Application of Elements of Numerical Methods in the Analysis of Journal Bearings in AC Induction Motors: An Industry Case Study

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Abstract

In product engineering there often arise design analysis problems for which a commercial software package is either unavailable or cost prohibitive. Further, these calculations often require successive iterations that can be time intensive when performed by hand, thus development of a software application is indicated.

This case relates to the development of a Visual Basic® application that utilizes numerical methods to solve journal bearing design problems in an AC induction motor application. Specific emphasis is given to the linkage between the industry design problem detailed in this article and the course numerical methods, an important component of the Mechanical Engineering Technology curriculum at the University of Cincinnati College of Applied Science (OCAS) where many employees of Siemens Energy & Automation, Inc (Norwood) have received their education. This article begins with a brief overview of the course Numerical Methods (OCAS, 32-MET-302) then follows with a description of journal bearing applications in AC induction motors, including design issues that frequently require analysis, then concludes with comments about the utility of this type of case as a pedagogical tool in a classroom context.

I. Background

Case studies from industry can be a valuable pedagogical tool to help create a linkage between theories covered in a course and field practice. At the University of Cincinnati College of Applied Science (OCAS) students learn numerical mathematics in the course 32-MET-302 Numerical Analysis with representative topics including elements of linear algebra, numerical differentiation and integration, differential equations, interpolation, and solving for roots. The incoming students typically have had limited exposure to the subject which, with complementing peer influences, have reinforced a perception that the course is difficult and abstract. It is desirable to create intrinsic motivation (inherent interest) for the course by presenting typical industry design problems where they could use the covered topics in their future careers.

II. Overview of Bearings

An AC induction motor comprises both rotating and static hardware. The rotating hardware, rotor, is supported on the frame by bearings. The most important objectives of bearing design are to maximize bearing life, reduce friction energy losses, and minimize maintenance expense and down time.

Bearing Classification

Bearings can be classified into four general categories based on their construction; rolling element, hydrodynamic, hydrostatic and electromagnetic. This categorization excludes some bearing types such as foil and air bearings which are not standard production bearings in the AC motor market.

1. Rolling-element bearings

These bearings are characterized by the rolling motion between an inner race and outer race separated by rolling elements. The two broad categories are ball and cylindrical rolling elements with a myriad of sub types for each. The advantage of rolling motion is that it involves much less friction and wear than sliding contact and are much stiffer than sleeve bearings. Rolling element bearings are the only suitable choice when the motor shaft is subjected to a radial load, as is the case for a belt drive application.

The disadvantages are;

- High alternating stresses (Hertzian) at the load zone (between rolling element and race) resulting in a bearing that may be life limited.
- More sensitive to contamination than sleeve bearings (due to the thinner EHL film separating the elements).
- Sensitive to both over lubrication and under lubrication which affect bearing operating characteristics such as temperature and life.

2. Hydrodynamic bearing

A hydrodynamic bearing, also known as a sleeve bearing, has the rotating element (journal) floating on a thin film of lubrication. The rotation of the bearing journal generates a hydrodynamic film with a high pressure gradient that creates a net force which supports the load. This film is much thicker than the EHL film generated in a rolling element bearing. Sleeve bearings will be discussed in more detail subsequently.

3. Hydrostatic bearing

A hydrostatic bearing generates a force vector in a fluid film by introducing lubricant to the bearing recess at high pressure from an external high-pressure pump. These bearings have the advantage of load capacity at zero velocity (hydrostatic jacking) and the higher lubrication flow rate increases the bearing heat rejection rate. Some motors may employ this bearing type where a heavy rotor, or slow start cycle, may result in excessive bearing journal wear at low speed. The disadvantage lies primarily with increased cost associated with the oil supply system.

4. Electromagnetic bearing

The bearing load capacity is generated by the magnetic field between rotating laminations mounted on the journal and the stator pole on the stationary bearing side. This is not a standard bearing type for the above NEMA market.

For the ANEMA (>400hp-10,000 hp) motors built by Siemens Energy & Automation (Norwood) rolling element bearings and hydrodynamic sleave bearings are used. Motors which support high radial loads, as with belt drive applications, or axial loads for vertical motors, rolling element bearings are used. In direct connect applications where the bearing supports only the rotor weight a sleeve bearing may be used.

There are three basic types of the sleeve bearings: Plain cylindrical bore, lobed (2 or 4), and tilting pad bearing (4 or 5 pads). These types are shown below in figure 1)[1]. Use of lobed or tilting pads bearings is driven primarily by oil film instability issues or the desire to increase effective bearing stiffness to increase the rotor critical speed. The plain bore sleave bearing is standard for the Norwood product line.

III. Case Study: AC Induction Motor Sleeve Bearing Lubricant Selection

Customers will often request lubricating oil for the motors they buy that is different than factory standard. This is often attributable to customer operational constraints such as the need to lube their motor from a common supply that is also servicing other hardware (pumps, compressors, motors etc) in their facility or simply a preference for a specific oil. The impact on motor bearing performance must be assessed before the proposed alternate can be approved. The most immediate impact a change in lubricant viscosity will have on a journal bearing is heat generation and minimum film thickness. A lower viscosity grade will reduce minimum film thickness whereas a higher viscosity lubricant will increase the heat generation and, hence decrease viscosity, or may result in lubricant degradation or coking if the temperature rise is too extreme.

For many years this calculation was performed at Siemens Energy & Automation, Inc. (Norwood) by a FORTRAN program on a mainframe computer. As the existing platform is due to be replaced in 2005, it was necessary to either transition the existing application to a new asset or recode the program. It was determined the latter option was more feasible as it could be performed quicker and afforded the opportunity to update the solution algorithm.

IV. Overview of Legacy Bearing Analysis Program DCL Sleeve

The original FORTRAN program utilized a solver that started with an initial guess for the eccentricity ratio, e, of .9 then incrementally decreased the value by .01 until the difference between the current guess for e and previous was less then the absolute value of .009. The eccentricity ratio, e, is a function of the leakage factor (eta) and load factor (a). The current guess for eccentricity ratio and the bearing L/D (bearing length/Diameter) is used in a table lookup to get a value for side leakage. Oil viscosity is obtained by a table lookup prior to the loop.

Get side leakage, eta
L/D=.8, e=.2

L/D	0.4	0.5	0.6	0.8	1	1.5	trial e
	0.12	0.17	0.22	0.33	0.42	0.57	0.2
	0.14	0.2	0.26	0.36	0.455	0.61	0.4

With eta the load factor, a, is calculated, where $a = (132/Eta)*(1E3*M)^2*(pressure/viscosity*rpm)$. M is the clearance modulus (diametral clearance/journal diameter). Using a and beta (1/2 the angle subtended by the lower bearing Babbitt) a new guess for e is obtained[2].

Find Load factor, a in the table
Get new trial e

New trial e	0.2	0.25	0.3	0.35	0.4	0.45	0.5	Beta
	0.52	0.62	0.83	1	1.25	1.48	1.81	45
	1.02	1.2	1.56	1.75	2.14	2.45	2.9	60

truncated

The loop iterates until the terminate criteria is met or a non-solution condition is encountered (eccentricity ratio not in the range [.2,.99]). The eccentricity ratio is then used to calculate minimum film thickness, power loss and attitude angle.

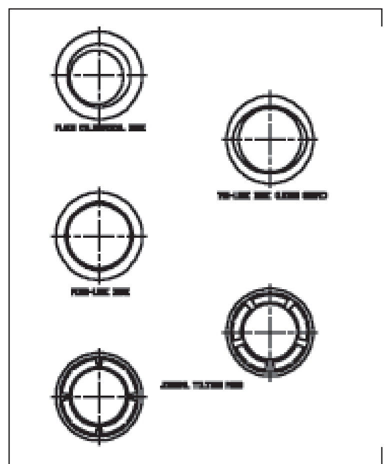

Figure 1. Sleeve Bearing Types

V. Description of New Bearing Analysis Program VBSleeve

The replacement program was written using the Visual Basic® language and the solution algorithm rewritten to incorporate elements of numerical methods. Specific enhancements include;

- Use of polynomial interpolation (column to column and row to row), in place of table look ups, for constants and viscosity values.
- Solution using the bisection method (a bracket root finding technique).
- Error trapping to allow the user to remedy errant input rather than the program crashing.
- Ability to save output file.

As the original program had been well validated by its long history and field experience, the data tables and formulae were retained in the new program. The program logic (fig. 4 and A1)[3] begins with the input screen (fig. 2) where the bearing geometry and load conditions input.

The solution employs bisection, a closed (bracket) root finding technique. In summary, when a solution is found the following relationship will be true; e=f(load factor, leakage factor). The load factor and leakage factor are a function of the load set. The leakage factor, eta, is itself a function of e

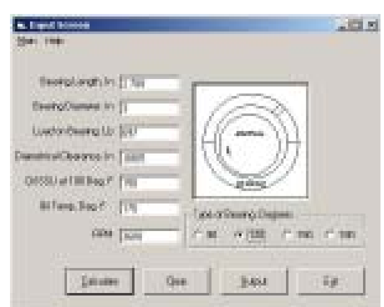

Figure 2. Input screen

which is why a direct solution is not possible. When the correct e has been found then this equation can be rewritten as 0=f(load factor, leakage factor)- e, the exact root resulting in no residual. As the solution technique is approximate, there will be a finite residual so this equation R= f(load factor, leakage factor)- e. The permissible residual, R, is controlled by the approximate error cutoff in the loop (E_a =.001%).

The initial bracket is for an eccentricity ratio, [min, max], [.2, 1.0] which is set by the physics of the bearing. An eccentricity ration of less than .2 corresponds to a very light load and potential stability issues whereas e=1.0 is a zero film thickness condition. The bisection technique is premised on the root being within the bracket (see fig. 3). The program will test for this by taking $f(e_{left}) * f(e_{right}) > 0$. If there exists a root within the initial bracket there will be a sign change (fig. 4) and this condition will not be true. The trial root is taken to be the midpoint of the bracket [4]. The next test is for $f(e_{left}) * f(e_{trial\ root})$. If this value is negative then there was a sign change (a root) in the left half of the bracket so the next bracket will set e_{right} to the current iteration of the trial root. The obverse case if this test value is positive then the left half of the bracket is truncated. The error, E_a, is estimated as $(e_{trial\ root} - e_{previous\ root})/e_{trial\ root}$. Successive iterations will make the bracket smaller with the relative change in the trial root also getting smaller until the loop terminates at the specified approximate error (.001%). Figure 3 depicts how the bracket truncates with each successive iteration and the bracket, within which the true solution lays, the root, is narrowed.

While bracketing techniques require more iterations than open techniques they have the advantage of always converging (if there is a root within the original bracket). An early version of VBSleeve did use the open technique fixed point iteration and there was a tendency to diverge even with test cases involving a known solution if the initial point was too far from the final solution. Therefore, the bracket technique was selected.

VI. Conclusion

The development of this program allowed a valuable analysis capability to be preserved and also facilitated the enhancements attendant with a more modern programming language. The use of select numerical methods results in a solution that is more accurate (as gauged against field data) and credible.

Concurrently, students have access to real industry applications of their course content that they would not have been exposed to in their pre-professional careers. Featuring case studies, as detailed in this paper, allows the course to be more intrinsically motivating and credible.

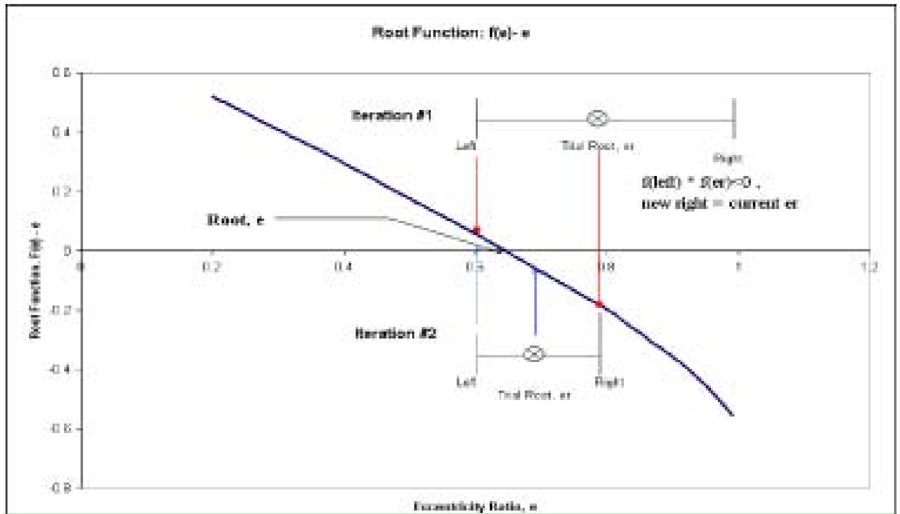

Figure 3. Root function and brackets

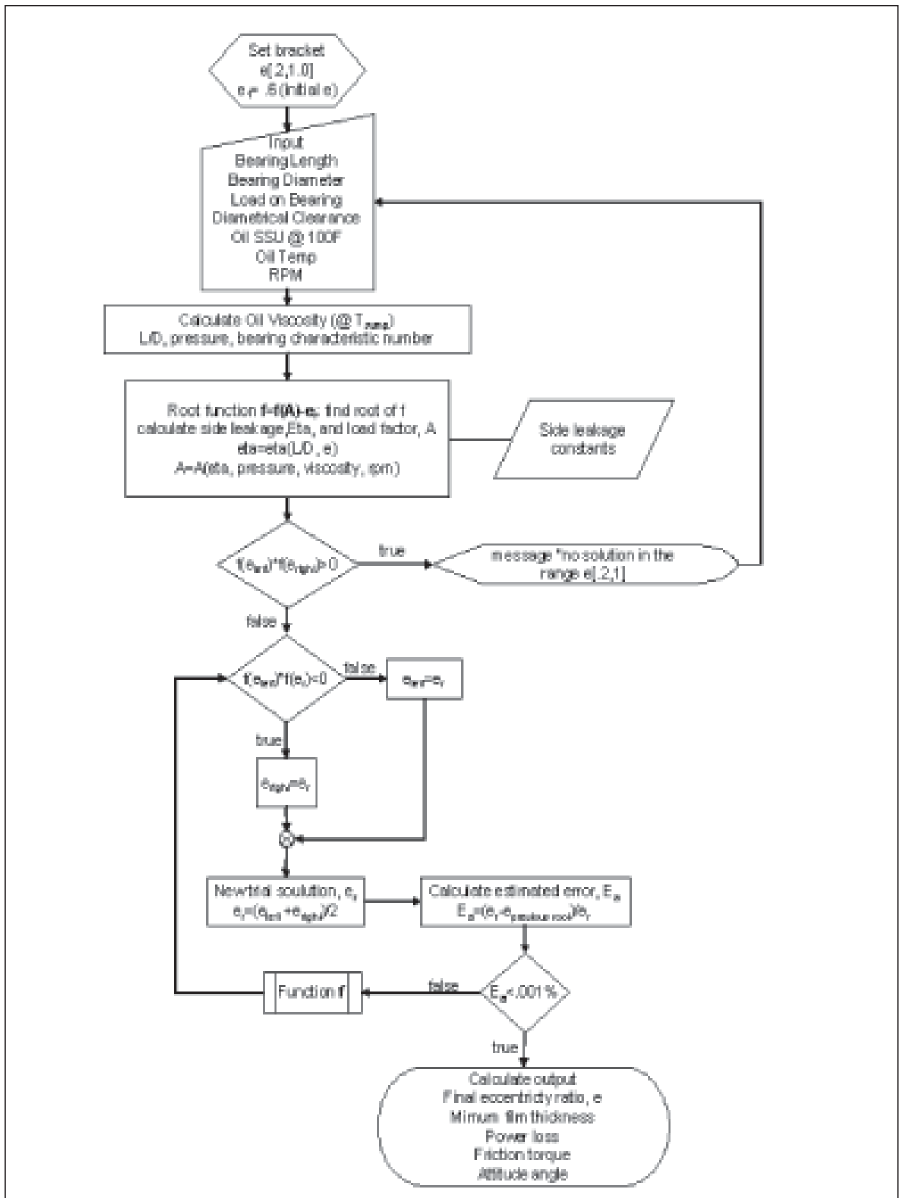

Figure 4. VBSSleeve program logic

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VII. Addendum

A1 Pseudo-code
A2 Calculation

Declare variables

Input load and geometry set

Calculate oil viscosity at oil sump temperature

Calculate intermediate constants; L/D, pressure, etc.

Set initial bracket e[.2,1]

Comment: eta=eta(L/D, e_{trial})
Comment: e = f(A) where A=A(eta, pressure, viscosity, rpm)
Comment: e_r is the trial eccentricity ratio
Comment: f(A)-e_r = 0 when the true e_r is found
Comment: Let f= f(A)-er where f is the root function
Comment: find e where f changes sign, the root

If f(e=.2) * f(e=1) >0 then no root (solution) in this range
else continue

Do while E_a> .001%; E_a=(e_r – $e_{previous}$)/e_r x 100

If f(left) * f(trial root)<0 is true then root is in the left _ bracket
else root is in right _ bracket

Bisect bracket, $e_r = (e_{left} + e_{right})/2$

Calculate approximate error, E_a =abs((e_r –$e_{previous\ root}$)/$e_{r)}$

Loop

Calculate final eccentricity ratio, min. film thickness, power loss, and friction torque and attitude angle

Output
End

Figure A1. Pseudocode for VBSleeve

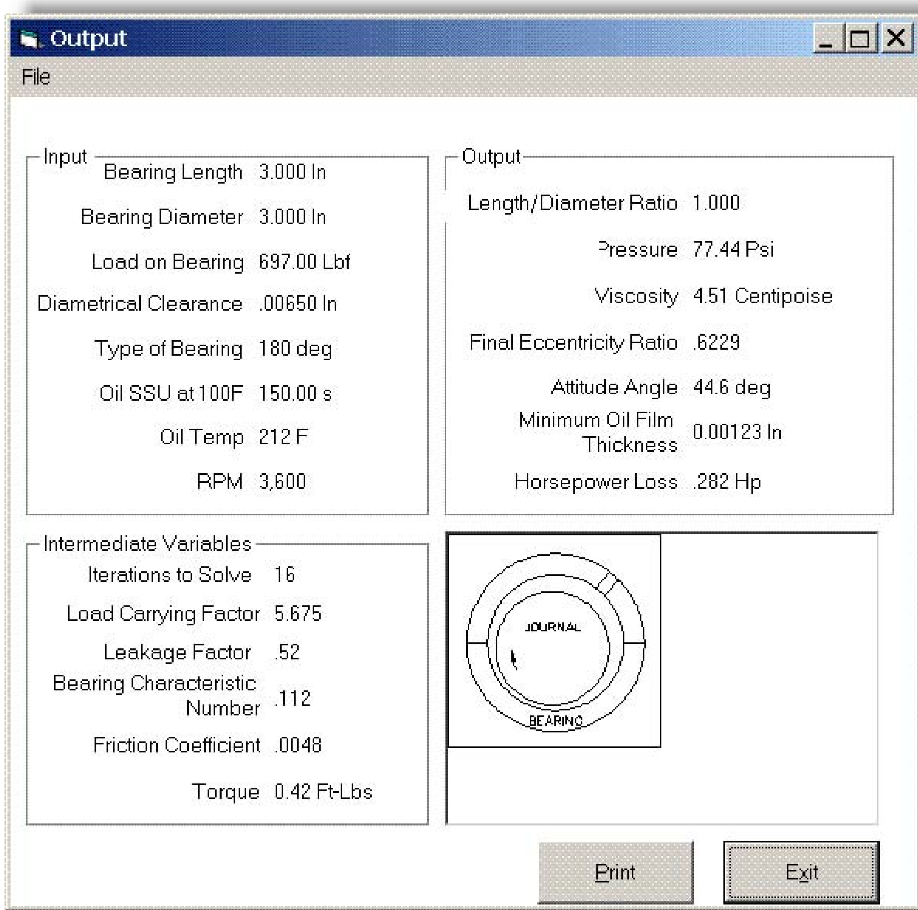

Figure A2. Example Calculation