(57) Abstract: The present invention relates to a bearing assembly comprising a rolling element bearing (100) and an electrically controlled grease pump (110). The rolling element bearing comprises an inner ring (102), an outer ring (105) and at least one set of rolling elements (107) disposed within a cavity of the bearing opposing inner and outer raceways. The grease pump comprises a pump drive mechanism, a grease reservoir (112) and a supply line (115) in connection with the reservoir. The supply line extends into the bearing cavity and has a discharge opening (117) arranged in close proximity to a rolling contact zone of the bearing. According to the invention, the pump drive mechanism is an electro-osmotic member which pumps a drive fluid, whereby the drive fluid exerts pressure on the grease reservoir in order to effect a supply of grease to the bearing.
BEARING ASSEMBLY WITH ACTIVE GREASE LUBRICATION

FIELD OF THE INVENTION
The invention relates to a bearing assembly comprising a rolling element bearing and a pump device for delivering a small amount of grease to the rolling contact zone of the bearing. The invention further relates to a method of controlling a grease pump.

BACKGROUND ART
If rolling element bearings are to operate reliably, they must be adequately lubricated to prevent direct contact between the rolling elements, raceways and cage. Loss of lubrication function results in friction and wear, and will quickly lead to bearing failure. Grease is the most commonly applied lubricant for bearings, because it is easy to retain within the bearing cavity and also helps prevent the ingress of contaminants and moisture. Grease comprises a base oil, such as a mineral oil, which is held within a thickener, such as a metallic soap. In a grease-lubricated bearing, oil released from the grease forms a thin film that separates the contact between rolling element and bearing raceways; the thickener plays little role in film formation.

After an initial churning-in phase when the grease-lubricated bearing is first put into operation, the grease gets distributed within the bearing cavity and comes to rest on certain surfaces. The grease itself exhibits little or no migration after the churning-in phase, and it has been found that grease which adheres to surfaces which are relatively distant from the rolling contact zone – such as an axially inner surface of a seal – makes hardly any contribution to bearing lubrication. It is therefore vital that reservoirs are present, close to the rolling contact zone, from where oil can bleed and thereby replenish the lubrication film. One such reservoir location is the underside of cage bars. Since it would be impossible to predict where a small amount of grease would migrate to during the churning-in phase, grease-lubricated bearings are generally packed with grease. This ensures that a sufficient amount of grease is distributed to locations where it is most needed.
The bearing cavity is filled with grease and the bearing is then either provided with annular seals or is mounted within a housing, which is likewise filled with a certain amount of grease. Generally, the housing is provided with a grease nipple, to enable the grease to be replenished according to a prescribed relubrication interval. Where relubrication of a bearing is concerned, the problem still remains of how to ensure that depleted grease at the important reservoir locations is replaced with fresh grease.

A bearing provided with active lubrication overcomes many of the problems. Active lubrication refers to the mechanical delivery of a small quantity of lubricant to the rolling contact zone. Thus, the supply of fresh grease to the desired location is guaranteed. In the bearing system described in EP 1548305, for example, the system comprises a grease tank arranged between inner and outer rings, for storing grease. A grease pressing mechanism delivers grease stored in the grease tank to the rolling elements and to the raceway surfaces of the bearing rings, at timed intervals. Compressed air is used as the grease pressing mechanism.

In a further example, disclosed in US 6357922, a high-speed antifriction bearing receives minute quantities of high performance grease at selected intervals from an electrically controlled injector having a nozzle that is directed at the rolling elements of the bearing.

There is still room for improvement, however.

SUMMARY OF THE INVENTION
The present invention relates to a bearing assembly comprising a rolling element bearing and an electrically controlled grease pump. The rolling element bearing comprises an inner ring, an outer ring and at least one set of rolling elements disposed within a cavity of the bearing on opposing inner and outer raceways. The grease lubricator comprises a grease reservoir and a pump drive mechanism. The assembly is further provided with a supply line, which is in connection with the
grease reservoir, which extends into the bearing cavity and which has a discharge opening arranged in close proximity to a rolling contact zone of the bearing. According to the invention, the pump drive mechanism is an electro-osmotic member which pumps a drive fluid, whereby the drive fluid exerts pressure on the grease reservoir in order to effect a supply of grease to the bearing.

Thus, in an assembly according to the invention, the pump is configured for indirect pumping of grease. The pump is an electro-osmosis pump which causes a drive fluid to be transported from a first side of the electro-osmotic member to a second side of the electro-osmotic member. The grease reservoir is arranged at the second side and suitably, the drive fluid and the grease in the reservoir are separated by a deformable membrane. As the drive fluid is pumped from the first to the second side of the electro-osmotic member, the fluid exerts pressure on the deformable membrane, which in turn causes grease to be pumped from a pump nozzle. An amount of drive fluid displaced equals an amount of oil displaced, and thus grease flow rate is controlled by controlling the flow rate of the drive fluid.

Controlling the flow rate of the drive fluid has several advantages. The principle of electro-osmosis allows extremely small, continuous flow rates to be achieved and controlled with great precision. Furthermore, there is an excellent linear relationship between a voltage applied across the osmotic member and the resulting flow rate, even at very small rates of flow. Thus, the precise, direct control of the drive fluid enables precise, indirect control of the grease, meaning that bearing lubrication can be optimized.

In one embodiment, the electro-osmosis pump is configured to deliver a continuous flow of grease at a flow rate of around e.g. 10 microliters per minute. A small, continuous flow rate is beneficial for a grease-lubricated bearing adapted for high speed operation, since friction losses from agitation resistance are minimised. Precise control of the flow rate is required to ensure that the bearing does not run dry, and an electro-osmosis pump, as used in the invention, enables this. Moreover, indirect pumping of grease using an electro-osmotic pump enables a
continuous flow of grease. In the case of pumps with a piezoelectric diaphragm, for example, grease is pumped directly and a pulsating flow is delivered.

In a further embodiment, the electro-osmosis pump is configured to deliver a prescribed quantity of grease at predetermined intervals. Again, an electro-osmosis pump allows the delivered quantity to be controlled with great precision.

In an electro-osmosis pump, the relationship between applied voltage and pressure – and the flow rate associated therewith - is linear, even at very small flow rates. This excellent controllability enables a further benefit in combination with grease lubrication. Namely, the start-up of the grease delivery can be controlled in order to minimise energy losses associated with causing grease to flow. Grease is a visco-elastic substance consisting of a base oil suspended within a thickener matrix. When a stress (pressure) is applied to grease, the strands of the thickener matrix initially deform elastically. This elastic strain response is followed by a viscoelastic strain response and then a plastic/viscous response when the grease starts to flow like a fluid. The elastic/visco-elastic strain is accompanied by a storage of elastic energy, proportional to the applied stress, which may be seen as a loss of energy. To minimise the loss of energy, the present inventors have found that it is advantageous initially to increase the applied stress in a stepwise of continuous fashion until the stored elastic energy has been dissipated. The time taken for the stored elastic energy to dissipate is known as the grease relaxation time.

Accordingly, in an advantageous further development, the grease pump in a bearing assembly according to the invention has control means configured to increase the supply voltage incrementally when the pump is started up. The incremental increase may be stepwise or continuous and is preferably applied at least for the duration of the grease relaxation time and until at least a voltage is reached at which the grease flows. Suitably, the control means is further configured to increase the voltage to a value at which a desired flow rate occurs, only after the grease relation time has elapsed. The relaxation time of a grease
varies depending on the composition, but may be approximated to around 1 second for most greases.

In a still further development, the bearing assembly of the invention is provided with means for sensing a breakdown in lubrication film thickness. Such a breakdown results in metal-to-metal contact between asperities on the rolling elements and asperities on the raceways. This generates heat and also causes an increase in acoustic emission. Thus, the assembly may be provided with a temperature sensor and/or an acoustic emission sensor. Loss of film thickness can also be detected by measuring the capacitance or electrical resistance of the lubrication film. The advantage of detecting film thickness breakdown is that a signal from the sensing means can be used to vary the pump supply voltage and thus the grease flow rate. For example, if the pump is configured to deliver a continuous flow of grease, the voltage control means may be configured to increase the voltage in response to an increase in e.g. a detected acoustic emission value. In a further embodiment, the pump is configured to deliver a quantity of grease when and as needed. The signal from e.g. a temperature sensor may be used to trigger the pump flow when the temperature exceeds a predetermined upper threshold, and then to shut down or reduce the flow when the temperature falls below a predetermined lower threshold.

In a still further development of the invention, the supply line from the grease reservoir to the bearing cavity has a diameter of at least 0.3 mm. It has been found that at smaller diameters, there is an increased risk of clogging.

In a still further development of the invention, the grease reservoir of the grease pump is provided with heating means. The advantage of heating the grease is that the grease will flow more easily.

Thus, a bearing assembly according to the invention has several advantages. The bearing is provided with active grease lubrication that may be controlled with extreme precision. Flow control is a straightforward process and is achieved
simply by varying a supply voltage. Furthermore, only low voltages and currents are needed, making the lubrication device economical to run and because the device comprises no moving parts, it is highly reliable.

The present invention also provides a method of controlling a grease pump. According to the inventive method, a step of initiating the flow of grease comprises increasing an applied pressure in continuous or stepwise increments at least until a pressure is reached at which grease flow occurs. Suitably, the step of initiating grease flow further comprises executing the incremental increase during a period of time that is at least equal to a relaxation time of the grease. As described above, the advantage of this method is that energy losses are reduced.

In an advantageous further development, the method comprises a further step of increasing the pressure to a value at which a desired flow rate occurs, whereby this step of increasing is performed only after the grease relaxation time has elapsed. The advantage of this development is that energy losses are minimised.

Other advantages of the present invention will become apparent from the detailed description and accompanying figures.

BRIEF DESCRIPTION OF THE DRAWINGS
The invention is explained in further detail, by way of example, and with reference to the accompanying drawings, wherein:

Figure 1: is a cross-sectional view of an example of part of a bearing assembly according to the invention;
Figure 2: is a cross-sectional view of a pump device suitable for use in the invention.
Figure 3: is a diagram showing the strain exhibited by a grease in response to an applied stress, as time elapses.
DETAILED DESCRIPTION

Figure 1 shows an example of part of a bearing assembly according to the invention. The assembly comprises a rolling element bearing 100 having an inner ring 102, an outer ring 105 and a set of rolling elements 107 disposed therebetween and retained in a cage 109. The assembly is further provided with an electro-osmotic pump 110 having a grease reservoir 112 and a grease supply line 115 that extends into a cavity of the bearing, to deliver a small amount of grease directly to a zone of rolling contact.

Figure 2 shows an example of an electro-osmotic pump that may be used in the assembly depicted in Figure 1. The pump 200 comprises a pump housing 202 that defines a first chamber 205 and a second chamber 207. The first chamber 205 contains a drive fluid 210, such as de-ionized water, which exhibits electro-osmosis. The second chamber 207 contains a grease 212, such as an NLGI grade 1 grease. Suitably, when stiffer greases are used having an NLGI grade greater than 2, the second chamber (grease reservoir) is provided with heating means to facilitate grease flow. The first and second chambers 205, 207 are separated by a deformable membrane 215, which prevents contact between the drive fluid and the grease. The pump 200 further comprises a drive mechanism 217 consisting of an electro-osmotic member 220 and first and second electrodes 222, 225 for generating an electric field across the electro-osmotic member 220. The drive mechanism 217 separates the first chamber 205 into an inlet side 227 and an outlet side 230, whereby the first electrode 222 is located at the inlet side of the electro-osmotic member 220 and the second electrode 225 is located at the outlet side. In the depicted example, the drive mechanism 217 is housed in a narrow portion of the first chamber, formed by a rigid wall 231 of the pump housing 202 that extends inwardly into the first chamber 205. In other examples, the drive mechanism spans a full diameter of the pump housing when higher flow rates are required.

When a DC voltage is placed across the electrodes 222, 225, the drive fluid (water) is transported from the inlet side 227 to the outlet side 230 of the first
chamber 205. The drive fluid 210 therefore exerts pressure on the deformable membrane 215, which in turn causes grease 212 to be pumped out of a nozzle 232. Pumping occurs on the basis of electro-osmotic flow, which will now be briefly explained.

The electro-osmotic member comprises a porous silica, such as glass fibre, and is preferably also hydrophilic, so that the drive liquid (water) is absorbed into the porous silica. In effect, the porous silica acts a set of capillary channels, whereby silanol groups form on an inner surface of each capillary channel. These silanol groups are ionized above pH3, meaning that the inner surface of the channel is negatively charged. In solutions containing ions, the cations will migrate to the negatively charged surfaces, thereby forming an electrical double layer. When an electrical potential is then applied to the channels, with an anode at one end of a channel and a cathode at another, the cations will migrate towards the cathode. Since these cations are solvated and clustered at the walls of the channel, they drag the rest of the solution with them, even the anions. In the depicted example, the first electrode 222 is the anode and the second electrode 225 is the cathode. Therefore, when a DC voltage is applied across the electrodes, electro-osmotic flow occurs in the direction indicated by the arrow on Figure 2.

The flow is continuous and may be precisely controlled by varying the voltage. A voltage of approximately 2 V is sufficient to induce flow, and flow rate increases with voltage in a linear manner. Precision control is possible, even at flow rates of less than 5 microlitres per minute, meaning that a bearing can be lubricated with an optimal amount of grease that generates minimal friction.

In some embodiments, a grease supply tube 235 is attached to the nozzle 232. For lubricating a bearing, this tube may be inserted into e.g. a hole drilled in a bearing outer ring and a corresponding hole drilled in the bearing housing, to deliver grease to the rolling elements. Alternatively, as shown in Figure 1, the lubricant supply tube may be inserted through an opening made in a radial seal.
Retuning to Figure 1, the bearing 100 is provided with a first radial seal 120 and a second radial seal 120'. The seals 120, 120' retain lubricant within the bearing cavity and prevent the ingress of contaminants. The first radial seal 120 is provided with a small opening, to allow the grease supply line 115 having a diameter of e.g. 0.5 mm to pass through and emerge in the bearing cavity. In this example, a discharge opening 117 of the grease supply line 115 is arranged just above a bar of the bearing cage 109, to deliver grease to the rolling contact zone directly.

In this example, the assembly is configured to provide the bearing with active lubrication as and when needed. Accordingly, the assembly further comprises a temperature sensor 122 mounted on a radially outer side of the bearing outer ring 105. Suitably, the sensor 122 is positioned at a loaded zone of the bearing. The sensor 122 may also be mounted in a bearing housing, close to the outer ring, or e.g. on a radially inner side of one of the first or second radial seals 120, 120'. When the bearing is started up, or before it is started up, the pump 110 may be configured to deliver a predetermined quantity of grease. Suitably, the pump comprises a controller (not shown) for regulating the supply voltage of the electro-osmotic pump 110 in order to deliver a suitable flow rate of grease for the necessary duration.

During bearing operation, the supplied grease is over-rolled and base oil is released which forms a lubrication film between the rolling elements 107 and raceways of the bearing. Over time, the thickness of the film will decrease until a starved lubrication condition is reached. In this condition, metal-to-metal contact between asperities on the rolling elements and on the bearing raceways occurs. This generates friction and heat, meaning that the temperature sensor 122 detects an increase in temperature. A signal from the sensor 122 is read by the controller, which in one embodiment is configured to initiate grease flow when the temperature exceeds a predetermined upper threshold value. In a further embodiment, the controller initiates grease flow when a predetermined temperature increase is exceeded. The controller may further be configured to
monitor the sensed temperature and vary the supply voltage to the pump according until the temperature falls below a predetermined lower threshold. When this value is reached, grease flow is terminated. The cycle as described above is repeated when the bearing again enters a starved lubrication condition. As will be understood, the temperature sensor 122 may be replaced by any sensing means adapted to detect a parameter indicative of lubrication film breakdown, such as e.g. an acoustic emission sensor.

In a further embodiment, the pump 110 is configured to deliver a continuous flow of grease. In this embodiment, the controller is suitably configured to vary the flow rate of grease in response to the sensed temperature.

When the pump is configured to provide active lubrication as and when needed, this necessarily involves a number of pump start-ups. In an advantageous further development of the invention, the controller is configured to initiate the flow of grease in a manner that minimises energy losses. This will be explained with reference to the diagram of Figure 3.

Figure shows the strain response of a grease when a stress is applied to initiate grease flow. A first vertical axis 300 represents the applied stress, a second vertical axis 305 represents the strain response and a horizontal axis 307 represents time (in seconds). With reference to an electro-osmotic pump as shown in Figure 2, let us assume that a voltage of 2V is required in order to initiate grease flow, which voltage corresponds to a certain pump pressure and an applied stress. Now let us assume a first case in which 2 Volts is supplied to the pump upon start-up, which corresponds to an applied stress indicated by a first line 310 in Figure 3. Grease is a visco-elastic substance comprising a thickener matrix, meaning that when a stress is applied, grease flow does not occur immediately. Strands of the thickener matrix initially deform elastically. This elastic strain response is followed by a viscoelastic strain response and then a plastic/viscous response when the grease starts to flow like a fluid. The elastic/visco-elastic strain is accompanied by a storage of elastic energy, proportional to the applied stress, which may be seen
as a loss of energy. The strain response of the grease is indicated by a second line 315 and a shaded area 317 between the first and second lines 310, 315 represents the energy loss. At a time \( t_1 \), the elastic energy stored within the grease has dissipated and the grease starts to flow like a fluid. The time \( t_1 \) is known as the grease relaxation time and for most greases lies around 1 second.

Now let us assume a second case where the applied stress (i.e. the voltage) is increased in incremental steps, as indicated by a third line 320. The grease again exhibits an elastic/visco-elastic strain response during the period up to \( t_1 \) (the grease relaxation time) represented by a fourth line 325. The shaded areas 330 between the incrementally applied stress 320 and the strain response 325 represent the energy loss. As may clearly be seen, the sum of the shaded areas 330 for the first case is less than the shaded area 317 for the second case.

Accordingly, in a bearing assembly according to the invention, the electro-osmotic pump is configured to initiate grease flow by increasing the voltage until a predetermined voltage is reached at which grease flow occurs. Suitably, the increase is executed for a period of time that is at least equal to the grease relaxation time. In Figure 3, a stepwise increase in Voltage is shown in order to clearly demonstrate the difference in energy loss between the first and second case. As will be understood, the duration of the stepwise increases may be reduced such that voltage increase is continuous.

Now let us assume that a voltage of 5V is needed in order to achieve a desired flow rate. Advantageously, the pump is further configured to execute the increase from 2V to 5V only after the grease relaxation time has elapsed. This increase may be executed in one leap, since the grease has started to behave like a fluid and energy will no longer be lost in overcoming its viscoelasticity. Consequently, the energy consumption of the pump can be optimised.

The present invention also defines a method of controlling a grease pump. The method comprises a step of initiating grease flow by increasing the applied
pressure in incremental steps at least until a first pressure is reached at which grease flow occurs. Suitably, this step further comprises executing the incremental increase for a period of time that is at least equal to the grease relaxation time.

In a further step, the method comprises a further step of increasing the applied pressure to a second pressure at which a desired flow rate occurs, where the step of increasing is executed only after the grease relaxation time has elapsed.

The linear controllability of electro-osmotic pumps makes these devices particularly suitable for implementing the method of the invention. The method is not restricted to these devices, however, and may be applied to any type of grease pump that allows pump pressure to be increased incrementally upon start up.

A number of aspects/embodiments of the invention have been described. It is to be understood that each aspect/embodiment may be combined with any other aspect/embodiment. The invention may thus be varied within the scope of the accompanying patent claims.
Reference numerals

Figure 1
100  Rolling element bearing
102  Bearing inner ring
5   105  Bearing outer ring
107  Rolling elements
109  Cage
110  Electro-osmotic pump
112  Grease reservoir
10  115  Grease supply line
117  Discharge opening
120  First radial seal
120' Second radial seal
122  Temperature sensor

Figure 2
200  Electro-osmotic pump
202  Pump housing
205  First chamber of pump housing
207  Second chamber of pump housing (grease reservoir)
210  Drive fluid
212  Grease
215  Deformable membrane
217  Drive mechanism
25  220  Electro-osmotic member
222  First electrode
225  Second electrode
227  Inlet side of first chamber
230  Outlet side of first chamber
30  231  Wall section of pump housing
232  Nozzle
235  Grease supply tube
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<tbody>
<tr>
<td>300</td>
<td>Vertical axis representing applied stress</td>
</tr>
<tr>
<td>305</td>
<td>Vertical axis representing strain response</td>
</tr>
<tr>
<td>307</td>
<td>Horizontal axis representing time in seconds</td>
</tr>
<tr>
<td>310</td>
<td>Line representing applied stress in a first case</td>
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<td>315</td>
<td>Line representing strain response in a first case</td>
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<tr>
<td>317</td>
<td>Shaded area representing energy loss in a first case</td>
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<tr>
<td>320</td>
<td>Line representing applied stress in a second case</td>
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<tr>
<td>325</td>
<td>Line representing strain response in a second case</td>
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<tr>
<td>330</td>
<td>Shaded areas representing energy loss in a second case</td>
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CLAIMS

1. A bearing assembly comprising a rolling element bearing (100) and an electrically controlled grease pump (110, 200) having a pump drive mechanism (217) and a grease reservoir (112, 207), the assembly further comprising a supply line (115, 235), in connection with the reservoir, which extends into a cavity of the bearing and which has a discharge opening (117) arranged in close proximity to a zone of rolling contact, characterized in that the pump drive mechanism (217) is an electro-osmotic member (220) which pumps a drive fluid (210), whereby the drive fluid exerts a pressure on the grease reservoir in order to effect a supply of grease to the rolling contact zone.

2. Bearing assembly according to claim 1, further comprising means for controlling a voltage supplied to the pump drive mechanism (217).

3. Bearing assembly according to claim 2, wherein the voltage control means, when initiating a flow of grease, is configured to increase the supply voltage in increments, at least until a voltage is reached at which grease flow occurs.

4. Bearing assembly according to claim 3, wherein the voltage control means is further configured to execute the incremental increase during a period of time that is at least equal to a relaxation time of the grease.

5. Bearing assembly according to claim 4, wherein the voltage control means is further configured to execute a second voltage increase up to a value at which a desired flow rate occurs, after the grease relaxation time has elapsed.

6. Bearing assembly according to any preceding claim, further comprising means (122) for sensing a breakdown of lubrication film thickness.
7. Bearing assembly according to claim 6, wherein the voltage control means is further configured to vary the supply voltage in response to a signal received from the sensing means (122), and/or is configured to initiate and terminate the supply of grease in response to predetermined threshold values of the received signal.

8. Bearing assembly according to any preceding claim, wherein the grease supply line (115, 135) has a diameter of at least 0.3 mm.

9. Bearing assembly according to any preceding claim, wherein the grease reservoir (112, 207) of the grease pump is provided with heating means.

10. Method of controlling a grease pump (110, 200), the method comprising a step of initiating grease flow by increasing an applied pressure incrementally, at least until a pressure is reached at which grease flow occurs.

11. The method of claim 10, wherein the step of initiating further comprises executing the incremental increase during a period of time that is at least equal to a relaxation time of the grease.

12. The method of claim 11, the method comprises a further step of increasing the applied pressure to a value at which a desired flow rate occurs, whereby the step of increasing is performed when the grease relaxation time has elapsed.

13. The method of claim 10, 11 or 12 wherein the grease pump has a drive mechanism (217) operating on the basis of electro-osmotic flow.
Figure 3
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<th>Relevant to claim No.</th>
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**Further documents are listed in the continuation of Box C.**

**See patent family annex.**

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**Document member of the same patent family.**

Date of the actual completion of the international search: 30 July 2010

Date of mailing of the international search report: 06/08/2010

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Authorized officer: Béguin-Adriaenssens
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