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MAINTENANCE AWARENESS IN GEAR-BOX DESIGN

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1. Introduction

Over the last fifty years the meaning of term maintenance and complexity of the subject have changed dramatically. From the 'fit when it's broken' concept to the 'new expectations' concept, where such issues as: reliability, cost effectiveness, safety, ecological irreproachability, safety, etc. need be considered [EFNMS 2000]. Maintainability is by some authors defined as the probability that a system, which has failed, will be restored to a functional condition within a period of time, when maintenance process is performed in accordance with prescribed procedures[Ebeling 1997]. Maintainability improvement represents a selection of measures taken to reduce required maintenance costs, increase productivity, quality, safety and delivery precision of technical systems, reduce costs per unit and environmental irreproachability. It can be partly achieved by improved organisation of the maintenance tasks, increased skills of the maintenance personnel and, to a high degree, by the maintenance awareness in design phase. To reduce downtime and enhance availability of the technical systems, the following categories have to be considered: reduced required amount of preventive and corrective maintenance, simplified maintenance tasks and reduced required maintenance resources [Dhillon 1999]. In order to provide means for assuring above mentioned design characteristics, attention has to be given to some design features as follows: Accessibility of maintainable components and test points; Ease of mounting, adjustment, calibration, replacing and discharge; Planed test and inspection points; Established unit labelling and coding system; Adequate support documentation and maintenance handbooks; Classified diagnostic and test reference information; Reliable lubrication system. Above presented criteria are very useful and important, but difficult to measure. Consequently some other methods have been developed to enable assessment of the product maintainability and to highlight the areas of a system, which exhibit poor maintainability. They should be used early in a system planning and design stages. Various computational models are available providing quantifiable measures that can be directly compared and used for the design evaluation. Some of the frequently used measures are: LCC (Life cycle cost), MTTF(Mean time to failure), MTTR(Mean time to repair), $\overline{M}$ (Mean system downtime), MTR(Mean time to restore), … When the maintainability oriented design goals are set and quantifiable design evaluation measures of maintainability are calculated and compared for all the treated design solutions, the conditions under which maintenance is to be performed must be determined. Balance between the cost of repair and discard of units has to be established. Different cost models can be applied to establish an acceptable maintainability level of a designed system. Iterative design process is schematically presented in Figure 1. If there are several alternative designs, a direct cost comparison is possible to decide on the design suitability. During the design phase some important questions must be asked:

- Which parts of a component (or a whole system where appropriate) are to be repaired and which discarded?
- What is the level of repair for repairable units?

- What is the level of complexity of required repair tasks?
- What is the frequency of the required preventive maintenance?
- What are the required maintenance and supply resources?

In the present work some aspects of the maintainability awareness in the gearbox design are discussed.

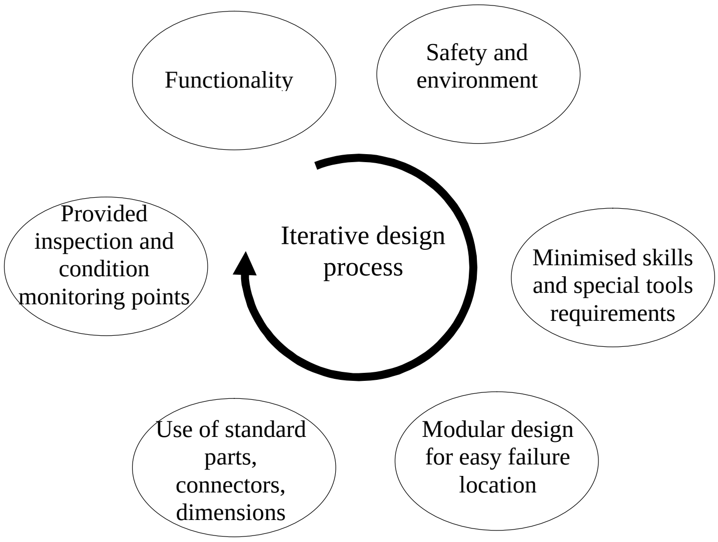

Figure 1. Self- check guidelines

2. Gearbox design and maintainability

During a gearbox design process many important issues must be considered:

- Technical requirements: gearbox type, output torque, and reduction ratio.
- Geometrical requirements: size limit, axis height, co-axial shafts, mounting mode, output shaft size and shape...
- Working conditions: driving and driven device, operation time, intermittency...
- Working environment: temperature, humidity, dust, aggressive media, ...
- Manufacturing feasibility and ease of mounting.
- Simplified maintenance tasks and reduced required maintenance resources.
- Predicted number of units and variants to be produced, potential manufacturer’s skills and resources, subcontractors…
- Some aspects of the maintainability awareness during the gearbox design phase are discussed in the present work. Balance between the cost of repair and discard of a gearbox a key-issue when deciding about the extent and complexity of maintenance tasks, which are allowed to be performed on a particular gearbox.

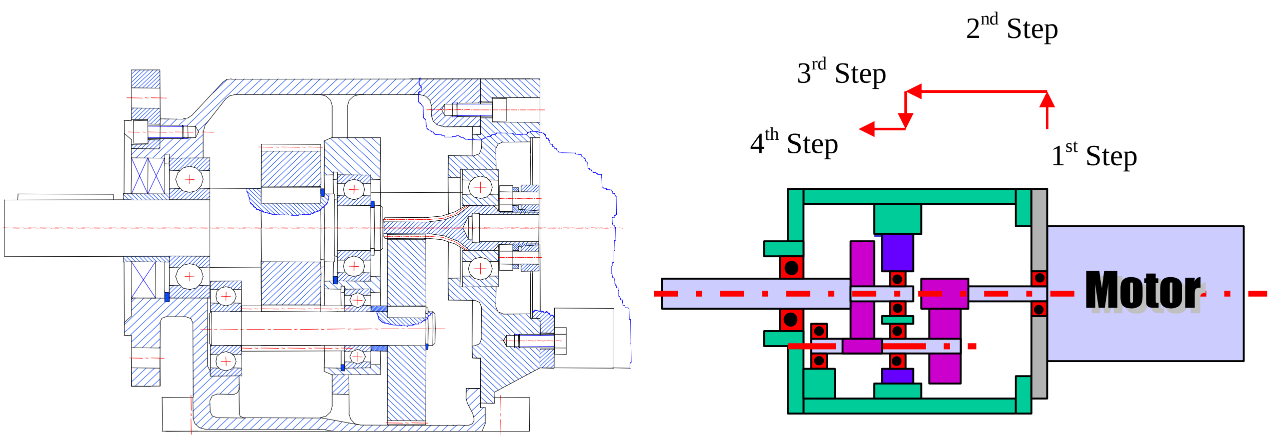

Figure 2. Two-stage spur gears drive

Regarding above criteria, gearboxes can be divided into three groups:

- Maintenance-free gearboxes
- Gearboxes with low extent and complexity of maintenance tasks.
- Maintainable gearboxes where complex interventions are planed, including repair and replacement of components.

An example of a two-stage spur gear drive is presented in Figer 2. Traditional manner of bearing fixing and housing configuration is changed, to reduce the number of components and to improve housing efficiency. Consequently assembly procedure has to be well considered to avoid collision of parts. Maintenance disassembly and assembly instructions should be unambiguous and consistent.

2.1 Maintenance-free gearboxes

First group comprise gearboxes that must be maintenance-free for various reasons. Usually the gearbox replacement value represents a minor cost comparing to a downtime cost of a plant. High overload capacity and reliability are usually required for this type of gearboxes, unless the failure of the gearbox represents no danger to the user and no damage to the environment. In the later case, it is in some applications acceptable to run the gearbox until it fails. Maintenance-free gearboxes are often used in case of a low accessibility as well. A spare gearbox has to be stocked. Discussed type of gearboxes may appear simple but it requires well-considered design solutions. Prescribed load capacity of the gearbox has to be assured with no maintenance personnel intervention for all the defined life cycle. Maintenance-free operation has to be enabled by selecting corresponding materials (metal and non-metal) and shape of components. Efficient and continuous lubrication with suitable slow ageing lubricants has to be provided. Maintenance-free bearings are frequently used. Maintenance-free gearboxes designed for heavy-duty working conditions (dust, heat, duty, duty) may become too expensive and are replaced by gearboxes where minimal maintenance is required. Maintenance-free gearboxes usually have simple design and are cheap. Typically they have a single block (‘unicase’) housing that is compact and extremely rigid. Consequently the sealing surfaces are not subject to any load pressure. Following the no-maintenance idea subsequent dismantle and assembly are not expected and are therefore complicated and time consuming. There are no maintenance openings in the housing. During the assembly of such gearboxes a special attention has to be devoted to cleanness of all components and tools, to avoid chemical degradation of lubricant. It is inevitable to prevent presence of any abrasive parts that may cause increased abrasive wear of sliding surfaces. For the above reasons worm gears are less suitable to be applied in maintenance-free gearboxes. In case of mass-produced industrial maintenance-free gearboxes, where it is difficult to exactly predict actual working conditions, there can be connector holes planed in the housing to accommodate different types of condition-monitoring and maintenance devices.

2.2 Gearboxes with low extent and complexity of maintenance tasks

A second group of gearboxes requires only routine maintenance work like lubricant change, control or supplementation and replacement of exploitable components (bearing, seals, …) No high skilled specialist and no special maintenance resources are expected. Gearboxes from the discussed group belong to the middle price and size range. Eventual fault isolation and correction costs would obstruct balance between the cost of repair and discard of units. Gearbox design must enable systematic condition monitoring and simple maintenance tasks to provide expected reliability.To meet the expectations, a specific type of maintainability has to be reached and some requirements added to a list of design features. Simple and cheap maintenance tasks, no expensive spare parts needed, simple manufacturing and assembly, minimised variety of parts. Resulting gearbox must be cheap and reliable enough to require minimum maintenance and is cheap enough to discard, rather than replace worn out and broken parts. For some gearboxes it is required to wash the interior of the housing before lubricant is changed. The design solution must enable washing without dismantling a gearbox from the motor. Spare seal material must be planned where precedent condition cannot be fulfilled. When a maintainable gearbox is designed, type and complexity of the required maintenance tools must be studied carefully. The number, complexity and variety of them should be minimised, while the quality and suitability must be retained. For example, in some cases it is undesirable or even dangerous for some screws to be unscrewed during maintenance tasks. Using specifically designed screw joints that cannot be unscrewed using prescribed maintenance tools can prevent it. Designer should provide unequivocal maintenance handbook particularly where specific maintenance procedures are required to avoid damage or injuries. Maintainable parts must be labelled and systematically coded. Dangerous spots must be marked. Accessibility of the maintainable parts in all gearbox-mounting positions is crucial as well as positioning of the breather plugs. Two levels of accessibility need to be considered: local accessibility, which is exclusively a function of gearbox design and global accessibility, where the mounting position and a position of the surrounding machinery must be taken into account. It is beneficial to use a special colour system to mark important spots of the gearbox to simplify maintenance tasks.

2.3 Maintainable gearboxes where complex interventions are planed

In the previous chapter replacement of the worn out parts has been discussed, but it has been restricted to simple and planned routine maintenance tasks. In the present section presented gearboxes are designed to be subject to a complex required repair tasks. These gearboxes are usually bigger and expensive where pretentious maintenance tasks represent relatively small cost comparing to the gearbox replacement value. Expected maintenance tasks can include both, simple locally performed repairs and complex interventions performed by external experts. Special approach must be employed when designing this type of gearboxes. Construction must enable implementation of all needed condition monitoring and repair tasks. Attention must be focused on the following features:

- Simple dismantle and reassembly: special tools may be required, but the task must be plain and accurately repeatable. Damage to the spare parts and to the surrounding components due to the complicated reassembly method must be prevented.
- Exactly prescribed maintenance procedures must be planed and feasibility checked during the design phase. They must be described in a well-prepared maintenance reference book, which should be an inherent part of gearbox design documentation. Training and on-line information should be available to the maintenance personnel.
- Systematics of the maintenance tasks and spare parts logistics must be precisely defined.
- Unambiguous spare parts catalogue should be prepared during the design phase, based on the reliability analysis of gearbox components. It is particularly important when the gearbox structure enables various variants of settings (reduction ratio, mounting positions, shaft adapters, mounting positions, different motors, …). It is necessary to indicate trains of spare parts that must be replaced simultaneously and regulate the replacement regime.
- Maintainability definition:' … is probability that a system, which has failed, will be restored to a functional condition within a period of time, when maintenance process is performed in accordance with prescribed procedures!' captures all the vital categories that must be considered during the maintainable gearbox design phase.

3. Gearbox design and condition monitoring

Cost of the equipment down time required to restore the failed equipment or perform planned maintenance tasks has induced a request to increase intervals between maintenance interventions and reduce restoration times. Many non-destructive methods have been developed for detection of the incipient problems in rotating machinery. They enable monitoring of actual mechanical condition of machinery and consequently minimize the number and cost of unscheduled machine outages. Gearbox design is not directly influenced by the condition-driven maintenance techniques, but the intended condition-monitoring actions must be realizable on the suggested design. In case of condition-driven gearbox maintenance the following indicators are generally monitored:

- Visual inspection: surface fractures, rust, visible wear and damage.
- Inspection of the operation parameters: torque, rotation speed, the state of lubricant (pressure, temperature, flux, …).
- Vibration analysis of rotating gears and bearings: to determine the location and type of damage or to identify imbalance and misalignment of components.

- Liquid testing techniques: ferrography, viscosity testing and acid number testing are cooperative methods to complement other condition monitoring methods. Wear problems like excessive load, misalignment, fractures, rolling contact failure, poor lubrication, outside contamination, lubricant additive depletion can be detected on-line.

3.1 Condition monitoring sampling points

During the gearbox design phase it is necessary to be consider every expected condition-monitoring method that is to be applied for the particular power-transmission system. Some basic requirements are listed below:

- Visual inspection: Sufficient visibility, accessibility, work clearances and access ways for monitoring tasks must be planed. To avoid the injuries the edges of the access openings should be rounded.
- Liquid testing techniques: Lubricant-sampling points must be planed in the gearbox design phase. For consistent results lubricant samples must be taken from the same place in the system. In case of static sampling it is from the lubricant container when the machine is turned off. When the dynamic sampling is applied, samples should be taken from the turbulent zone before the oil filter. Wear particles sedimentation area must be provided for the gearboxes without external lubrication system.
- Vibration analysis of rotating gears and bearings: Vibrations are commonly monitored using accelerometers that are usually screwed, glued or fixed by a magnet to the rotating part. Most common sampling points are on the housing – next to the bearing and as close to the engagement line as possible. During the gearbox design sampling points and necessary bores must be predicted together with the belonging installation. An example of sensors location is presented in Figure 3.

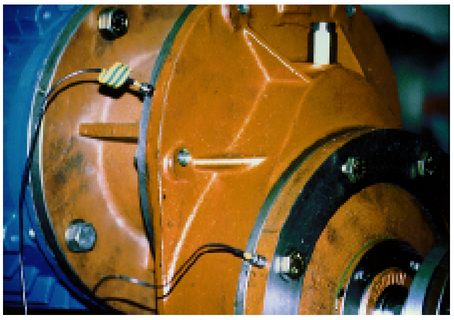

Figure 3. Location of vibration-monitoring sensors

- Temperature inspection: Temperature is usually monitored for the purpose of thermal protection of the power transmission. Thermal cutout is placed on the electro motor and shuts out the power if the boundary temperature is exceeded. Gearbox design must enable installation of the sensors.

Figure 4. Installation of sensors

- Imbalance and misalignment: Premature bearing, gear and seal wear is often induced by imbalance and misalignment. To avoid the above irregularities an exact assembly and fitting procedure has to be prescribed and all the required tools must be planed.

State-of-the-art gearbox condition monitoring systems are integrated into the machine-train monitoring system where the vital information is collected and processed centrally. Different levels and types of the feedback information are generated and transmitted to the authorised users.

4. Conclusion

Pressure to reduce LCC has increased importance of maintainability awareness of technical systems during the design phase. In the present work some aspects of the gearbox design with respect to the maintainability improvement and LCC reduction are discussed. Gearboxes are, regarding required amount of maintenance, divided into three categories. Categorisation is grounded on the price and lifecycle cost of the gearbox, maintainability of the system where the particular gearbox is employed and the downtime cost-per-unit for the process where the gearbox is applied. Some techniques of the on-line condition monitoring are stated and specific gearbox design requirement are presented for each of the methods. It can be concluded that complexity and level of maintenance activities are dictated by the justifiable costs, operational safety and environmental suitability, but can only be performed on a adequately designed technical systems.

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