CHAPTER II

THEORY AND LITERATURE REVIEWS

2.1 Bearing

2.1.1 General structural features

A bearing is a device to permit constrained relative motion between two parts, typically rotation or linear movement. Bearings may be classified broadly according to the motions they allow and according to their principle of operation.

2.1.2 Classification of bearing

There are at least six common principles of operation:

- sliding bearings, usually called "bushings", "journal bearings", "sleeve bearings", or "plain bearings"
- rolling-element bearings such as ball bearings and roller bearings
- jewel bearings, in which the load is carried by rolling the axle slightly off-center
- fluid bearings, in which the load is carried by liquid
- magnetic bearings, in which the load is carried by a magnetic field
- flexure bearings, in which the motion is supported by a load element which bends.

In this research, lubricants which were applied to fluid dynamic bearing, was studied. Therefore, feature and function of bearing's motor for hard disk drive computer via ball bearing and fluid bearing were described as follow.

Ball bearing [2]

The term ball bearing sometimes means a bearing assembly which uses spherical bearings as the rolling elements. It also means an individual ball for a bearing assembly. The remainder of this entry uses the term ball for the individual component and ball bearing or just "bearing" for the assembly as shown in Fig 2.1.

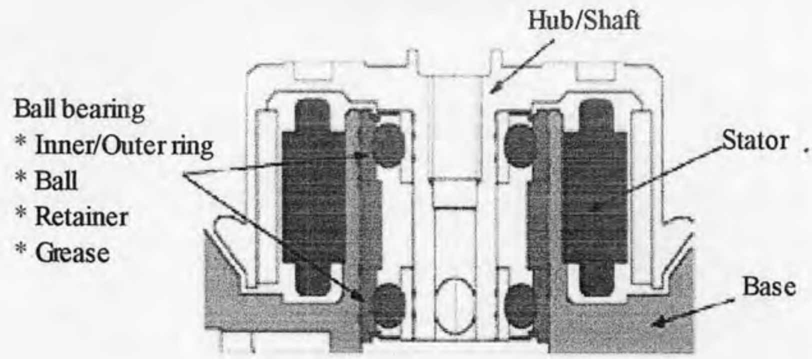


Figure 2.1 Ball bearing motor's components

Ball bearings typically support both axial and radial loads and can tolerate some misalignment of the inner and outer races. Also, balls are relatively easy to make cheaply compared to other kinds of rolling elements. Ball bearings tend to have lower load capacity for their size than other kinds of rolling-element bearings due to the smaller contact area that spherical shapes provide.

- Common designs

There are several common designs of ball bearings, each offering various tradeoffs.

A radial ball bearing uses axially symmetric inner and outer races that are shaped so a radial load passes radically through the bearing. Most radial designs also support modest axial loads.

An angular contact ball bearing uses axially asymmetric races. An angular load passes in a straight line through the bearing, whereas a radial load takes an oblique path that tends to separate the races axially. So the angle of contact on the inner race is the same as that on the outer race. In high speed applications, such as turbines, jet engines, dentistry equipment, the centrifugal forces generated by the balls will change the contact angle at the inner and outer race. Ceramics such as silicon nitride are now regularly used in such applications due to its low density, its ability to function in high temperature environments, and the fact that it tends to wear in a similar way to bearing steel.

An axial ball bearing uses side-by-side races. An axial load is transmitted directly through the bearing, while a radial load is poorly-supported, tends to separate the races, and anything other than a small radial load is likely to damage the bearing.

A deep-groove radial bearing is one in which the race dimensions are close to the dimensions of the balls that run in it. Deep-groove bearings have higher load ratings for their size than shallow-groove bearings, but are also less tolerant of misalignment of the inner and outer races. A misaligned shallow-groove bearing may support a larger load than a similar deep-groove bearing with similar misalignment.

Anyway, ball bearing technology used in conventional disk drive motors have limitations. Ball bearing are not perfectly round and races deform slightly under preload. Any imperfections in roundness or in raceways can cause nonrepeatable run out (NRRO) that keeps tracks written to the disk from being regular. This is important because drive design has run into technology barriers that may limit increases in linear bit density. Thus, future capacity increases may largely come from increasing track density. And ball-bearing motors may soon reach the limit of their ability to work at the track densities that will be required. Fortunately, the solution that will allow hard-drive manufacturers to maintain rate of performance improvements and low noise products were given in fluid dynamic bearings.

Fluid dynamic bearing (FDB) [3]

Fluid bearings are bearings which solely support the bearing's loads on a thin layer of liquid. They can be broadly classified as fluid dynamic bearings, hydrostatic bearings. They are frequently used in high load, high speed or high precision applications where ordinary ball bearings have short life or high noise and vibration. They are also used increasingly to reduce cost. For example, hard disk drive motor fluid bearings are both quieter and cheaper than the ball bearings they replace.

A fluid bearing device including a shaft, a sleeve, a thrust bearing plate supported by the sleeve, a radial groove formed on one of an outer periphery of the shaft and an inner periphery of the sleeve, and a spiral groove formed on one of one end face of the shaft and one face of the thrust bearing plate such that the radial groove retains oil, while the spiral groove retains grease containing thickener and base oil identical, in compositions and viscosity, with the oil of the radial groove as shown in Fig 2.2.

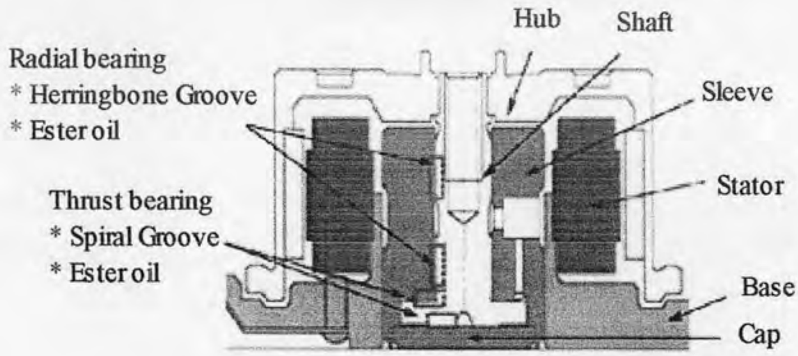


Figure 2.2 Fluid dynamic spindle motor's components

- Principles of operation

Fluid bearings use a thin layer of liquid or gas fluid between the bearing faces, typically sealed around or under the rotating shaft. Pressure-oiled journal bearings appear to be plain bearings but are arguably fluid bearings. As the bearing rotates, oil is carried into the working part of the bearing, where it is compressed, with oil viscosity preventing the oil's escape. As a result, the bearing "hydroplanes" on a layer of oil, rather than on metal-on-metal contact as it may appear.

- The principal ways of getting the fluid in to the bearing.

In hydrodynamic bearings, bearing rotation sweeps the fluid in to the bearing, forming a lubricating wedge under or around the shaft.

Hydrodynamic bearings rely on bearing motion to sweep fluid in to the bearing and may have high friction and short life at low speed or during starts and stops. Thus, a secondary bearing may be used for startup and shutdown to prevent damage to the hydrodynamic bearing. A secondary bearing may have high friction and short operating life, but good overall service life if bearing starts and stops are infrequent.

- Characteristics

Fluid bearings can be relatively cheap compared to other bearings with a similar load rating. The bearing can be as simple as two smooth surfaces with seals to keep in the working fluid. In contrast, a conventional bearing may require many high-precision rollers with complicated shapes.

Most fluid bearings require little or no maintenance, and have almost unlimited life. Conventional mechanical ball bearings usually have shorter life and require regular maintenance. Fluid bearings generally have very low friction which one source of friction in a fluid bearing is the viscosity of the fluid. Also fluid bearings have clearances that change less under load than ball bearings. It might seem that bearing stiffness, as with maximum design load, would be a simple function of average fluid pressure and the bearing surface area. This significantly increases the pressure of the fluid between the bearing faces. As fluid bearings faces are comparatively large areas, even small fluid pressure differences cause large restoring forces, maintaining the gap.

It is also very difficult to make a ball bearing which is atomically smooth and round and ball bearings deform in high-speed operation due to centripetal force. In contrast, fluid-bearings self-correct for minor imperfections.

Fluid bearings are typically quieter and smoother (more consistent friction) than ball bearings. For example, hard disks manufactured with fluid bearings have noise ratings for bearings/motors on the order of 20-24 dB, which is a little more than the background noise of a quiet room. Drives based on rolling-element bearings are typically at least 4 dB noisier.

2.2 Bearing lubricants

A Lubricant is a substance which is used to reduce friction between moving parts. The lubricants that are used on bearings are called bearing lubricants.

2.2.1 Classification and feature of bearing lubricants

- Grease lubricant
- Solid lubricant
- Oil lubricant

Greases lubricant [4]

Grease is a lubricant used on the bearings. Grease is used for numerous types of bearings which the reason behind this is its thickness. A poor quality of bearing grease leads to the flow of grease onto the brake linings thereby causing safety hazards. Commonly, grease lubrication is carried out on ball or roller bearings. Grease lubrication exhibits a property of self-sealing which means the contaminants are prevented from entering the bearing.

A grease is lubricating oil thickened with a gelling agent such as a metallic soap or a nonmelting powder. For design simplicity, decreased sealing requirements, and low maintenance, greases are given first consideration for lubricating ball or roller bearings in electric motors, aircraft accessories, household appliances, machine tools, automotive wheel bearings, instruments and railroad and construction equipment. Greases are also a common choice for slow-speed sliding applications and small gear units.

- Oils in greases

Petroleum mineral oils are used in 98-99% of the grease produced. Oils in this viscosity range provide low volatility for long life at elevated temperature together with sufficiently low torque for use down to subzero temperatures.

Higher-viscosity oils up to the 450 to 650 mm^2/s range at 40 °C are employed for some high-temperature greases and for compounding with extreme pressure additives in greases for high-contact stresses at relatively low speeds.

Synthetic oils are employed in about 1-2% of current greases, where their higher cost is justified by unusual temperature conditions or other demands that cannot be met with mineral oil greases.

- Thickeners

Gelling agents used include fatty acid soaps of lithium, calcium, aluminum and sodium in concentrations of 6 - 20 wt%. Lithium soaps predominate with use in about 65% of grease production. Fatty acids employed are usually oleic, palmitic, stearic, and other carboxylic acids obtained from tallow, hydrogenated fish oil and castor oil. The relatively low upper temperature limit of 65 - 80 °C with traditional simple soap calcium and aluminum greases can be raised to the 120 - 125 °C range with new complex soaps. Calcium complex soaps, for instance are prepared by reacting both a high molecular weight fatty acid such as stearic acid and low molecular weight acetic acid with calcium hydroxide dispersed in mineral oil.

Solid lubricant [4]

Solid lubricants are made of lubricant materials, such as graphite or molybdenum. The friction of the solid soft film lubricants does not depend on the temperature, and they do not change to gas or vapor form in the space or terrestrial vacuum environments. Solid lubricants provide thin films of a solid between two moving surfaces to reduce friction and wear, usually for high temperatures, aerospace and other environments not tolerated by conventional oils and greases. The samples of solid lubricant are graphite, molybdenum disulphide, teflon and boron nitride.

Oil lubricant [4]

Oil is used as a lubricant on bearings and it is considered to be very effective. Oil is preferred when the surface speed or the operating temperature of the rollers or balls is high. The speed limits are enforced by the cage design and the size of the bearing. Oil can be used even at higher temperatures and speeds. In general, mineral oils are used as lubricants. Whereas, at very low or very high temperatures, synthetic oils such as synthetic esters, phosphate esters, silicate esters, poly alpha olefins (PAO), poly alkylene glycols (PAG) and ionic fluids are used. The application of oil on the bearings is based on the bearing running speed. For low and medium running speeds of the bearing, splash systems and oil bath are adapted. The circulation systems are adapted for medium running speeds and spraying off or mist is adapted for higher running speeds.

Liquid lubricants may be characterized in many different ways. One of the most common ways is by the type of base oil used. Following are the most common types.

- Mineral oils
- Polyalpha-olefin (PAO)
- Synthetic esters
- Alkylated naphthalenes (AN)
- Silicate esters
- Ionic fluids

One of base oil which popular to use for prepare fluid dynamic bearing's lubricant, is synthetic ester base oils. As reasons from this base oils have heat resistance, a small quantity of evaporation and low cost, etc.

Synthetic esters

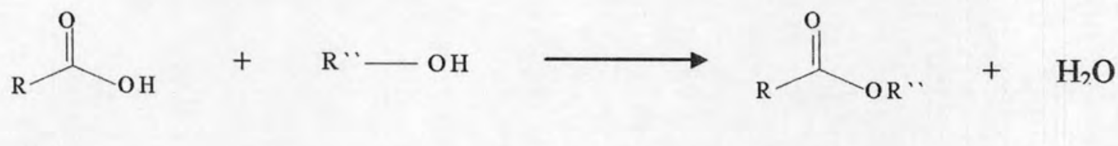
Synthetic esters are used most widely for instrument bearings with reason from their excellent lubrication properties under heavy load and high-speed conditions.

Also synthetic oils are used as lubricants under conditions where mineral oils would be unsuitable, for example at very high or low temperatures, or where low flammability is vital.

Ester synthesis

An ester can be thought of as a product of a condensation reaction of an acid (usually an organic acid) and an alcohol, although there are other ways to form esters.

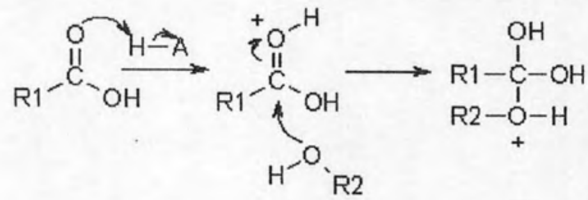
Condensation is a type of chemical reaction in which two molecules are joined together and eliminate a small molecule, in this case two-OH groups are joined eliminating a water molecule. A condensation reaction to form an ester is called esterification. Esterification can be catalyzed by the presence of H^+ ions. Sulfuric acid is often used as a catalyst for this reaction as can be shown in Scheme 2.1 and Scheme 2.2, respectively.



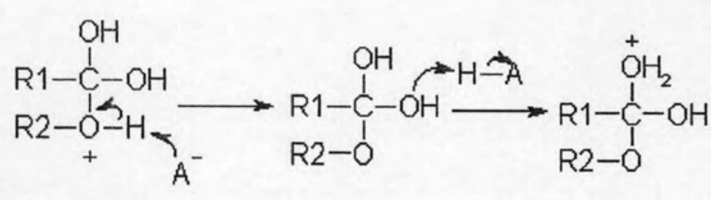
Scheme 2.1 Ester synthesis by esterification reaction

Esterification mechanism :

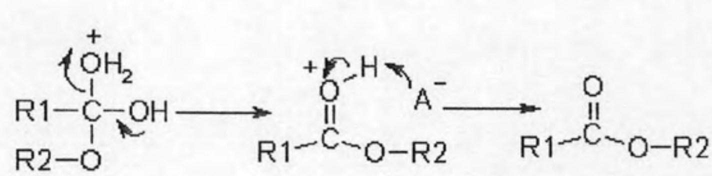
Step 1



Step 2



Step 3



Scheme 2.2 Mechanism of esterification

Classification of synthetic ester

- Monoester

While diesters and polyol esters represent the most widely used ester families in synthetic lubrication, monoester are worth mentioning. Monoesters are made by reacting monohydric alcohols with monobasic fatty acids creating a molecule with a single ester linkage and linear or branched alkyl groups. These products are generally very low in viscosity (usually under 2 mm^2/s at 100 ^{o}C) and exhibit extremely low pour points and high viscosity index. The presence of the ester linkage imparts polarity which helps to offset the high volatility expected with such small molecules. Hence, when compared to a hydrocarbon of equal molecular weight, a monoester will have a significantly higher flash point giving it a broader temperature range in use. Monoesters are used primarily for extremely cold applications such as in Arctic hydraulic oils and deep sea drilling. They can also be used in formulating automotive aftermarket additives to improve cold starting.

- Diester

Diesters were the original ester structures introduced in synthetic lubricants. These products are made by reacting monohydric alcohols with dibasic acids creating a molecule which may be linear, branched, or aromatic and with two ester groups. Diesters are named after the type of dibasic acid used and are often abbreviated with letters. For example, a diester made by reacting octyl alcohol with adipic acid would be known as an "adipate" type diester and would be abbreviated "DOA" (Dioctyl adipate).

Listed in table 2.1 are the more common dibasic acids used in synthetic lubricants, the family name for such products, and the alcohols most commonly employed.

Table 2.1 Commonly used type of diester

Diester types and available alcohols			
Common Acids	**No. of Carbon**	**Ester family**	**Available alcohol**
Adipic	6	Adipates	n-octyl
Azaleic	9	Azelates	isooctyl
Sebacic	10	Sebacates	2-Ethylhexyl
Dodecanedioic	12	Dodecanedioates	isononyl
Phthalic	8	Phthalates	isodecyl
Dimer	36	Dimerates	tridecyl

- Polyol esters

Like diesters, many different acids and alcohols are available for manufacturing polyol esters and indeed an even greater number of permutations are possible due to the multiple ester linkages. Unlike diesters, polyol esters (POEs) are named after the alcohol instead of the acid and the acids are often represented by their carbon chain length.

In general, polyol esters represent the highest performance level available for high temperature applications at a reasonable price. Although they cost more than many other types of synthetics, the benefits often combine to make this chemistry the most cost effective in severe environment applications. The primary benefits include extended life, higher temperature operation, reduced maintenance and downtime, lower energy consumption, reduced smoke and disposal, and biodegradability.

Polyol esters can extend the high temperature operating range of a lubricant by as much as 50 - 100 °C due to their superior stability and low volatility. They are also renowned for their film strength and increased lubricity which is useful in reducing energy consumption in many applications. The only downside of polyol esters compared to diesters is their higher price; they are generally 20 - 70% higher on a wholesale basis.

Properties of ester lubricants

- Good thermal and oxidative stability
- Control of viscosity, pour point, flash point etc.
- Good lubricity

- Reduce volatility
- Improve solvency and seal swelling
- Ester are more biodegradable than mineral oil

2.2.2 Purpose of bearing lubricants

The resistance motion that is produced between the moving surfaces is reduced to a great extent.

- Promotes corrosion resistance
- Used as a protective agent against wear
- Heat transfer between mobile parts

2.2.3 Factors involved in the selection of bearing lubricants

- Lubricant viscosity at operating temperature
- Bearing speed
- Minimum and maximum allowable operating temperatures

2.2.4 Properties of bearing lubricants

- Antioxidant
- Corrosion resistance
- Thermal resistance
- Conductivity
- Viscosity

Antioxidant

By resisting oxidation reaction, bearing lubricants help in preventing damage and also protect the bearings from the corrosive effects of harmful chemicals.

Corrosion Resistance

It is the property that exhibits resistance towards atmospheric corrosion. Bearing lubricants possess higher corrosion resistance.

Thermal Resistance

Thermal resistance refers to the resistance offered by the substance when it is exposed to heat. In general, bearing lubricants have high thermal resistance. The thermal resistance of bearing grease is lower than that of bearing oil thermal resistance.

Conductivity

It is the property of transference of heat. Bearing lubricants exhibit poor conductivity.

Viscosity [5]

Viscosity is defined as the resistance to flow of a fluid under gravity with respect temperature. The viscosity is important property which has effect to friction of bearing and the relationships between friction and oil's viscosity can be shown as equation 2.1

$$F/A = ZN \tag{2.1}$$

$$P = ZN$$

So,

$$\mu = (ZN)/P \tag{2.2}$$

Where, μ denotes friction coefficient

Z denotes dynamic viscosity in mPa.s unit

N denotes velocity in rpm unit

P denotes ratio of friction per moving plate area in N/m^2 unit

F denotes friction in N unit

A denotes moving plate area in m^2 unit

From equation 2.2 can be shown the relationships of each factor as shown in Stribeck's curve (Fig. 2.3) [6].

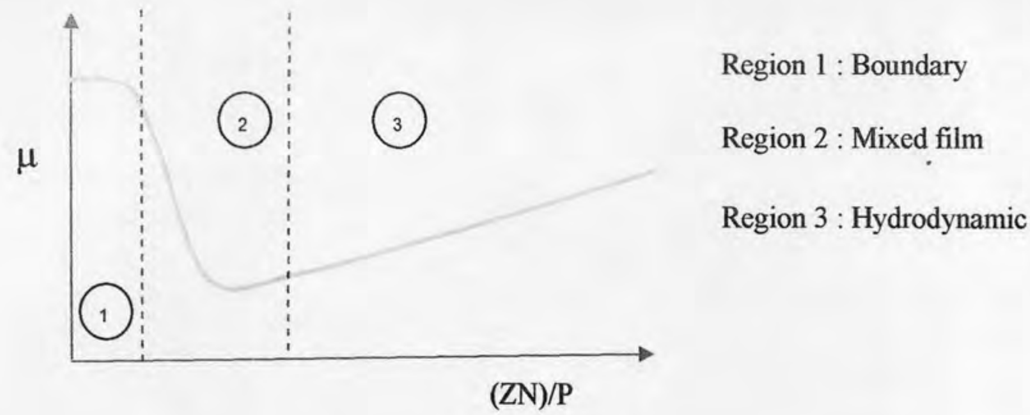


Figure 2.3 Stribek's curve

The coefficient of friction in a lubricated bearing varies depending upon the absolute viscosity, the speed and the pressure per unit projected area, but has the same general form shown in this 'Stribeck' plot which can be separated lubrication conditions to 3 regions :

Region 1 : Boundary Lubrication

If the speed is very low there will be no pressure build up in the lubricant at all and hence the loading is for 100% carried by the asperities in the contact area, protected by adsorbed molecules of the lubricant and/or a thin oxide layer. Characteristic for boundary lubrication is the absence of hydrodynamic pressure. Dry contact is excluded from boundary lubrication.

Region 2 : Mixed Lubrication

A hydrodynamic pressure is build up in the lubricant when the speed increases. Characteristic for mixed lubrication is that the loading is carried by a combination of the hydrodynamic pressure and the contact pressure between the asperities of both surfaces. It is the intermediate region between boundary lubrication and hydrodynamic lubrication.

Region 3 : Hydrodynamic Lubrication

At high speed the hydrodynamic pressure increases such that the surface asperities are completely separated by a lubricant film. Characteristic for hydrodynamic lubrication is that the load and hydrodynamic pressure are in equilibrium.

Furthermore, oil's viscosity also has effect to torque property as show the relation by mention to Newton's law of viscous flow as follows.

Newton's law of viscous flow [5]

In general, in any flow, layers move at different velocities and the fluid's thickness arises from the shear stress between the layers that ultimately opposes any applied force. Friction between the fluid and the moving boundaries causes the fluid to shear. The force required for this action is a measure of the fluid's viscosity. Laminar shear, the non-linear gradient, is a result of the geometry the fluid is flowing through as illustrated Fig. 2.4.

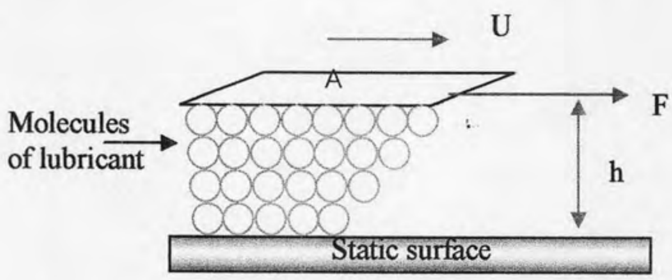


Figure 2.4 Illustration of oil's flow in linear direction

From Fig. 2.4, the relationships of each factor can be shown in equation 2.3.

$$\tau = F/A$$
$$\tau = ZU/h \quad (2.3)$$

Where, τ denotes torque in N/m^2 unit
Z denotes kinematic viscosity in N.s/m^2 unit
F denotes force in N unit
U denotes velocity in m/s unit
A denotes moving plate area in m^2 unit
h denotes oil's film thickness in m unit

In many situations, we are concerned with the ratio of the viscous force to the inertial force, the latter characterized by the fluid density ρ. This ratio is characterized by the kinematic viscosity, defined as follows;

$$\text{Kinematic viscosity: } \nu = \mu / \rho \quad (2.4)$$

Kinematic viscosity (Greek symbol: ν) has SI units ($mm^2 \cdot s^{-1}$). The cgs physical unit for kinematic viscosity is the stokes (abbreviated S or St), named after George Gabriel Stokes. It is sometimes expressed in terms of centistokes (cS or cSt). In U.S. usage, stoke is sometimes used as the singular form.

kinematic viscosity – temperature relations [7]

Oil viscosity decrease rapidly with increasing temperature in the general pattern shown in Fig. 2.5 such a chart, available in pad from, ASTM D341, a straight line drawn through viscosity valued for an oil at any two temperatures (typically 40 °C and 100 °C) enables estimation of viscosity at any other. Such a straight line relates kinematic viscosity ν in mm^2/s to absolute temperature T (°C + 273) by the Walther equation.

$$\log \log(\nu+0.7) = A - B \log T \qquad (2.5)$$

where, A and B are constants for any given oil.

This relation holds well for most mineral and synthetic oils. With this versatility, equation 2.5 is a common choice for establishing viscosity at various temperature in computer programs for analyzes of bearing oil films, in calculating losses in gears and bearings.

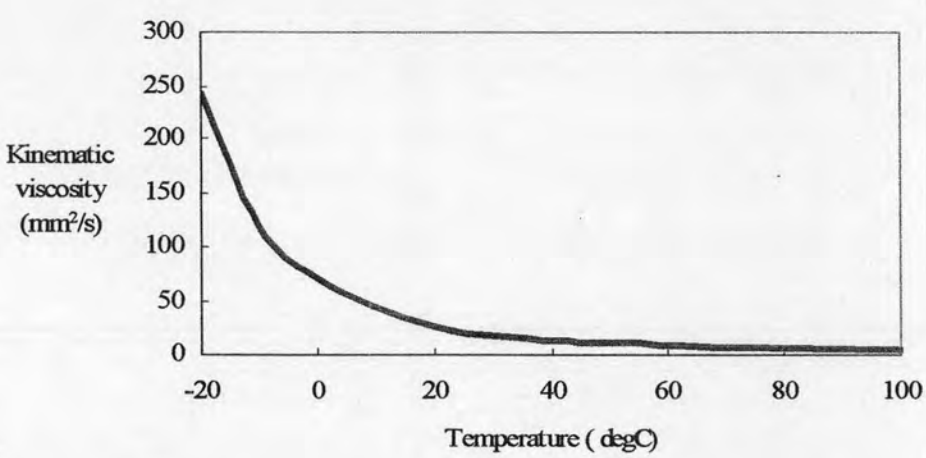


Figure 2.5 The relationship between kinematic viscosity and temperature

2.2.5 Applications of bearing lubricants

- Used in dental hand piece turbines
- In aircraft instruments
- In military applications
- In sound recording and control equipments
- In communication equipments

2.3 Oil's properties assessment

In this work, many techniques which were chosen for characterization of the properties of developed oils for FDB spindle motor for 2.5 inch HDD will be explained in appendix A.

2.4 Literature Reviews

As of today, lubricants for a fluid dynamic bearing are more study with reasons to improve the performance of bearing which can be used to support the information technology. Three research groups published work on preparation and analysis of liquid lubricant which are applied for fluid dynamic bearing. The first group, Schmid, Bongardt and Wuest [1] prepared a low-viscosity lubricants which their composition stable to high and low temperatures. In their research, the ester oils which are the esterfication product of an aliphatic dicarboxylic acid having 8 or 9 carbon atoms and a branched Guerbet alcohol having from 12 to 20 carbon atoms are found to give good low viscosity at high and low temperatures. The second group, Suekuni, Yoshizaki, Komiya [8] provided a conductive lubricant for a fluid dynamic bearing which is able to ground static electricity occurring at the fluid dynamic bearing without impairing the performance of the fluid dynamic bearing. In their conductive lubricant for a fluid dynamic bearing, the lubricant is prepared from an ester base oil such as dioctyl sebacate which has heat resistance, a small quantity of evaporation loss, low cost and good wettability to metal, which are necessary for a fluid dynamic bearing. The conductive lubricant contains 0.1 to 5 percent by weight of antistatic additive such as alkyl aryl sulfonate having an affinity for this ester base oil. Therefore, this antistatic additive imparts conductivity to the base oil, by which the static electricity occurring at the fluid dynamic bearing can be grounded without impairing the lubrication performance. Nagano, et al [9] improved lubricating oil for fluid dynamic bearings to give durable low-torque which is suitable for use as bearings in small-sized spindle motors for information equipments. They found that lubricating oil can meet target property when used a diester of a monovalent aliphatic alcohol containing 6-10 carbon atoms and a saturated aliphatic dicarboxylic acid containing 10 carbon atoms as base oil and 3-20% by weight of a low-viscosity lubricating oil with a kinematic viscosity of less than 11 mm^2/s at 40 °C. Moreover, Weller, et al [10] investigated the effects of chemical structure of synthetic base fluids on friction and wear. They studied the type and number of ester linkages *via* alcohol structure, acid chain length and acid chain branching by using a four ball wear tester. Moreover, they studied properties of synthetic base fluids in the presence of extreme pressure (EP) and antiwear (AW) additives. It was found that the tendency of friction and wear increase when the number of ester linkages is increased. On the contrary, friction and wear decreases when acid chain length is increased. Furthermore, acid with chain branching has been found to increase friction and wear more than linear chain acid. The addition of additives can improve the performance of synthetic base fluids, but it can not overcome the effects from chemical structure.