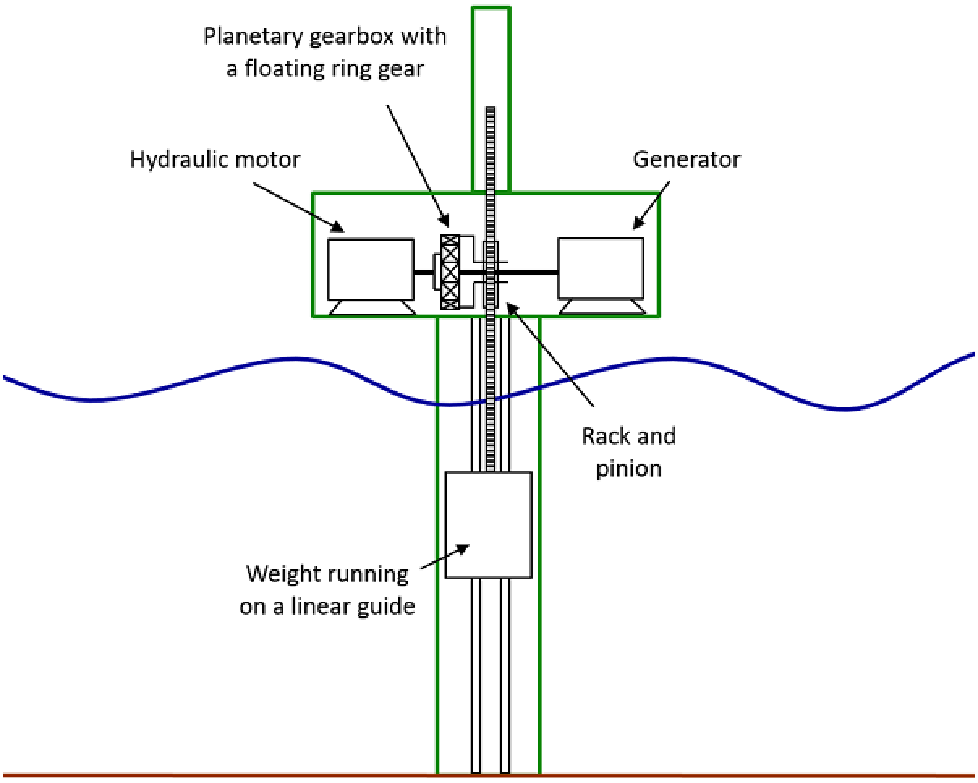

Figure 2 Working principle

3 VMEA – Variation and Mode Effect Analysis

The overall goal of industrial design for wave and tidal technologies is to make a robust and reliable product that meets the demands of the customers; (Bergman & Klefsjö, 2010). In order to achieve this goal it is important not only to predict the life of a product, but also to investigate and take into account the sources of variability and their influence on life prediction. This topic is addressed in Reliability and Robust Design Methodologies, see e.g. (Bergman et al., 2009; Johannesson et al., 2013; O'Connor, 2002), but also in related methodologies like Design for Six Sigma, Design for Variation, (Reinman et al., 2012) and Failure Mode Avoidance, (Davis, 2006).

Reliability is identified as a key aspect in "Guidelines on design and operation of wave energy converters", (DNV, 2005), in the development of wave energy devices. However, guidance on how to deal with reliability is only given on a very generic level. Several methods are suggested to help reliability assessment, such as Life Cycle Costing (LCC), Fault Tree Analysis (FTA), Reliability Block Diagram, Failure Modes and Effects and Criticality Analysis (FMECA) and Reliability Centered Maintenance (RCM), (EMEC, 2009). A more specific, yet still general, framework is given in "State of the Art Descriptions and Tasks for Structural Design of Wave Energy Devices", (SWED, 2010). In this study the components of a wave energy device are divided into two groups with regards to reliability assessment:

1. Electrical and mechanical components where the reliability and failure rates are estimated using classical reliability models and reliability is often modelled by a Weibull distribution.
2. Structural components where a limit state equation can be formulated defining failure or unacceptable behaviour. The parameters then are modelled by stochastic variables and the reliability is estimated using Structural Reliability Methods, e.g., FORM/SORM, see e.g.(Ditlevsen & Madsen, 1996).

As mentioned above, an important goal of engineering design is to get a reliable system, structure or component. In industry, the method of Failure Mode and Effect Analysis (FMEA) is often used for reliability assessments, where the aim is to identify possible failure modes and evaluate their effect. Studies of FMEA have indicated that the failure modes are in most cases triggered by unwanted variation, (Lönnqvist, 2009). Further, a general design philosophy, within robust design methodology, is to make designs that avoid failure modes as much as possible, see e.g. (Davis, 2006; Bergman et al., 2009). Thus, it is important that the design is robust against different sources of unavoidable variation. Therefore, a tool for addressing robustness against variation was developed, namely the so-called Variation Mode and Effect Analysis (VMEA) that was first presented by (Chakhunashvili et al., 2004; Johansson et al., 2006) and further developed in e.g. (Chakhunashvili et al., 2009; Johannesson et al., 2009; Svensson et al., 2009). A more general presentation of the methodology is found in (Bergman et al., 2009; Johannesson et al., 2013; Svensson & Johannesson, 2013). The VMEA takes the quantitative measures of failure causes into account and the method is based on ideas from statistics, reliability and robust design.

Another important principle is parsimony, which is the idea of making things as simple as possible (but not simpler). Together with VMEA, the parsimony principle can be used in order to achieve a balanced model complexity. Further, according to (Clausing, 1994; Davis, 2006), causes of failures can be divided into two categories. The first category is called “lack of robustness” and the second category is labelled “mistakes”. Thus, minimizing the possibilities for making mistakes are also important in the design process.

The reliability target for the ocean energy sector is a design that can withstand existing environmental conditions during the 20-25 year lifespan of an array. There are mainly two quantities influencing the life, namely the load the construction is exposed to, and the structural strength of the construction. Statistical methods provide useful tools for describing and quantifying the variability in load and strength. Here we will use the concept of Variation Mode and Effect Analysis (VMEA), which is a method aimed at guiding engineers to find critical areas in terms of the effects of unwanted variation. Assessing the uncertainty using VMEA allows proper safety factors to be established with regard to a required service life or strength, (Svensson & Johannesson, 2013). The factors that cause the most uncertainty can also be identified giving opportunity to reduce the uncertainty, which can lead to more efficient and optimized WEC and TEC devices. The VMEA method has been successfully implemented for fatigue design and maintenance in vehicle and aeronautic industries, see e.g. (Svensson et al., 2009; Johannesson et al., 2009). This experience will be used to enable efficient knowledge transfer to the ocean energy sector, as demonstrated in the pre-study (Svensson & Sandström, 2014).

Modern engineering relies heavily on simulations with methods like FEM, CFD etc. These can shorten and improve testing. Design for variation with the VMEA method is fully usable together with simulation analysis. When the most current design methods used today in the ocean energy industry are combined with the proposed reliability analysis based on VMEA, new and more accurate reliability methods will be available. The WEC/TEC companies will then have new tools to both increase service life and lower overall costs. This new capability can be a significant step towards commerciality of the WEC/TEC concept.

3.1 VMEA in different design phases

The VMEA is split into three different levels (see **Figure 3**), namely 1) basic VMEA, in the early design stage, when we only have vague knowledge about the variation, and the goal is to compare different design concepts, 2) enhanced VMEA, further in the design process when we can better judge the sources of variation, and 3) probabilistic VMEA, in the later design stages where we have more detailed information, and the goal is to assess the reliability and safety factors.

3.1.1 Work process

The general VMEA procedure can be described in the following steps:

1. Define the target function, i.e. the property to be predicted
   e.g. the life of a component or structure.
2. Find all sources of uncertainty
   e.g. classified as scatter, statistical and model uncertainties.
3. Quantify the size of the different sources of uncertainty,
   e.g. by experiments, previous experience, or engineering judgement.

4. Evaluate the sensitivity coefficients,
   e.g. by numerical calculations, experiments, or previous experience.
5. Calculate the total prediction uncertainty
   by combining the contributions from all uncertainty sources.
6. Evaluate the reliability and robustness,
   e.g. compare design concepts, find the dominating uncertainties or derive safety factors.

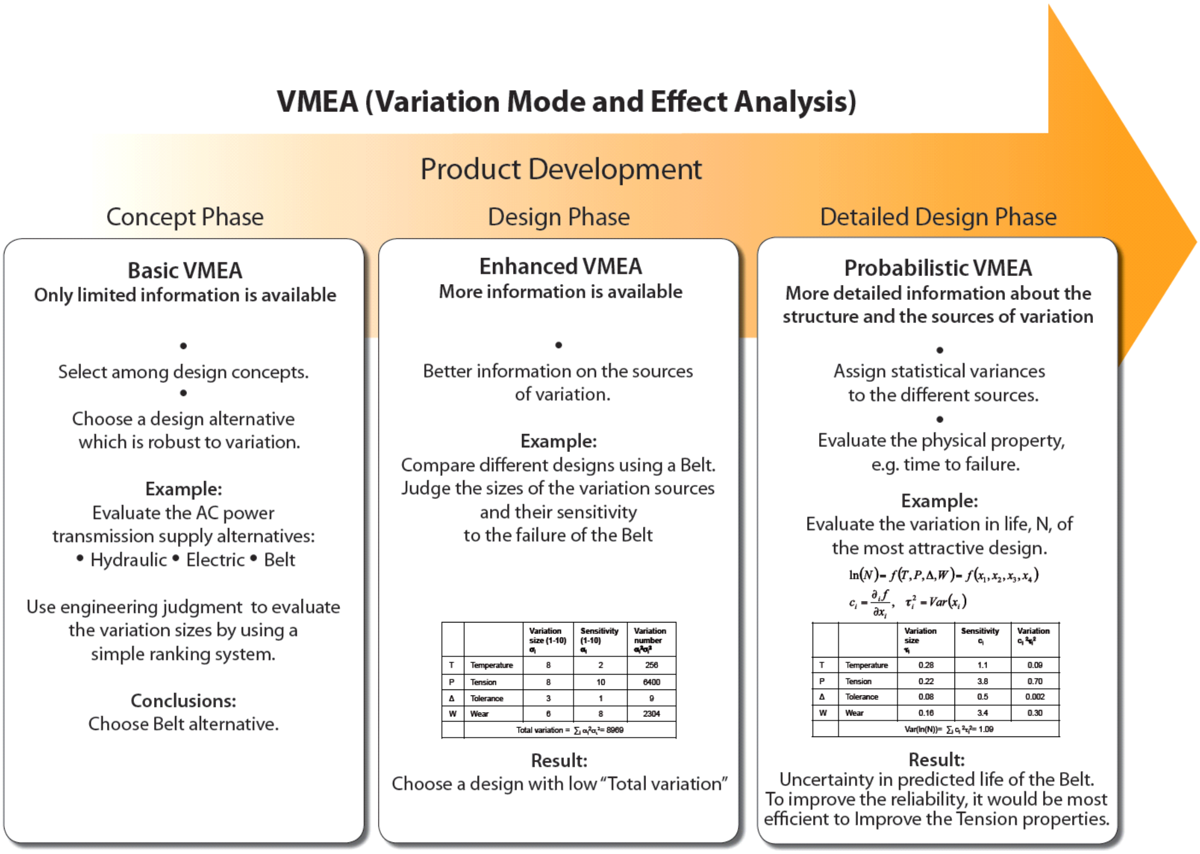

Figure 3 VMEA in different design stages

3.1.2 Mathematical principles of VMEA

The method is based on characterizing each source by a statistical standard deviation and calculating its sensitivity with respect to the target function, e.g. fatigue life of maximum stress. The VMEA method combines these into the total prediction uncertainty, denoted τ, which is obtained by the root sum of squares (RSS) of the uncertainties

$$\tau = \sqrt{\tau_1^2 + \tau_2^2 + \tau_3^2 + \cdots} = \sqrt{c_1^2\sigma_1^2 + c_2^2\sigma_2^2 + c_3^2\sigma_3^2 + \cdots} \tag{1}$$

where τ_i is the resulting uncertainty from source $i$and is calculated as the product of the sensitivity coefficient c_i and the uncertainty σ_i of source i. Note that VMEA is a so-called second-moment method since it uses only the standard deviation to characterize the distribution of the uncertainty sources.

3.1.3 Basic VMEA

In a basic VMEA, (Chakhunashvili et al., 2004; Johansson et al., 2006), the goal is to identify the most important sources of variation, for example when different design solutions are evaluated. The sizes of the sources of variation as well as their sensitivities to the studied product property are evaluated on a scale from 1 to 10. The robustness of the product is characterized by the summing the square of the product of sensitivity and variation size. To conduct an adequate VMEA that incorporates different views and competences, a cross-functional team of experts should be formed. Such an analysis will indicate which sub-systems or components that are most critical, and thus need to be studied in more detail.

3.1.4 Enhanced VMEA

The enhanced VMEA,(Chakhunashvili et al., 2009), is a refinement of the basic VMEA further into the design process with the aim to understand and quantify the uncertainty sources in more detail. The main difference is that the sensitivities and variation sizes are assessed in real physical units instead of the 1 to 10 scale. The assessment uncertainties can be based on engineering judgement, but also be supported by initial testing, literature and data sheets from manufacturers.

3.1.5 Probabilistic VMEA

The probabilistic VMEA, (Chakhunashvili et al., 2009; Johannesson et al., 2009; Svensson et al., 2009), is well suited in the later design phases, for example, when there is a need to predict the life of the product and to determine proper safety factors or tolerances. The general procedure of the probabilistic VMEA is the same as for the basic VMEA. The main difference compared to the basic VMEA is that here we make use of a model for the prediction and thus we need to include both statistical uncertainties and model uncertainties, together with the random variation. Further, as in the enhanced VMEA, we assess the magnitude of the uncertainties by standard deviations, instead of using a ranking scale. Different types of uncertainties are analysed, such as

- ***Scatter*** or physical uncertainty which is that identified with the inherent random nature of the phenomenon, e.g. the variation in strength between different components.
- ***Statistical uncertainty*** which is that associated with the uncertainty due to statistical estimation of physical model parameters based on available data, e.g. estimation of parameters in the Coffin-Manson model for life based on fatigue tests.
- ***Model uncertainty*** which is that associated with the use of one (or more) simplified relationship to represent the 'real' relationship or phenomenon of interest, e.g. a finite element model for the relation between outer loads and local stresses.

Scatter cannot be avoided, but needs to be handled by using safety factors, while the last two types of uncertainties can be decreased by gaining more data or by building better models. In a probabilistic VMEA the goal is to quantify the (most) important sources of uncertainty in physical units, and thus the result can be used for deriving design margins or planning of maintenance.

The probabilistic VMEA represents the concept of First-Order Second-Moment (FOSM) reliability theory (Ditlevsen & Madsen, 1996; Melchers, 1999). The First-Order refers to the linearization of the target function, and the Second-Moment refers to the fact that only the means and variances (and covariances if needed) are used. The result is a prediction uncertainty in terms of the standard deviation of the response. The total uncertainty can be used to calculate a reliability index as a measure of the distance to the failure mode. Further, it can also be used to calculate a safety factor for design.

3.2 Load-strength concept

A failure will occur if the demand/load placed on the product exceeds its capacity/strength. For robustness, reliability and survivability analysis we will use the load-strength concept together with Variation Mode and Effect Analysis (VMEA), see **Figure 4**. The basic VMEA will be used for assessing which sub-systems and/or components that are most critical, and thus need to be studied in more detail. The most critical components may then be studied using the enhanced and probabilistic VMEA, which is a second-moment reliability method, which can be used in order to derive adequate safety factors for design. The uncertainties in load and strength are assessed by components testing, measuring of load conditions, numerical evaluations, as well as data and knowledge from literature and engineering experience. The different kinds of uncertainties, e.g. scatter, parameters uncertainties and model errors, are combined into a resulting uncertainty for the life prediction. The result of the probabilistic VMEA will give the safety margin of the design, but also indicate where it is most cost effective to reduce the uncertainty and thus improve the reliability of the component.

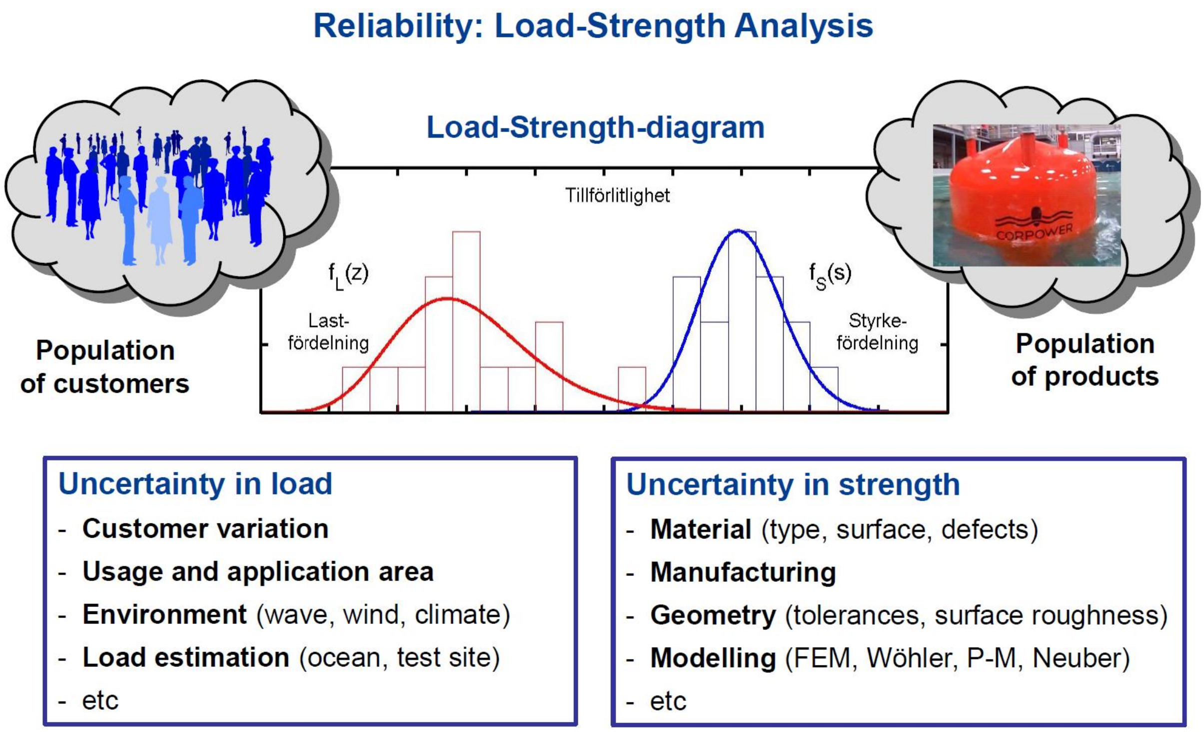

Figure 4 The load-strength concept.

3.3 Probabilistic VMEA in detailed design phase

3.3.1 Introduction

The main difference between probabilistic VMEA and basic and enhanced is that it evaluates final quantitative measures on uncertainty in order to dimension the design to fulfil demanded safety. The quantitative measures are the same as for the enhanced VMEA, namely, 1) measures of uncertainty or dispersion by means of ***statistical standard deviations*** and 2) sensitivities by means of mathematical ***sensitivity coefficients***. Since, for the probabilistic VMEA, these quantifications demand detailed studies of the influencing parts and external loads, it is focussed on specific weak spots in the design, identified by engineering experience or from preceding basic and enhanced VMEA studies.

The first evaluation of the probabilistic VMEA is usually not the final step in a reliability assessment but is rather a frame work to compare and combine detailed investigations on the influences on a weak spot. The first evaluation often results in demands of too large safety factors and new knowledge must be added to reduce some uncertainties. This may be done by searching for more detailed material specifications, making physical experiments, or find validations for more correct model theory. By comparing the dominating sources of uncertainty with unavoidable sources, exaggerated detailed mathematical models may be avoided and efforts be more focussed on essentials. Step by step, the procedure hopefully converges to a final design that can be given proper dimensions for demanded safety.

3.3.2 Probabilistic VMEA – work process

The general work process follows Section 3.1.1, according to

1. **Define a model of the limit state** e.g. based on life, equivalent load/strength, max stress or max defect.
2. **Find all sources of uncertainty** (scatter, statistical and model uncertainties).
3. **Quantify the size of the uncertainty sources** e.g. by experiments, previous experience, or engineering judgement.
4. **Evaluate the sensitivity coefficients** e.g. by numerical calculations, experiments, or previous experience.
5. **Calculate the total prediction uncertainty** i.e. by combining the contributions from all uncertainty sources.

3.3.3 Define a model of the limit state

In mechanical engineering, failure modes of primary interest are the rupture of items caused by external forces. A practical reliability model is then to compare the ***strength*** of an item with the ***load*** that will act on it in service. ***Strength*** and ***load*** must in this respect be comparable metrics, but may consist of different physical features such as 'expected fatigue life'/'demanded life', 'equivalent fatigue strength'/'equivalent fatigue load', 'ultimate stress strength'/'max stress in service', or 'largest defect'/'allowed defect size'.

Once the strength and load are defined as two comparable metrics they are regarded as ***random variables***, meaning that they can be pictured as taken from two populations, each having its ***expected value*** (usually taken as its nominal value) and a dispersion around this expected value. The dispersion is given a single value, its ***standard deviation that*** represent both random scatter and non-random but unknown model errors. This two parameter description is a simplification of the true random distribution of each variable, but is usually the most exact description that can be achieved in structural design.

However, in order to increase the robustness of this simplification it is in most cases wise to let the metrics be the ***logarithms*** of the physical measures of strength and load. Other reasons to use logarithms include the desire for linearity in physical models, constant variance and additivity.

The limit state for the design is defined as the state when the load equals the strength, i.e. when the difference between log strength and log load equals zero. When this difference exceeds zero we have built in a ***safety distance*** and taking anti-logarithm of this safety distance results in a ***safety factor***.

The difference between the two random variables 'log strength' and 'log load' is also a random variable and the VMEA analysis is a methodology to assess the expected value and the standard deviation of this random difference.

3.3.4 Evaluate size, sensitivity and prediction uncertainty

The next step is to evaluate the sizes of the uncertainties and their sensitivities to the limit state function (or target function), which is often performed in parallel.

3.3.5 Evaluate reliability

The result of the probabilistic VMEA is used to evaluate the reliability, and to guide the engineers in the improvement work.

3.3.6 Distance to failure mode – the Cornell reliability index

A FOSM reliability method, i.e. a First Order, Second Moment method, is often formulated by means of the Cornell reliability index. A ***limit state*** is defined as the state when the load on the interesting structural part equals the strength. The reliability is the ability of the design to keep the structure “below” the limit state, i.e. to keep the strength above the load regardless possible variations in load and strength and regardless errors in the engineering model.

The Cornell reliability index is a mathematical criterion for a reliable structure, where the limit state is defined by the ***logarithms*** of strength and load. In order to define a reliable ***distance*** between log strength and log load, the design (or nominal) distance is divided by the estimated ***standard deviation of this distance*** and the result, the ***reliability index***, is compared to a predetermined criterion, say 3. The ***standard deviation of the distance*** is estimated by pooling different sources of variation and uncertainty, weighted by their sensitivity coefficients.

The statistical interpretation of the Cornell reliability index is the number of standard deviations from the limit state. If the log distance can be assumed to be ***normal distributed*** (Gaussian), then the index can be translated to a ***probability of survival***.

If the assumption of normal distribution is true, a reliability index value of 1.64 corresponds to 95% probability of survival, 1.96 to 97.5% , 3 to 99.9%, and the value 3.8 to 99.99% probability of survival

In conclusion, by adding the normal distribution assumption, the simple FOSM methodology achieves a ***probabilistic interpretation*** of reliability from assessments of an expected value and its standard deviation.

However, the probabilistic interpretation becomes doubtful for large values of the index. Namely, the assumption of normality is based on the powerful statistical ***central limit theorem***, which says that the distribution of a sum of a large number of random variables approaches the normal distribution, regardless the distributions of the including variables. It turns out that in practice, such a sum may converge very fast for ***fairly symmetric*** term distributions of the ***same order of magnitude***. But, this is only true in the ***central part*** of the final distribution; for the “tails” the convergence demands a huge number of terms.

In reliability assessment, the structure variation and uncertainty are often dominated by a few components, whose individual distributions often are far from normality. Therefore, usage of large values of reliability index cannot be translated to probability of failure. Instead, there is a large risk that such translations are highly misleading and should therefore be avoided.

3.3.7 **The two safety factor approach**

The problematic interpretation of large reliability indices needs not to discriminate the usage of the probabilistic methodology. In fact, in most reliability cases the ***central limit theorem*** holds good enough for the central part of the distribution. This justifies the usage of the Cornell reliability index for moderate values of the index, say for probabilities of survival from 95% to 98%.

For the VMEA methodology presented here we chose to trust the statistical theory up to 95% probability of survival, corresponding to the reliability index 1.64.

For a normal engineering design a 95% probability of survival is not sufficient and the reliability index, the statistical safety distance, need to be completed by an additional distance for larger safety. However, since the knowledge about rare events that represent the tail in the statistical distribution is too weak to be given a probabilistic measure, we construct an extra safety distance based on ***engineering judgement***.

The magnitude of this extra factor must be very specific for each application and should be based on 1) the expected consequences of failure, with the largest values for structural designs that put human life in hazard and 2) the engineering judgement of the likelihood of rare events like human mistakes and environmental catastrophes. Table 1 gives extra safety distances and corresponding factors that can be used as an overall guideline.

Table 1 Safety distances and corresponding factors according to risk and consequences of failure.

Likelihood of detrimental rare events	Consequences of failure					
	Minor		Moderate		Large	
	dist.	factor	dist.	factor	dist.	factor
Small	0.44	1.5	0.50	1.6	0.62	1.9
Normal	0.62	1.9	0.77	2.2	0.83	2.3
Large	0.77	2.2	0.83	2.3	0.92	2.5

The VMEA reliability approach then adjusts the Cornell approach by demanding that the ***safety distance***, the difference between log strength and log load, should be larger than the sum of two safety distances, 1) 1.64 times the estimated standard deviation and 2) an extra distance based on engineering judgement.

By taking anti-log of this criterion we arrive at a ***safety factor*** that is the product of the anti-logs of the two safety distances.

4 Gear design with AGMA

The designing of the gear and pinion is made with an OHT design practice based on AGMA (American Gear Manufacturers Association). It works by designing against fatigue in the gear root due to tooth bending. The design is made to achieve infinite life.

The AGMA procedure is of load-strength comparison. This means that load and strength are calculated separately and compared so the strength is confidently larger than the load. "Confidently larger" is achieved by use of a safety (factor) and considering reliability. But for reliability, the uncertainty in the load and strength needs also to be considered. In AGMA this taken care of by a factor as explained later. The load/strength quantity that is compared in AGMA is stress. The load is bending stress in the gear root and strength is the fatigue limit of the material.

Calculation of these stresses is performed by using correction factors that handles different issues for the gear application. The root bending stress is calculated as

$$\sigma = \frac{F_{\mathrm{t}}}{bmJ} K_{\mathrm{v}} K_{\mathrm{o}} K_{\mathrm{m}} \tag{2}$$

The bending is considered as a cantilever beam where F_{t} is the tangential force transferring the power between the gears and b is the width of the gear with the gear module m. J is the AGMA spur gear geometry factor which further takes in to account the geometry of the gear teeth including stress concentration effects for fatigue. The J factor also accounts for other effects, e.g. when load is divided on more the one single tooth. The K factors are used for further correction and are as

- K_{v} Velocity
- K_{o} overload
- K_{m} load distribution

The strength or permissible bending stress is calculated as

$$\sigma_e = \sigma_e' k_{\mathrm{L}} k_{\mathrm{v}} k_{\mathrm{s}} k_{\mathrm{r}} k_{\mathrm{T}} k_{\mathrm{m}} \tag{3}$$

This is the endurance limit for the gear root with operational factors taken into account and σ_e' is the endurance limit for the gear material determined with rotating beam specimens. The k factors are used for further correction and are as

- k_{L} load
- k_{v} size
- k_{s} surface
- k_{r} reliability
- k_{T} temperature
- k_{m} miscellaneous

5 Implementing VMEA for uncertainty and reliability

The VMEA is performed to estimate the total variation in the design from all sources of scatter and uncertainty. In the following, all these sources identified and will be handled. In addition and as required in probabilistic VMEA, a load/strength on nominal values is performed. The AGMA design procedure handles all uncertainty with one single uncertainty factor.

In VMEA, logarithmic quantities are always used for the result values (here load and strength) and usually also for the input parameters. In this case the use of logarithms is very suitable as load and strength are pure products of factors. The load expression in equation (2) becomes in logarithms

$$\ln \sigma = \ln F_{\mathrm{t}} - \ln b - \ln m - \ln J + \ln K_{\mathrm{v}} + \ln K_{\mathrm{o}} + \ln K_{\mathrm{m}} \tag{4}$$

Here it is seen that the load expression (4) becomes a sum of terms and that there is no interaction between the terms. Furthermore, if it is instead the logarithms of the input parameters that are taken as input parameters (e.g. $\ln F_{\mathrm{t}}$ instead of F_{t}) the expression becomes linear. When the normal distribution is used to describe the uncertainty of parameters in logarithm-form, the results is that the original parameter is lognormal distributed. Specifically, this would mean that if $\ln F_{\mathrm{t}}$ is modelled as normal distributed, the force F_{t} is lognormal distributed. This also holds for the output result σ.

In the following, the different sources of uncertainty will be analysed and quantified.

5.1 Sources of uncertainty

5.1.1 AGMA – $\boldsymbol{k_{\mathrm{r}}}$

All methods have uncertainties which are referred as model uncertainty. In AGMA this uncertainty is included with the reliability factor k_{r} that includes all uncertainty when applying the method. This uncertainty also includes the variation in the material property endurance limit. Since fatigue inherently has large variation it can be thought that most uncertainty is due to material fatigue properties. Therefore, when categorizing the sources of uncertainty, the AGMA - k_r uncertainty is categorized as uncertainty in strength.

The reliability factor k_r is used in a way that when set to a certain value a reliability is achieved as given in Table 2. Since $k_r = 1$ gives reliability 0.5, the AGMA procedure without using k_r corresponds to a nominal calculation, i.e. 50 % probability of failure, which fits well into the VMEA framework. It is a reasonable assumption that the reliability of AGMA is predicted by a lognormal distribution since it acts as a factor (multiplied). This would implicate that $\ln k_r$ is normal distributed.

Table 2 Probabilities for corresponding to the reliability factor

k_r	0.702	0.753	0.814	0.868	0.897	1
$\ln k_r$	-0.354	-0.284	-0.206	-0.142	-0.109	0
reliability -	0.9999	0.999	0.99	0.95	0.9	0.5
cumulative probability (of failure)	0.0001	0.001	0.01	0.05	0.1	0.5

In the VMEA framework, the standard deviation is used to quantify the uncertainty. To find the standard deviation s, a curve fit is made for the cumulative distribution function for a normal distribution with mean 0 and standard deviation s to the cumulative probability for $\ln k_r$. An optimization method in Matlab (Mathworks) is here used for the curve fitting. The result is given in **Figure 5** where it is seen that the curve fit is good. The resulting standard deviation of $\ln k_r$ to be used in the VMEA is $s = 0.0933$.

The sensitivity is here 1 since the variation is given for the logarithmic input, which can also be viewed as that the variation given as relative to real input (no logarithm).

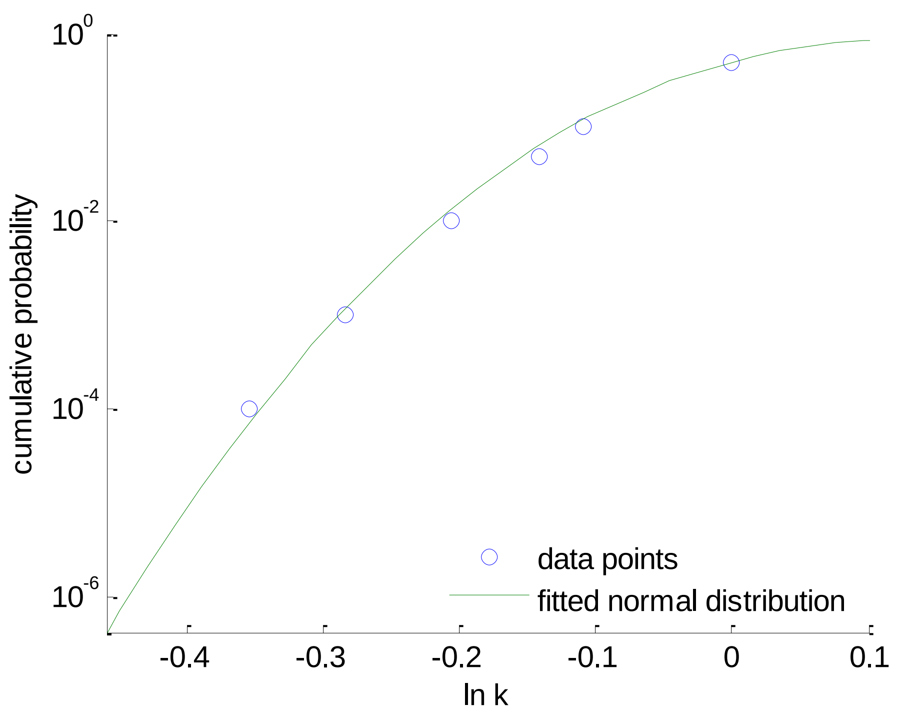

Figure 5 Curve fit for reliability - cumulative probability (of failure).

5.1.2 **Feed force – $\boldsymbol{F_\mathrm{t}}$**

There is uncertainty on the force F_t on the teeth, stemming both from that it varies during operation and uncertainty in the simulation result. The simulation of the operation gives average force 204 kN and maximum value 245 kN. Since AGMA already corrects for the varying force, the impact of this variation is low or none. Nevertheless, the uncertainty in estimation of force due to uncertainty in the simulation remains. Assuming normal distribution and a probability of 1/1000 to exceed the maximum value, the uncertainty in the average force is one third of the span to the maximum force, i.e. $(245 - 204)/3 = 13.7$ kN. If this is taken as the standard deviation, the relative uncertainty (or coefficient of variation) is $13.7/204 = 0.067$. This means that the standard deviation for $\ln(F_\mathrm{t})$ is approximately 0.067. The sensitivity coefficient is 1 since the dependence of $\ln(F_\mathrm{t})$ is linear in equation (4).

5.1.3 **Surface factor – $\boldsymbol{k_\mathrm{s}}$**

There is some uncertainty in the ultimate strength as used in AGMA of the material in use. The ultimate strength is related to how surface finish affects the fatigue strength. The endurance limit of the material is 695 MPa. Typically, the ultimate strength is twice the value of endurance limit, i.e. 1390 MPa. On the other hand, a relatively low value of about 700 MPa is used in the current OHT design. According to AGMA, the surface factor k_s varies between 0.635 and 0.715 for the ultimate strength values 700 MPa and 1390 MPa respectively. In Table 3 are the limits, min/max-difference and standard deviations given for both the cases that either k_s or $\ln k_\mathrm{s}$ varies uniformly between the limits. For the uniform distribution, the standard deviation of a variable x varying between the values x_min and x_max is given by

$$\frac{x_\mathrm{max} - x_\mathrm{min}}{\sqrt{12}} \tag{5}$$

Table 3 Limits and standard deviation for the surface factor when it varies according to the uniform distribution.

	min	max	distance	standard deviation
k_s	0.635	0.715	0.08	0.0231
$\ln k_\mathrm{s}$	-0.454	-0.335	0.119	0.0343

The logarithm version with standard deviation 0.0343 is here chosen to be used in the uncertainty analysis. This also has the consequence that the sensitivity factor is 1 as explained previously.

5.1.4 Miscellaneous effects factor – k_{m}

Similarly as in the case of the surface factor, there is uncertainty in the miscellaneous effects factor due to uncertainty in the ultimate strength of the material. Again reasoning similarly as for the surface factor and usage of AGMA, the variation given in Table 4 for k_{m} is calculated.

Table 4 Limits and standard deviation for the miscellaneous effects factor when it varies according to the uniform distribution.

	min	max	distance	standard deviation
k_{m}	1.33	1.45	0.12	0.0346
$\ln k_{\mathrm{m}}$	0.285	0.372	0.086	0.0249

The logarithm version with standard deviation 0.0249 is here chosen to be used in the uncertainty analysis. This also has the consequence that the sensitivity factor is 1 as explained previously.

5.1.5 Velocity factor – K_{V}

The velocity V of the pitch circle affects the load which is handled with the factor K_{V}. The expression for this effect is according to AGMA

$$K_{\mathrm{V}} = \frac{6 + V}{6} \tag{6}$$

According to OHT simulations, the rack speed varies between 3.1 and -2.0 m/s (up and down). The OHT gear design uses an average velocity of 0.5 m/s. Considering the max velocities are 3.1 m/s up and 2.0 m/s down (sign of velocity does not matter), the velocity to be considered for K_{V} might therefore be larger. To account for this, a normal distributed uncertainty with standard deviation 0.75 m/s is used.

The sensitivity of $\ln K_{\mathrm{V}}$ is calculated from equation (6) as

$$\text{sensitivity} = \frac{d}{dV}\ln K_{\mathrm{V}}\bigg|_{V=V_{\mathrm{nom}}} = \frac{d}{dV}\ln\frac{6+V}{6}\bigg|_{V=V_{\mathrm{nom}}} = \frac{1}{6+V_{\mathrm{nom}}} = 0.1538\ \mathrm{s/m} \tag{7}$$

where V_{nom} is the velocity 0.5 m/s used for the nominal load evaluation.

5.1.6 Overload factor – K_o

The overload factor K_o handles impact of uneven load transfer in the drivetrain. In the OHT machinery, the weight of the gravity accumulator is one part in the system from which the load can be considered fully uniform since the weight is constant at all times. The force from the gravity accumulator changes between driving the system and being driven. The other parts in the system are the generator and hydraulic motors. The generator is probably acting with a rather uniform load since this is the actual purpose of OHT system. The hydraulic motors can have some uneven running. This running is judged to be small to moderate in effect. AGMA gives for this case K_o=1.25. The assumed distribution is here taken as the uniform distribution which leads to the uncertainty in Table 5 as previously explained.

Table 5 Limits and standard deviation for the overload effects factor when it varies according to the uniform distribution.

	min	max	distance	standard deviation
k_o	1	1.25	0.25	0.0722
$\ln k_o$	0	0.223	0.223	0.0644

The logarithm version with standard deviation 0.0644 is here chosen to be used in the uncertainty analysis. This also has the consequence that the sensitivity factor is 1 as explained previously.

5.1.7 Load distribution factor – K_m

Uneven distribution of contact pressure on the gear tooth faces increases the stress in the gear teeth root. It can be caused by inaccurate tolerances and large deflection in the mountings. For gear face width around 150 mm, the load distribution factor K_m for different categories of support is given in Table 6. The OHT design features a specially designed mounting for the generator-motor-gearbox with pinion. By introducing flexibility in the mountings, the design shall self-align the pinion on the rack when the rack and tower-structure displaces. The goal of the design is that a high evenness of the contact pressure is achieved. Nonetheless, the new design is novel and untested. As a result, some uncertainty should be attributed to the load distribution factor. It is here assumed that K_m is uniformly distributed between the values 1.4 and 1.7 according to the characteristics in Table 6. The calculated uncertainty is given in Table 7. The logarithm version is here chosen and the sensitivity factor is then 1 as explained previously.

Table 6 The load distribution factor K_m for different categories of support.

Characteristics of Support	K_m
Accurate mountings, small bearing clearances, minimum deflection, precision gears	1.4
Less rigid mountings, less accurate gears, contact across the full face	1.7
Accuracy and mounting such that less than full-face contact exists	Over 2.2

Table 7 Limits and standard deviation for the load distribution factor K_m when it varies according to the uniform distribution.

	min	max	distance	standard deviation
K_m	1.4	1.7	0.3	0.0866
$\ln K_m$	0.336	0.531	0.194	0.0560

5.2 Total uncertainty

In the first level of VMEA – basic VMEA, as described in section 3.1.3, the uncertainty contribution is for each source summed so the total uncertainty is computed. How large part the different sources contribute to the total uncertainty also become apparent. In Table 8 is the different uncertainty presented with the resulting total uncertainty. To illustrate the relation between the contributions of the different sources, the pie chart in **Figure 6** is given.

Table 8 VMEA estimation of uncertainties.

UNCERTAINTY	Sensitivity	Standard deviation	Total	
Load				
Force on tooth	1	0.067	**0.067**	
Velocity factor	0.15	0.75	**0.115**	
Overload factor	1	0.064	**0.064**	
Load distribution factor	1	0.056	**0.056**	
Total load				**0.158**
Strength				
Surface factor	1	0.034	**0.034**	
AGMA variation (reliability factor)	1	0.093	**0.093**	
Miscellaneous effects	1	0.025	**0.025**	
Total strength				**0.102**
Total				**0.188**

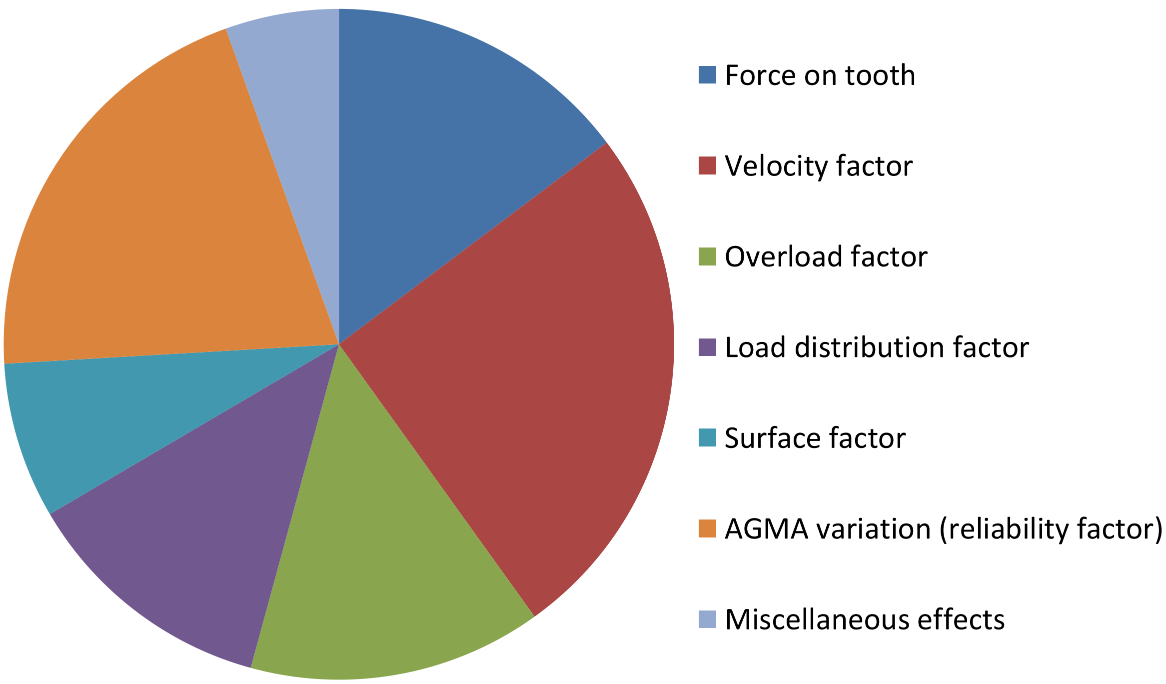

Figure 6 Contribution of the different sources of uncertainty.

5.3 Reliability – Probabilistic analysis VMEA

A reliability analysis using probabilistic VMEA, as described in section 3.3 is performed by analysing the distance between the log load and log strength. To perform the analysis, a limit state function is formed which here is log load subtracted from log strength. This reduces the statistical analysis to one quantity or variable – the load strength distance. The uncertainty in this quantity is the total uncertainty computed with VMEA. Recall that this is performed in logarithmic quantities, so the limit state quantity L, using the AGMA names, is

$$L = \ln \sigma_e - \ln \sigma = \ln \frac{\sigma_e}{\sigma} \tag{8}$$

The interpretation of L is that if it is less or equal than zero failure occurs. When load and strength are random variables, L may be modelled as normal distributed as discussed in section 3.3.6. One important quantity in the probabilistic VMEA analysis is a lower quantile of L. A common used quantile is the 95 %, quantile giving reliability index value 1.645. This means that in 95 % of all cases, L is greater than zero resulting in no failure. In reliability terms this can be called the 95 % reliability. The reliability distance is then defined as

$$R = 1.645\tau \tag{9}$$

where τ is the total uncertainty computed with VMEA. In the design of a component or a system, the 95 % percent reliability is usually not safe enough and higher reliability quantified in probability of failure is difficult to accurately calculate. Hence, a second quantity is calculated. This is the extra safety distance S and is related to the traditional safety factor or partial factor used in many design standards such as AGMA and Eurocode. The extra safety distance is the difference between nominal (mean) L and the chosen reliability level as reformulated in equation (10).

$$L_{\text{nominal}} = S + R \tag{10}$$

The distances defined here are for loagarithmic quantities. Appling the exponential function (anti-logarithm) to the distances gives the traditional factors

$$\begin{aligned} &\exp(L_{\text{nominal}}) \text{ – safety factor for nominal values} \\ &\exp(R) \text{ – variational safety factor} \\ &\exp(S) \text{ – extra safety factor} \end{aligned} \tag{11}$$

To complete the probabilistic analysis, the nominal evaluation is also needed. This is performed on nominal values suggested by OHT. The nominal values, used together with the design formulas in section 4 and variation calculated in section 5.2, can then be used to calculate the reliability quantities. The resulting reliability distances are illustrated in **Figure 7** and given in Table 9. The safety distance S becomes 1.09 which possibly is too low to achieve a comfortable safety.

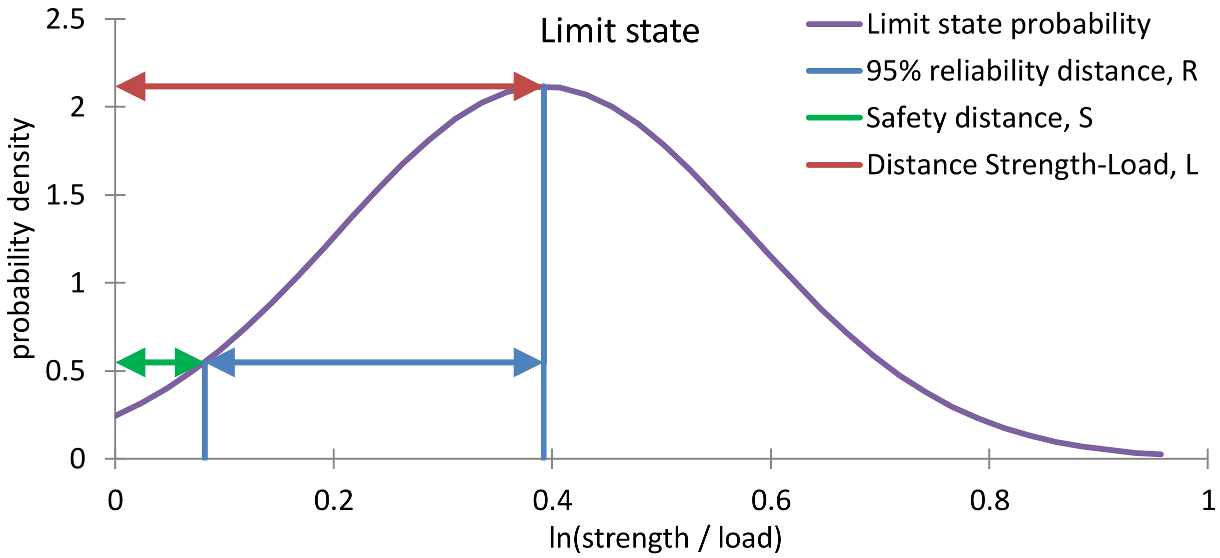

Figure 7 Probability density for the limit state with reliability distances indicated.

Table 9 Reliability quantities.

	logarithm values	original values
Nominal Strength [MPa]	6.23	506 MPa
Nominal Load [MPa]	5.83	342 MPa
	difference	ratio
Distance Strength-Load, L	0.392	1.48
95% reliability distance, R	0.310	1.36
Safety distance, S	0.082	1.09

5.4 Comparison to previous design

A previous OHT design lacked the feature to align the pinions to the rack. This caused the load distribution along the teeth faces to be less uniform. In this section, a VMEA analysis is performed with larger uncertainty in the effect of the load distribution. In Table 6 is the load distribution factor $K_{\mathrm{m}} > 2.2$ for situations with contact distributions that are to a large degree non-uniform. Replacing $K_{\mathrm{m}} = 2.2$ as the maximum value in Table 7, results in the standard deviation of 0.13 for $\ln K_{\mathrm{m}}$. The total uncertainty then increases to 22.2 % as seen in Table 10. The probabilistic analysis in Table 11 is performed with the increased value $K_{\mathrm{m}} = 1.7$. It is the seen that the extra safety factor is only 0.85, i.e. lower than 1, implicating that a 95 % reliability is not achieved. This clearly shows that the previous design is not reliable enough.

Table 10 VMEA estimation of uncertainties for a previous design.

UNCERTAINTY	**Sensitivity**	**Standard deviation**		**Total**
Load				
Force on tooth	1	0.067	**0.067**	
Velocity factor	0.15	0.75	**0.115**	
Overload factor	1	0.064	**0.064**	
Load distribution factor	1	0.13	**0.13**	
Total load				**0.197**
Strength				
Surface factor	1	0.034	**0.034**	
AGMA variation (reliability factor)	1	0.093	**0.093**	
Miscellaneous effects	1	0.025	**0.025**	
Total strength				**0.102**
Total				**0.222**

Table 11 Reliability quantities for a previous design.

	logarithm values	original values
Nominal Strength [MPa]	6.23	506 MPa
Nominal Load [MPa]	5.83	415 MPa
	difference	ratio
Distance Strength-Load, L	0.198	1.22
95% reliability distance, R	0.365	1.44
Safety distance, S	-0.167	0.85

5.5 Refining the analysis

The design process with VMEA can be refined to account for better estimations (reductions of uncertainty) and more detailed analysis of a certain contribution to the uncertainty. In the analysis performed here, some of the sources of uncertainty are due to unspecified material strength. This uncertainty can thus be easily reduced by closer specification of material strength.

A large and important uncertainty for the OHT concept is the influence of the face load distribution. The OHT design features a special assembly of the pinions with accompanying gearbox, hydraulic motor and generator that aligns the pinions to the rack to make the face load distribution more uniform. The effect of the load distribution in AGMA is quantified in terms of descriptions of the characteristics of support as given in Table 6. These descriptions are not quantifiable and cause difficulties when refining the design.

The Swedish standard "Spur and helical gears - Calculation of load capacity" (SS 1871) gives some aid for quantification of load distribution. Compared to AGMA, it works in the same way by designing against fatigue in the gear root through a calculation of bending stress and fatigue strength in the notch. It also uses factors that are similar to AGMA to take various effects into account. In SS 1871 the factor $K_{\mathrm{F}\beta}$ corrects for the load distribution. It expresses the effect (factor $K_{\mathrm{F}\beta}$) in terms of how large the contact along the gear width is relative to the gear width as given in Table 12.

Table 12 The load distribution factor $K_{\mathrm{F}\beta}$ in SS 1871 for gear widths up to the gear diameter.

Contact length in % of *b*		$K_{\mathrm{F}\beta}$	
at 1/3 load	at full load	at 1/3 load	at full load
95	95	1.4	1.1
75	95	1.8	1.3
35	95	2.5	1.9
20	75	4	2.5

The factor $K_{\mathrm{F}\beta}$ cannot replace the AGMA factor K_{m} directly since other factors not equivalent between AGMA and SS 1871 . Nevertheless, since both factors work in a multiplicative way, a linear relation between them will be assumed.

For the OHT design, the load is constant so the $K_{\mathrm{F}\beta}$ at full load is the relevant quantity. It is also seen from Table 12 that contact length at 1/3 load has most impact on $K_{\mathrm{F}\beta}$. To evaluate the dependence of the contact length on $K_{\mathrm{F}\beta}$, the values in Table 6 are plotted in logarithmic scales in **Figure 8**. A linear curve fit is presented in **Figure 8** with a slope around 0.5. Since $K_{\mathrm{F}\beta}$ acts multiplicative in the design process, the sensitivity coefficient is the 0.5 slope and the variation is simply the relative uncertainty in the contact length at 1/3 load.

To perform the nominal design calculation with use of the quantity contact length at 1/3 load, a translation to the K_{m} factor is needed. A rough translation is performed with the following assumptions:

- the lowest values of K_{m} and $K_{\mathrm{F\beta}}$ corresponds to the same situation (contact length at 1/3 load)
- the slope is the same

With these assumptions, values of the contact length at 1/3 load corresponding to the characteristics of support in Table 6 are adjusted to give the curve in **Figure 8**. The resulting adjusted values are included in

Table 13 and a resulting expression for calculating K_m based on a = "contact length at 1/3 load" becomes

$$K_m = \exp(-0.523 \ln a + 2.72) = \frac{15.12}{a^{0.523}} \tag{12}$$

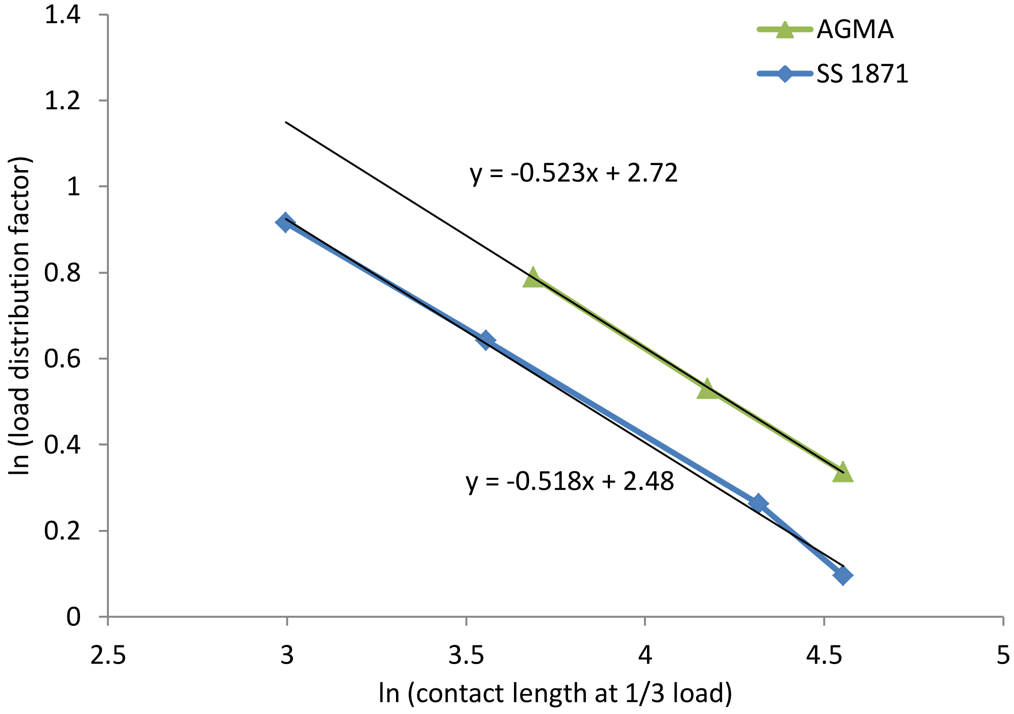

Figure 8 The load distribution factor dependence on contact length at 1/3 load.

Table 13 Adjusted contact length at 1/3 load corresponding to the AGMA factor K_m.

Characteristics of Support	K_m	contact length at 1/3 load
Accurate mountings, small bearing clearances, minimum deflection, precision gears	1.4	95 %
Less rigid mountings, less accurate gears, contact across the full face	1.7	65 %
Accuracy and mounting such that less than full-face contact exists	Over 2.2	Less than 40 %

With the use of the SS 1871 method for the load distribution, the load distribution can be analysed with a quantifiable parameter. An example of this will be shown here. With a detailed analysis it is in the example assumed that the contact length at 1/3 load could be calculated together with some uncertainty. Say that, with FEM or similar analysis, the contact length at 1/3 load is calculated to be 80 % and the relative uncertainty (coefficient of variation) of the analysis is 10 %. Then with the use of sensitivity coefficient 0.5, the VMEA uncertainty becomes as follows in Table 14 and **Figure 9**.

It can be observed that the total uncertainty decreases somewhat from 0.188 to 0.184. The dominating uncertainty is still the "velocity factor" and AGMA variation"

Table 14 VMEA estimation of uncertainties using SS 1871.

UNCERTAINTY	**Standard deviation**	**Sensitivity**		**Total**
Load				
Force on tooth	0.067	1	**0.067**	
Velocity factor	0.75	0.15	**0.115**	
Overload factor	0.064	1	**0.064**	
Load distribution factor SS 1871	0.08	0.5	**0.040**	
Total				**0.153**
Strength				
Surface factor	0.034	1	**0.034**	
AGMA variation (reliability factor)	0.093	1	**0.093**	
Miscellaneous effects	0.025	1	**0.025**	
Total				**0.102**
Total				**0.184**

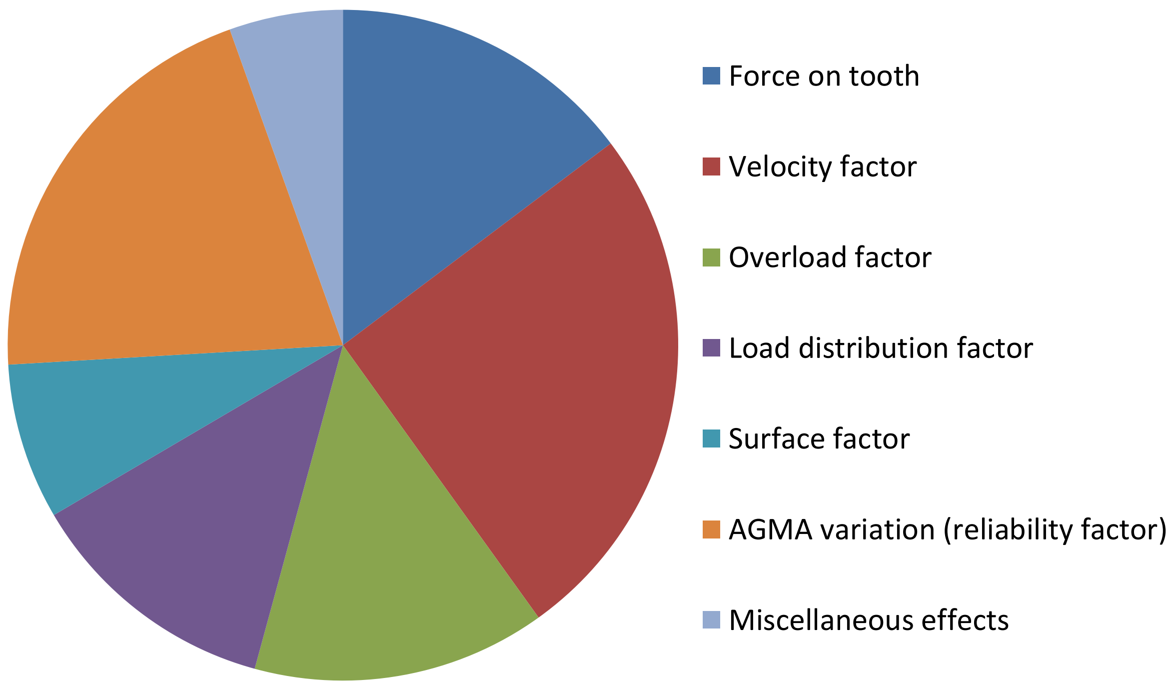

Figure 9 Contribution of the different sources of uncertainty using SS 1871.

6 Conclusions

The method Variation and Mode Effect Analysis (VMEA) is successfully implemented for the AMGA based gear design of the rack pinion mechanism. The rack and pinion is a feature in Ocean Harvesting Technologies (OHT) gravity accumulator device. The purpose of it is to make the electrical power output to the grid more uniform. This is a novel technology where previous experience in designing is absent. The VMEA method is there for useful for incorporating all known uncertainties to estimate the uncertainty and reliability of the technology. This allows for adequate safety factors to be set so the desired reliability can be achieved.

The uncertainty and reliability analysis is performed for different OHT designs and methods where the reliability is calculated. This calculation can be used as basis for further analysis when more design details are determined and modifications are made, thus allowing for more optimized and reliable design to be made.

7 Acknowledgements

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Box 24036, SE-400 22 GÖTEBORG, Sweden
Telephone: +46 10 516 50 00
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