A Major Step Forward in Life Modeling

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The SKF Generalized Bearing Life Model is (GBLM) an innovative new bearing rating life model that is designed to help engineers calculate bearing rating life in a more realistic manner. The new model is a major step forward for the industry and will play an important role in enabling OEMs and end users to better match bearings and applications, resulting in improved machine life and reduced operating costs.

The fundamentals of the new model are presented here.

Up to now the estimation of rolling bearing life has relied on engineering models that consider an equivalent stress — originated beneath the contact surface — that is applied to the stressed volume of the rolling contact. Through the years, surface-originated fatigue resulting from reduced lubrication or contamination has been incorporated into the estimation of the bearing life by applying a penalty to the overall equivalent stress of the rolling contact. In the SKF GBLM this issue is addressed by developing a general approach for rolling contact life in which the surface-originated damage is explicitly formulated into the basic fatigue equations of the rolling contact. This new formulation supplies the power to better represent the tribology of rolling bearings in rating life calculations. Further, it gives a better knowledge of the surface endurance that dominates the field performance of rolling bearings. The ability of the present general method to account for the tribology and surface-subsurface competing fatigue mechanisms taking place in rolling bearings is discussed.

Modern rolling bearings have become increasingly reliable when correctly used and lubricated. This is due to good practices and the successful understanding and application of the traditional rolling contact fatigue mechanisms. Increased material cleanliness and good manufacturing quality, combined with reliable life-rating methods, have made this possible. However, industrial trends of downsizing and higher demands for efficiency in field performance keep imposing additional, severe conditions upon rolling bearings — especially on the contacting surfaces. This is why most bearing failures are surface-related (Ref. 1). In order to prevent rolling bearings from causing a bottleneck in furthering the performance increase of modern machinery, the tribology of bearing surfaces must be better assessed with respect to bearing performance. In the past decade SKF has made substantial progress in the surface life modeling area (Refs. 2–8). Finally, the integration of this knowledge into rolling bearing life rating has been made possible (Ref. 9) with the introduction of the SKF generalized bearing life model (GBLM). It separates surface from subsurface and thus different physical models can be applied for those two regions. Subsurface rolling contact fatigue can be treated in the usual way following the classic, dynamic capacity model of Lundberg and Palmgren (Ref. 10), while treatment of the surface requires more advanced tribological models that address the complex physical interactions occurring in highly stressed, concentrated Hertzian contacts (such as lubrication, friction, wear, fatigue or running-in).

This enables SKF to reflect, in its bearing life predictions, more customized designs with specific features that can impact the field performance of bearing applications. Examples of this are bearings with specific heat treatment, advanced microgeometry or of a particular design or quality.

Customers can take advantage of the unique features of SKF bearings that are available in the product catalogue and use them in rating life calculations. At the end of the day, customers will be able to better utilize the features and quality of SKF products that can't be represented simply by a single "sub-surface" dynamic load rating (C), as is done today (Ref. 11).

The ability of this new approach to deal specifically with the degradation mechanisms and tribology of the raceway surface will enable the use of a more advanced version of the GBLM in bearing product development.

SKF engineers will use the GBLM to develop improved bearing designs targeting special applications or particular field performance requirements. In short, the GBLM represents a modern and flexible bearing performance rating tool, one able to incorporate new knowledge and technologies as they are developed.

Generalized Modeling Approach

The present model will retain the standardized probabilistic approach used up to now in rolling bearing life ratings based on a two-parameter Weibull distribution (Ref. 12). Waloddi Weibull (Ref. 13), with his "weakest link" theory, introduced stochastic concepts in the determination of strength and rupture of structural elements.

If a structure composed of n elements is subjected to different stress states — thus with a different probability of survival $S_1, S_2, \ldots, S_n$ following the product law of reliability — the probability that the whole structure will survive is:

$$S_1^n = S_1 \cdot S_2 \cdots S_n = \prod_{i=1}^{n} S_i \tag{1}$$

Lundberg and Palmgren, in their classic original formulation of the basic dynamic load rating of rolling bearings (Ref. 10), applied the product law of reliability of Weibull (Eq. 1), to derive the survival function of a structure made of n — independent physical elements accounting for the degradation process from 0 to N load cycles:

$$ln\left[\frac{1}{S(N)}\right] = ln\left[\frac{1}{\Delta S_1(N)}\right] + ln\left[\frac{1}{\Delta S_2(N)}\right] + \cdots + ln\left[\frac{1}{\Delta S_n(N)}\right] \tag{2}$$

The volume V can be divided into two or more independent sources of damage risk for the structure; consider that G is a material degradation function accounting for the effect of the accumulation of load cycles (fatigue). Therefore, regions can be characterized by different material degradation functions that could describe different (or a single) degradation processes $G_{v.1}$, $G_{v.2}$,…, $G_{v.n}$. Their combined effect on the survival of the complete structure can be expressed by using Equation 2. However, consider now only two regions, one for the subsurface (region v) and another for the surface (region s), from which the following can be derived:

$$ln\left[\frac{1}{S(N)}\right] = \int_{V_v} G_v(N)\,dV_v + \hat{h}\int_{V_v} G_s(N)\,dA \qquad (3)$$

Following Reference 14, the fatigue damage volume integral can be obtained by using the stress amplitude σ_v originated from the Hertzian stress field:

$$\int_{V_v} G_v(N)\,dV_v = \bar{A}N^e \int_{V_v} \frac{\langle \sigma_v - \sigma_{u.v}\rangle^c}{z^h}\,dV_v \qquad (4)$$

Where c and h are exponents, e represents the Weibull slope for the subsurface, N is the contact life in number of load cycles, z represents the depth of analysis, V_v is the integration volume, $\sigma_{u.v}$ is the fatigue limit at the volume, and $\bar{A}$ is a set-up constant.

In a similar manner one can rewrite the surface damage function. If the constant $\hat{h}$ is included into the surface damage proportionality constant, one obtains:

$$\hat{h}\int_A G_s(N)\,dA = \bar{B}N^m \int_A \langle\sigma_s - \sigma_{u.s}\rangle^c\,dA \qquad (5)$$

Here, m is the Weibull slope for the surface, A is the integration surface, $\sigma_{u.s}$ is the fatigue limit at the surface and is B a set-up constant.

In the surface damage Equation 5, the surface stresses σ_s must be obtained from the actual surface geometry of the contact and frictional stresses.

Now by combining Equations 4 and 5 with 3 it is possible to obtain a contact life equation with separate terms for the surface and the subsurface. Note that the life in number of revolutions can be related to the number of load cycles by $L=N/u$, where u is the number of load-cycles-per-revolution, and considering that the two Weibull slopes are very similar — $e=m$ — which is the case of the relevant surface failure modes in bearings, and finally leads to:

$$L_{1-S} = \frac{\left[ln\left(\frac{1}{S}\right)\right]^{1/e}}{u}\left[\bar{A}\int_{V_v}\frac{\langle\sigma_v-\sigma_{u.v}\rangle^c}{z^h}\,dV_v = \bar{B}N^m\int_A\langle\sigma_s-\sigma_{u.s}\rangle^c\,dA\right]^{-1/e} \qquad (6)$$

This represents the basis of a bearing life model that explicitly separates the surface from the sub-surface. The subsurface term, represented by the volume integral, can be solved in the same way as in Reference 14, with the use of traditional Hertzian rolling contact fatigue techniques. However, the surface term represented by the area integral now offers the possibility to consistently include in the model many of the tribological phenomena that characterize the endurance of the raceway surface.

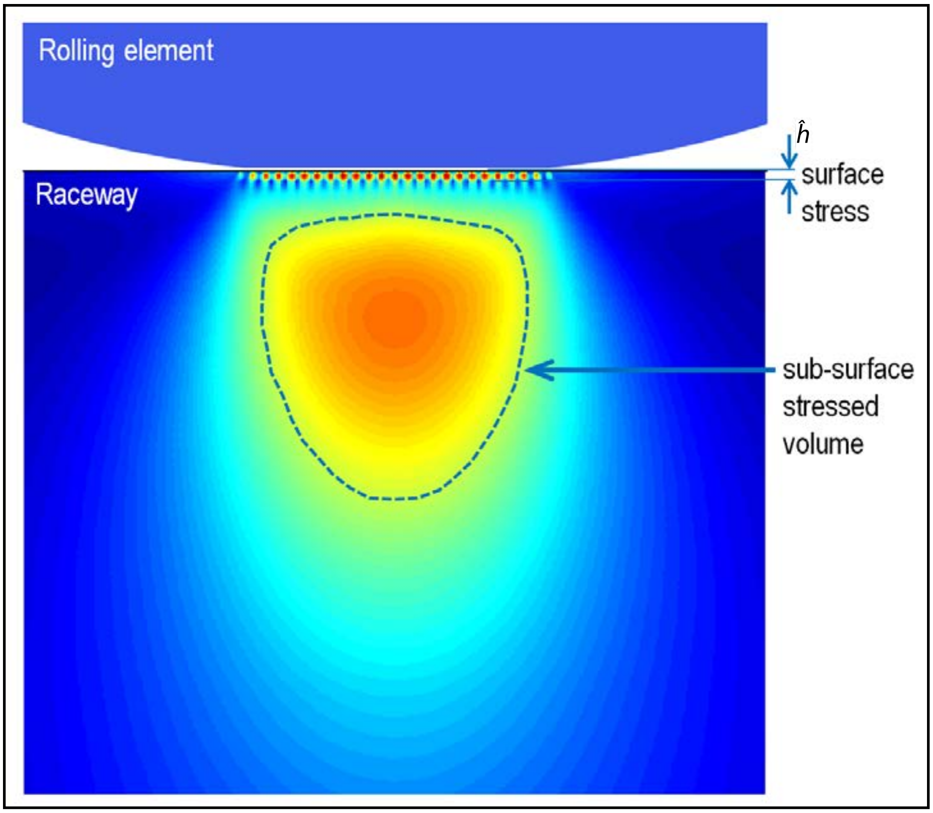

Figure 1 Separation of surface and subsurface as proposed by generalized bearing life model (GBLM).

Of course in this development the use of advanced numerical models is required. Indeed, it is required to represent complex interaction of competitive degradation mechanisms. For instance: i) surface fatigue in combination with mild wear; ii) indentation damage evolution; iii) tribochemical interactions; and many others. The schematic view of the GBLM main concept is represented in Figure 1.

Surface Models

A numerical surface distress model that combines fatigue and mild wear is described in (Ref. 5); this model requires as input the digitized surface roughness maps of the contacting surfaces (Fig. 2), and it solves the mixed-lubrication elastohydrodynamic problem (with non-Newtonian rheology).

$$R_s = f_1 exp\left[\frac{f_2}{(P/P_u)^{f_3}} + \frac{f_4}{(P/P_u)^{f_5}}\right] \qquad (7)$$

The solution is performed in time steps for calculated pressures and stresses. The calculation model applies a damage criterion and a wear model to update the surface topography and proceed to the next calculation time step until a complete over-rolling load cycle is completed. This numerical process is repeated millions of times for all calculation points of the surface. This enables a good simulation of the physical phenomena of the wear/fatigue damage accumulation process on the raceway surface for each given number of over-rollings. Typical results of this numerical model are shown (Fig. 3) and are compared with experimental results of tests

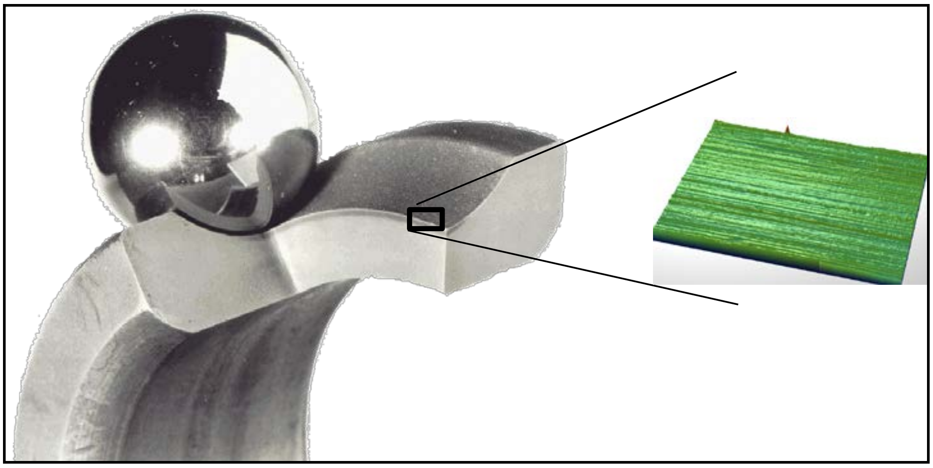

Figure 2 Bearing raceway roughness digitization using optical profilometer for 3-D surface mapping.

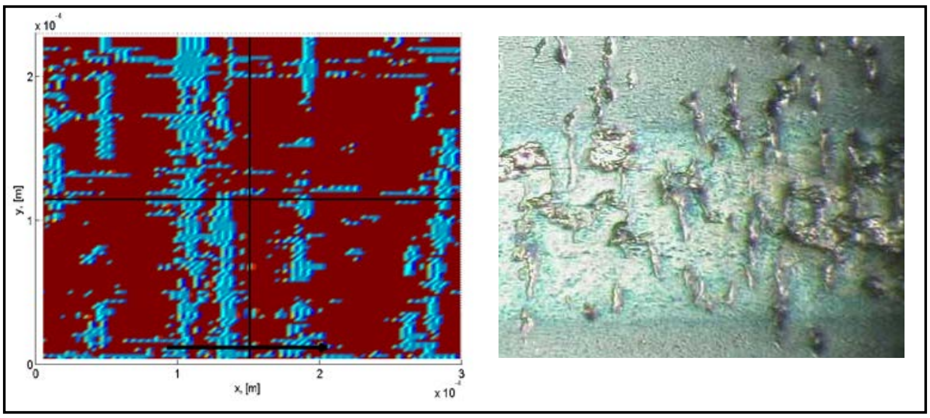

Figure 3 Typical results from the advanced surface distress (Ref. 5).

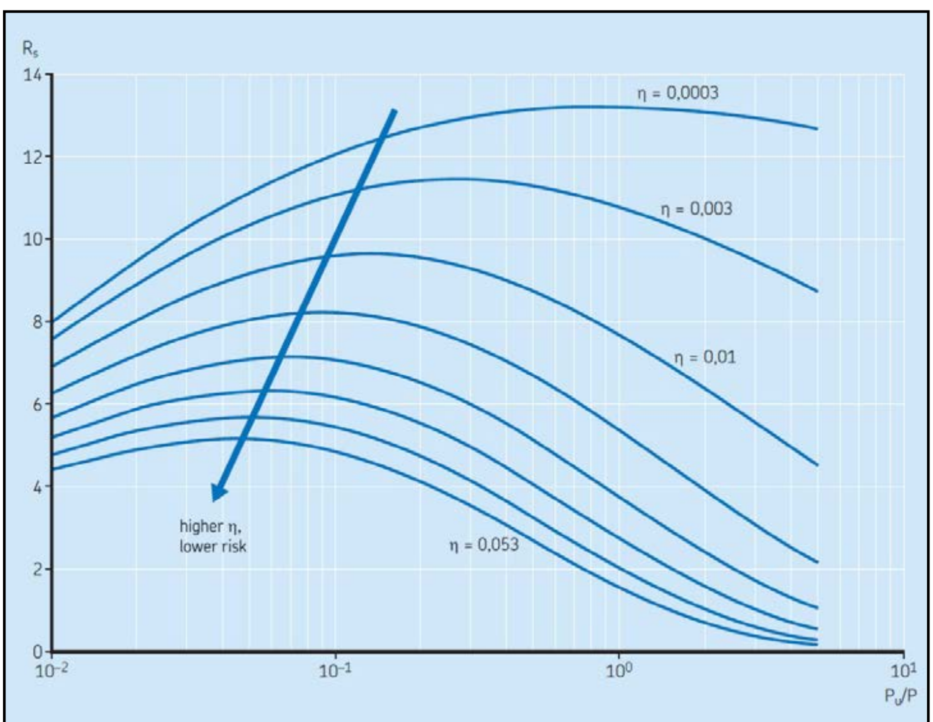

Figure 4 Example of surface risk rating as function of load and lubrication contamination regimes.

performed under the same conditions of the numerical simulation.

Other surface models that can be used with results integrated in GBLM are (Refs. 3, 6–7). As an example of the flexibility of the GBLM to integrate advanced surface damage models, for clarity only the surface distress model described in (Ref. 5) is considered. This model was used to run a parametric study using different operating conditions, roughness from different bearing types and sizes, and different lubrication and contamination regimes (Ref. 9). With this parametric study, the surface fatigue integral was normalized and curve-fitted to the following function using bearing parameters (Eq. 7)

Here, f_1, f_2,…, f_5 are constants, P is the equivalent dynamic bearing load, and P_u is the fatigue load limit of the bearing. The parameter R_s represents a surface damage risk rating; i.e.—it is a measure of the stresses imposed at the bearing running surfaces.

By using the advanced surface distress model, different lubrication and contamination conditions of the bearing can be computed, and their effect on the surface survival probability derived. In this way, by introducing the parameter $\eta = \eta_b\ \eta_c$ (Ref. 3) (to indicate the higher or lower risk of surface interaction), one can obtain a representation of Equation 7 as function of the dimensionless equivalent load P_u/P for a particular bearing type (Fig. 4).

Performance Factors

Unique design features of SKF bearings can eventually be taken into account using the above-discussed methodology to derive specifically designed "performance factors." These factors could be developed to give a better account of the performance of particular design features and specific operating conditions.

Typically these performance factors will apply to surface performance resulting, for instance, from novel heat treatments or materials resulting in improved raceway hardness, use of coating, introduction of improved raceway micro-geometry and surface finishing. However, the use of specific performance factors could in future also cover subsurface and even particular aspects of lubricants or lubrication. Basically, the structure of the GBLM enables the consistent incorporation of new bearing technologies and related performance prediction knowledge as they become available.

As an example of a performance factor related to the survival probability of the raceway surface, one can consider the introduction of bearing raceways with improved hardness, i.e. — better resistance to wear and contamination, particularly under reduced lubrication conditions. The knowledge of the expected improved performance of the surface endurance can be a factor in Equation 7, using a performance factor that reduces the surface damage risk (Fig. 5).

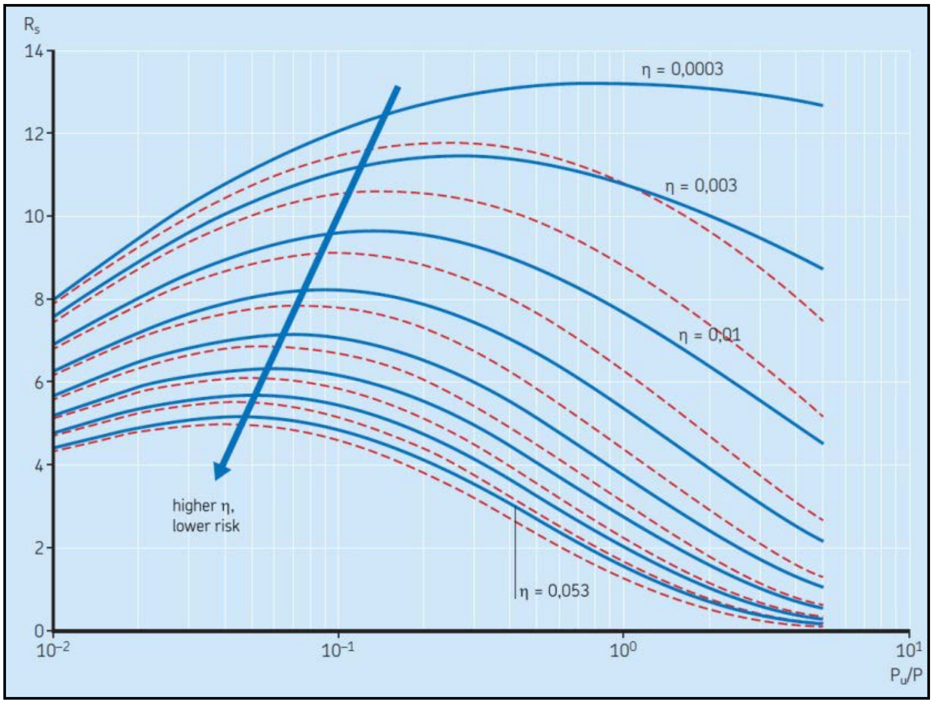

Figure 5 Example of surface risk rating as function of load and lubrication and contamination regimes; red dashed lines show effect of performance factor resulting from introduction of heat treatment that produces improved hardness of raceway surface.

Notice that in this particular case the performance factor was developed to target only a certain region of the operating conditions of the bearing. As shown (Fig. 5), the more significant surface risk rating reduction happens in the area of high risk for the surface; as the parameter η increases and the risk is reduced, the influence of the performance factor is also reduced. This shows the ability of this GBLM performance factor to target specifically the poor lubrication or high contamination levels of the bearing condition in which the more significant reduction of the surface survival risk is expected.

Normalized Surface Risk

Since the GBLM is able to separate the surface and subsurface endurance terms, it is possible to weight their relative impact to the overall dynamic performance of the bearing.

For instance, by introducing: i) the normalized surface integral or surface damage risk R_s; ii) the normalized subsurface stress integral or subsurface damage risk R_{ss}; and iii) the scaling coefficient *c*, one can derive the normalized surface risk of a bearing that is:

$$S_R = \frac{cR_S}{R_{SS}} \tag{8}$$

This parameter can vary from 0 to 1. When it is close to 1 the weight of fatigue on the surface is dominant in respect to the subsurface; when it is close to 0 the opposite is true. This is an important parameter in order to understand which stress area of the bearing carries higher risk. With this information application engineers and customers can plan corrective measures to maximize bearing performance and reduce costs.

Model Validation

When the operating conditions are similar, the GBLM gives results that are consistent with the current SKF life rating, and also to a large extent to the ISO 281 life rating models. This is because the GBLM has been validated against the extensive SKF database of endurance test results. This database is constantly increased and updated to follow new bearing technology development.

The introduction of performance factors will eventually alter the life that is predicted. However, this is a consequence of the performance modifications introduced by new bearing design aspects, which now will be visible in the rating life. In all cases SKF ensures that bearing performance changes are backed up by properly conducted endurance tests.

Customer Benefits with the GBLM

Customers can take significant advantage of the introduction of the GBLM in bearing life rating. Indeed, the calculation of the expected endurance performance of the bearing will be supplemented by knowledge of the surface risk of the application. In case the application condition of the bearing results in a predominant risk for the surface, corrective measures can be taken and their effect on the surface survival risk can be quantified. In other words, the GBLM can provide a diagnostic tool to improve field performance of the bearing by reducing surface-originated failures.

In general a high risk for the surface resulting from reduced lubrication and increased contamination cannot be resolved by adopting a bearing with an increased dynamic load rating and bearing size. This can be quickly checked by the effect of increased load rating and bearing size on the normalized surface risk. Therefore, customers can benefit from the use of the GBLM by making a more informed selection of the bearing, the surrounding components, and lubrication system for maximization of performance and reduction of the overall cost of the application.

Summary and Conclusions

A more flexible way to express bearing life — by splitting explicitly the terms related to surface failure modes from the general subsurface rolling contact fatigue terms — has been presented with the introduction of the SKF generalized bearing life model (GBLM). This model introduces the use of performance factors and makes possible targeting specific bearing features and more customized designs or applications. The model, apart from estimating the rating life of bearings, also calculates a normalized surface risk value S_R to give a clear indication of the surface fatigue weight in comparison to the subsurface one.

In general, the following conclusions can be made:

The new SKF generalized bearing life model (GBLM) provides a clear split between terms affecting the surface and terms affecting the subsurface, and can be explained as a more flexible way to express the current SKF life rating.

This model is the only existing bearing life model able to explicitly contain separate subsurface and surface-related terms in its formulation, incorporating easily the knowledge gained with the use of advanced numerical tribology models.

Novel elements in the model are the performance factors to account for specific SKF proprietary design improvements in the bearing, and/or design features affecting the performance of the bearing in an application in targeted operating conditions.

The GBLM can be regarded as a platform of models that can be grown as new knowledge is developed, enabling easy incorporation with the consideration of different phenomena affecting specifically the surface or the subsurface areas in the bearings.

The SKF generalized bearing life model will be available for customers in the near future. **PTE**

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