OPEN-GEAR LUBRICATION: MEETING INDUSTRIAL REQUIREMENTS USING LABORATORY TECHNIQUES

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ABSTRACT

In this paper a general overview of open-gear lubricants is given. It is shown that factors like environmental acceptance, toxicity and ease of disposal of spent lubricant plays an equally important role in the formulation of new products as the requirements related to performance, like pumpability, sprayability, adhesiveness, load-carrying ability and wear protection capability.

In order to evaluate various contenders, laboratory tests are often used as a preliminary means of screening. It is shown that, when care is taken to perform laboratory tests under conditions which represent the actual operating conditions, simple laboratory tests can be conducted to evaluate products before a product is selected for use in trial runs on actual equipment. When planning laboratory tests, the industrial requirements need to be clearly defined - from the perspective of the supplier as well as that of the user.

INTRODUCTION

Although specifications for the use of open-gear lubricants exist (1),(2), test methods for determination of the performance of these lubricants are not standardized. The reasons for this state of affairs can be attributed to the following:

- a variety of products using different technologies, but fulfilling the same purpose.
- a wide range of laboratory test techniques the results of which do not necessarily corellate with field experience.

Linked to this is the problem of fast-changing technology - both with regard to development of new products and with regard to the design of gear drives. The continuing pressure to use products that conform to environmental requirements in terms of usage and disposal has also caused fundamental changes in the philosophy and practice of open-gear lubrication (4),(6),(9). Open-gear lubrication involves many facets of the operation of the total system, of which good housekeeping and maintenance practice, safe disposal (and possible reclamation) and measurement of gear wear form a not so insignificant part.

In order to put laboratory test techniques into proper perspective, it is necessary to be aware of the changes that have taken place in the formulation of open-gear lubricants, methods of aplication, typical operating conditions requiring lubricants with specific properties and methods to monitor the performance of the lubricant in use.

DEVELOPMENT OF OPEN-GEAR LUBRICANTS

The present trend in industry is to move away from asphaltic (bituminous) products thinned down with a solvent to oil-based products (greases, compounds, pastes and gels) with a variety of additives. The reasons for this include the need for improved lubricant performance due to increased loading per unit tooth width, reduction in amount of lubricant used, the toxicity of the products to operating personnel, the possible harmful effects that the lubricants may have on personnel handling it, or on the environment, ease of handling of lubricants and related maintenance on geared systems, and finally the safe disposal and/or reclamation of spent lubricant.

Asphaltics have traditionally been the product of choice. These products were cheap and performed well due to their high viscosities. When spray application systems were introduced it became necessary to pump these products, and they were thinned down with volatile solvents, which evaporated once sprayed onto the gear surfaces. Low temperatures cause these products to solidify in

the pipework, cause root buildup in the gears and cause general difficulties in housekeeping and maintenance of the systems. They are largely being replaced in favour of more environmentally-friendly and easier-to-handle products, including greases, compounds, pastes and lately gels. (4)
Greases (low, medium and high base-oil viscosity), when used for open-gear lubrication, make use of base oils with fairly high viscosities (in the range 680 - 2 000 cSt @ 40°C). The grease soaps used are calcium, lithium complex, aluminium complex and also combinations of these. Pastes and compounds contain high concentrations of solid lubricants (20 - 70% m/m). Base oil viscosities range from 1 000 - 10 000 cSt @ 40°C. Some of these compounds require a solvent or a volatile oil for ease of distribution and application.

Fluids are essentially greases with a low consistency (in the range NLGI 000 or 00) containing very small quantities of soap or thickeners. Base oil viscosities range between 100 and 3 500 cSt @ 40°C. They contain low percentages of solid additives like graphite and molybdenum disulphide.

Mineral oils (EP and R&O) as described in the current AGMA standards (1),(2) are available for use on open-gear drives. Synthetic and semi-synthetic oils may, in addition to the synthetic oil component, like poly-alpha olefins, esters and polyalkylene glycols, include polymers as thickening agents, tackifiers and EP additives. Viscosities of 10 000 cSt @ 40°C are easily achieved.

Gels can be described as lubricants using a base-oil with a high viscosity and using a gel thickener. Various viscosity grades can be formulated. They offer particular advantages due to their filterability, which means that they can be used in enclosed recirculating systems, where only minimal additional attention is required to control leakage from enclosures. (4)

The type of lubricant to be used depends on a number of related factors, including application method and distribution method. It is due to this large variation in product technologies that it is difficult to obtain representative performance test procedures.

OPERATING CONDITIONS OF TYPICAL OPEN-GEAR SYSTEMS

The factors regarding operational conditions that need to be taken into account when open-gear systems are lubricated are: (3),(6)

(i) The operating load, which is typically in the region of 450 - 800 MPa.
(ii) The operating temperature.
(iii) The sliding speed.
(iv) The dimensions of the gear and pinion(s) and the rotational speed of the gears.

In Table 1 below (8) it is clear that the design philosophies of European and US gear designers differ, for example with regard to gear ratios employed, pinion diameter, shaft diameters and bearing distances. This will have an important influence on the lubrication requirements of the gear system, in addition to non-lubricant-related problems like the load-distribution accross the face-width.

LUBRICATION TECHNIQUES

In addition to the two basic methods of utilizing the lubricant, namely once-through (total loss system) or reciculating (primarily in enclosed or partly enclosed systems), a variety of lubricant application techniques are in use, (4),(12) namely:

(i) Continuous spray
(ii) Splash or sump lubrication
(iii) Idler immersion
(iv) Intermittent spray

Depending on the lubrication technique and the distribution system employed, a lubricant with corresponding properties will have to be selected.

TABLE 1 TYPICAL GEAR SYSTEM DESIGN DATA			
	Units	US OEM	Europe
Motor Power	kW	1 500	1 500
Pinion Speed	rpm	188	135
Gear speed	rpm	15,4	15,3
Pitch Line Velocity	m/s	5,04	5,37
Helix angle	deg	7,50	-
Gear tooth width	mm	700	550
Pinion PCD	mm	512	760
Gear outside diameter	mm	6 246	6 680
Diameter:contact width ratio (P)		1,36	0,77
Diameter:contact width ratio (G)		8,9	12,16

LUBRICANT REQUIREMENTS

Apart form the basic physical and chemical properties required when open gear lubricants are specified, there is a number of other properties that are normally included in the specification of a particular product. These can be classified as performance properties. Based on the operating conditions as well as the distribution method in use, the lubricant will be selected according to the following requirements: (3),(6)

(i) Adequate base oil viscosity (in the case of greases).
(ii) High load-carrying capacity.
(iii) High film strength and stability.
(iv) Good anti-wear, anti-scuff and EP properties.
(v) Good adhesive properties.
(vi) Good flowability characteristics in order to form even films.
(vii) Pumpability.
(viii) Sprayability characteristics.
(ix) Environmentally acceptable.
(x) Low consumption to reduce disposal costs.
(xi) Good filterability (in the case of enclosed, recirculating systems)
(xii) Acceptable oxidation stability.
(xiii) Adequate corrosion protection
(xiv) High shearing stability.

Most of these requirements depend to a greater or lesser extent on temperature, therefore these requirements have to be met over the operational temperature range. It is often in this regard that products fail to meet the requirements.

LABORATORY-BASED TESTS

What needs to be measured in a laboratory test? In general, tests required to ascertain whether a particular product would be suitable, could be classified as follows:

(i) Physical and chemical properties, including viscosity, density etc.
(ii) Performance-related tests, like pumpability, adhesiveness, sprayability, shear properties, surface tension etc.
(iii) Load and wear performance by means of load-carrying capacity and wear-resisting property determination.

In Table 2 a list of some of the tests, that are used to evaluate open gear lubricant properties, is presented.

TABLE 2
LABORATORY TESTS TO DETERMINE OPEN GEAR GREASE PROPERTIES

PROPERTY	TEST METHOD
Kinematic Viscosity of base fluid	ASTM D445
Viscosity index of base fluid	ASTM D2270
Flash point of base oil	ASTM D92; IP35; IP36
Pour point	ASTM D97
Density @ 20°C	ASTM D1298
Penetration	ASTM D217, DIN ISO 2137, DIN 51804
Drop point	ASTM D566, DIN 51801
Consistency class	DIN 51818
Oxidation stability	DIN 51808 Pt 1
Water resistance	DIN 51807, ASTM D4049
ASTM Rust prevention test	ASTM D665, D1743
Copper corrosion	ASTM D130, DIN 51811
Neutralisation by colour titration	ASTM D 974
Load-carrying capacity	FZG DIN 51354 A/2,76/50
4-ball EP test (grease)	DIN 51350 Pt 4, ASTM D2596
4-ball EP test (fluids)	ASTM D2783, IP 239
4-ball wear preventing characteristics of lubricating fluids	ASTM D4172
Continuous wear test (4-ball)	ASTM D2266
SRV test	DIN 51834
Timken Load Test	ASTM D2509, ASTM D2782
Load-carrying capacity (Ryder machine)	ASTM D1947
Lubricating film endurance/retention	Timken US Steel method
Falex test	ASTM D2670 and ASTM D3233
Grease pumpability	Lincoln ventmeter test
Grease Mobility	US Steel mobility
Grease Conveying characteristics (Shell-Delimon rheometer)	DIN 51816
Adhesion and plasticity	DIN 21258

Although a lot of controversy exists regarding laboratory-based performance tests for the determination of load and wear behaviour, they are necessary, since the only methods to determine performance properties of a lubricant in question are by means of:

(i) Laboratory testing.

(ii) Field testing, which may not be feasible in many cases, may prove to be exorbitantly expensive and may also be prone to inability to maintain constant operating conditions during the test.

(iii) Theoretical calculations to determine the relevant properties, which will be highly inaccurate, due to a lack of understanding of the behaviour of the systems in question and the interactive role that the lubricant, and specifically complex lubricants like gear greases play.

Calculation of film-thicknesses depend heavily on the ability to describe the behaviour of a system in mathematical terms (lubricating regime, ie EHD, mixed friction or boundary lubrication) and also on the accuracy of the physical properties of the lubricating medium. Non-Newtonian fluids increase the uncertainties associated with such calculations. In the case of a grease or compound, only the physical properties of the base oil are taken into account. In addition, an important parameter like the pressure coefficient of viscosity is in many cases an assumed value, while the role that additives play are not taken into account.

The only use that equations of this kind have, is to give an indication of the role that various parameters play in the lubrication of a system. The use of an equation relating lubricating film-thickness to the factors influencing the tribological system, namely load, lubricant, speed and material, can be obtained by means of dimensionless groups in the following way:

Film-thickness parameter = velocity parameter * materials parameter * load parameter

As an example of the EHD equations for the calculation of film-thickness, the equation by Dowson and Higginson (10) can be used:

$$\frac{h_{min}}{R'} = 1{,}6\left(\frac{\eta U}{E_D R'}\right)^{0,7} (\alpha E_D)^{0,6} \left(\frac{W/L}{E_D R'}\right)^{-0,13}$$

where:

h_{min}	=	minimum film thickness
R'	=	radius of relative curvature
η_o	=	viscosity at atmospheric conditions
E_D	=	composite or reduced elastic modulus
α	=	pressure coefficient of viscosity
W/L	=	normal load per unit tooth contact width
U	=	velocity

Of the three possibilities, the laboratory-based approach holds promise, provided that certain important requirements regarding test conditions are met.

Laboratory performance tests may contribute towards the following:

(i) Obtaining comparative results during development of new products or modifying existing products, identifying the presence of desired and undesired lubricant properties.
(ii) Minimising the risc and cost of in-service damage to lubricated parts.
(iii) Screening of candidate products during evaluation.
(iv) Determining the friction and wear behaviour of a lubricant under carefully controlled conditions.
(v) Determining optimum lubricant supply rates and relubricating intervals.

Of these, the last two have the least chance of success unless very special care is taken to ensure that conditions of test relate to the operating conditions.

A large variety of friction and wear and also load-carrying ability tests have been developed. Before any tests are performed, it is important to evaluate the relevance of such a test in terms of the test conditions as opposed to the operating conditions. Several authors have reported on this (5),(16). Determination of load and wear characteristics using laboratory test devices are prone to misinterpretation and should be used with caution. In all cases the following basic requirements have to be met:

(i) Material-related properties, ie roughness and hardness.
(ii) Load per unit area.

(iii) Temperature.
(iv) Relative movement, ie rate of sliding, rolling or combination thereof.
(v) Direction of movement, ie unidirectional or oscillating.
(vi) Test duration.
(vii) Contact configuration, ie point, line or area contact.

In many cases test machines are configured and run under conditions not vaguely resembling the practical system to be simulated. An additional fact to consider is that a laboratory performance test should be performed under more extreme conditions than those that prevail during operation, otherwise measurable wear results will not be available within a reasonable time. The determination of test conditions, severe enough to accelerate the wear behaviour without changing conditions in such a way as to be non-representative, is of prime importance.

When looking at sliding velocities of different laboratory test machines, this can vary between 0,09 m/s for the Falex machine to 11,56 m/s for the FZG machine (5). This should be compared with an actual application where it soon becomes evident that practical conditions correlate in this respect to the FZG machine's sliding speed.

Another area of discrepancy is in load per unit area, where initial loads on laboratory machines often far exceed the load attainable in practice. (This is in cases where point contacts are applicable eg the 4-ball apparatus and the SRV-tester)

Other factors which also influence the total performance of the test system are:

(i) Volume of lubricant used (from a few drops up to 2 litres)
(ii) Duration of test run (from a few seconds up to days in case of the FZG test)

These factors influence the extent of "stressing" of the lubricant during the test (which should at least relate to that of the field application) and also the requirement for frictional heat dissipation, taking into account the size of the test specimens relative to the volume of lubricant used during the test.

As a last motivation for the careful use of a laboratory-based load and wear performance test, the requirements as stated by Paton and co-workers can be given: (14)

(i) It must be capable of modelling the loads, velocities, acceleration and direction changes experienced by gear sets in the field.
(ii) It should be capable of determining the wear resulting from the use of candidate lubricants under these simulated conditions.
(iii) It must be able to monitor the lubricating film not only during operation under the simulated field conditions but also over a range of lubricant supply mechanisms, ie drip, spray, etc.
(iv) It should be capable of conducting evaluations over the full operating temperature range.

From the abovementioned information a test machine like the FZG-apparatus, is one of the machines which conforms to most of the stated requirements.

In Table 3 the typical operating conditions on a typical mill drive is shown together with the test conditions of the FZG "grease" test (A/2,76/50) (13) and a modified FZG pocedure currently under investigation by the Laboratory for Advanced Engineering (11). From this it is clear that the latter test conditions correspond largely to field conditions.

A last aspect which may be addressed by an "ideal" laboratory test apparatus, is the determination of optimum application quantities and relubrication intervals, in the case of intermittent lubrication systems.

TABLE 3 COMPARISON OF FIELD AND FZG-TEST OPERATING CONDITIONS			
	COAL-FIRED POWER PLANT MILL	FZG PROCEDURE (A/2,76/50) DIP-LUBRICATION	FZG PROCEDURE (A/0,8/50) DRIP-LUBRICATION
OPERATING TEMPERATURE (°C)	55 - 65	50	50
CONTACT STRESS (MPa)	800	146 - 1 841	146 - 1 841
RELATIVE SLIDING VELOCITY (m/s)	0,90	1,848	0,536

This issue can be viewed from the requirements of the equipment user, who wants to use the economically optimal amount of grease to ensure safe operation and minimal wear of the system, and that of the lubricant manufacturer who would want to ensure a growing market for his product. (7)

Depending on the type of lubricant in use, a decision has to be made regarding the amount of lubricant required on the gear surface at any time as well as the interval between re-applications, where applicable. When laboratory performance tests are developed, it has to be taken into consideration that the amount of lubricant as well as the recommended re-lubrication interval needs to be determined, or the test needs to be performed according to the recommendations of the lubricant manufacturer.

Factors that should play a role in the determination of a formula to determine this would include the following:
- Area to be covered (face width and number of teeth)
- Rate of coverage (rotational speed of the gear)
- Desired film thickness based on eg EHL theory
- Relationship between spray time and interval between sprays.

Several formulas exist, an example being that proposed by Wollhoven: (17)

$$Q = m \frac{b_2}{\cos\beta} z_2 . n_2 . SK. x. y. \left(\frac{t_s}{t_p + t_s} \right)$$

where:

Q = lubricant rate (g/h)
m = gear module (cm)
b_2 = gear facewidth (cm)
z_2 = number of teeth
n_2 = rotational speed (rpm)
β = Helix angle (deg)
t_s = duration of spray cycle (min)
t_p = interval between spray cycles (minutes)
x = empirical factor which is a function of surface and bulk temperatures, installed capacity and relative sliding velocity, and also containing the impact and dynamic factor. For mill drives the following values can be used: 0,3 at $b_2n_2 < 800$ cm/min
0,2 at b_2n_2 = 800 - 1 200 cm/min
0,15 at $b_2n_2 > 1\,200$ cm/min
y = a factor containing the dimensional factor and face-width distribution factor
= $4{,}239 * 10^{-3} * b_2 + 0{,}99302$
SK = a lubricant factor which includes the contribution of the film thickness as well as factors like speed, lubrication condition and loadability (typically between $2{,}4*10^{-3}$ and $9{,}45*10^{-3}$ cm.)

It is clear from an equation like this, that use is made of several safety factors so as to accommodate uncertainty. It is therefore virtually impossible to provide an equation that can be used with a reasonable amount of accuracy for a variety of products.

NON-LUBRICANT RELATED CAUSES OF GEAR SYSTEM FAILURES

A discussion on open-gear lubrication cannot be complete unless mention is also made of the possible causes of failure not related to the performance of the lubricant. These can be attributed to:

(i) Contamination of the lubricant.
(ii) Misalignment of the gears causing uneven load-distribution accross the face-width.
(iii) Manufacturing defects.
(iv) Failure to provide the lubricant onto the gear surface due to a faulty distribution system or spray application system.
(v) Loading of the gears beyond their design capacity.

The large increase in replacement cost of equipment necessitates enhanced maintenance procedures in order to achieve the longest possible life from equipment. In the case of open gear systems on mills and draglines, efforts are made to increase the useful life of gear sets to possibly double their design life. This can be achieved by careful monitoring of wear rates while ensuring minimal contamination and associated abrasion and use of suitable lubricants so as to ensure adequate protection of gear surfaces. To monitor operational performance requires sufficiently accurate techniques to measure annual wear rates on gears.

In order to ensure efficient operation of open gear drives, care should be taken to monitor operational performance. This is normally achieved by the following methods:

(i) Temperature measurement.
(ii) Vibration analysis.
(iii) Photographs.
(iv) Silicone (kautschuk) impressions of tooth flanks.
(v) Blue prints.
(vi) Surface roughness measurements.

Due to slow wear rates, there are currently no methods of quantifying the rate of wear on large girth gears. Gear tooth verniers are not accurate enough and profile measurements of replicasts cannot quantify changes. A recent technique which holds a lot of promise is by using image analysis (15). Using this technique, it is reported that a measuring accuracy of 2,5 microns is attainable.

Provided that adequate correlation exists between the laboratory results and practical behaviour, laboratory testing may assist in screening of competitive products and may also be useful during the development of new and improved formulations. Lastly, it would be ideal if laboratory tests could be used to obtain guidelines for the optimal use of lubricants in application, ie lubricant quantities and relubrication intervals.

CONCLUSIONS

At first sight it might seem that lubricant testing for open-gear lubricants is just a matter of combining a few standard tests. A moment's reflection shows that a lot more than that is involved. A lot of progress has been made through the years, but, like in any technical environment, the system is dynamic and provision has to be made to adapt to the fast changing world of lubrication and gear system design. A few challenges always remain, these being:

- Accurate measurement of wear on large gear teeth
- Reclamation and disposal of spent lubricant.
- Accurately determining the relationship between gear operating conditions, required film thickness and optimal amount of grease required as well as an optimal relubricating interval.

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