Instructor: Dr. Luis San Andrés, MEOB 118, Phone: 862-4744, LSanAndres@tamu.edu

Class Time:  PETR 104  MWF 3:00-3:50 pm
Office hours: MW 2 – 3 pm MEOB 117 or by appointment

Catalog Course Description: Development of Reynolds Equation from Navier Stokes equations for study of hydrodynamic lubrication theory as the basis for bearing design; applications to simple thrust and journal bearings and pads of various geometries; hydrostatic lubrication, floating ring bearings, compressible fluid (gas) lubrication, grease lubrication, dynamically loaded bearings, half speed whirl and stability.

Prerequisites: MATH 308, MEEN 345 or equivalent.

OBJECTIVES: To introduce the fundamental physical principles of the classical theory of hydrodynamic lubrication, to learn about the applications of bearings and seals in oil & gas rotating machinery, and to introduce process fluid film bearings for high speed applications. The class material emphasizes the understanding of physical principles and the effects of fluid film bearings on the dynamics of rotating machinery.

Text Book: San Andrés, L. Modern Lubrication Theory, Class Notes (~450 pages) available at URL site http://rotorlab.tamu.edu/me626/default.htm


• Selected journal papers (mandatory reading) listed in Index of Notes (pages 7-ff Syllabus).
• TRIBOLOGY SOFTWARE http://www.tribology-abc.com/calculators/window.htm

Course Outline: Three 50’ lectures/week. Group homework assigned & graded. Two (in class) exams and a group selected project.

EXAMS: 1: Design of simple thrust and journal bearings, (FRI Oct 7)
2: Rotordynamic and Bearings, (FRI Nov 18)

GRADING: Group Assignments 40%
Weekly (individual) quizzes 10%
First Exam 15%
Second Exam 15%
Class Project 30% (proposal due by FRI Oct 14)
110% (*)

Notes: University justification required for missing Exams. All background material on prerequisites is responsibility of each student.
Project topic approved by instructor on F Oct 21, Project report & presentation on Monday December 5.
(*) Your grade can be > 100. Better than the perfect student. Go for it!

Reading material assigned is mandatory. In class discussions and quizzes on the assigned reading topics are regularly conducted.
### MEEN 626, Class Syllabus

**L. San Andrés - Instructor**

Reading assignments (technical papers) listed in Section 17 of your Class Notes (Syllabus – pages 7-ff).


<table>
<thead>
<tr>
<th>W (Dates)</th>
<th>Lecture Material (subject to revision)</th>
<th>Notes</th>
<th>Reading Assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 09/05 09/09</td>
<td><strong>Classical Lubrication:</strong> Laminar Flow Fluid Film Bearings. The Reynolds Equation. Magnitude of fluid inertia effects. Boundary conditions and the notion of liquid cavitation. <strong>1-Dimensional bearings:</strong> Evaluation of pressure field and forces for slider, Rayleigh-step bearings and simple dampers.</td>
<td>2 2- App</td>
<td>Széki, 1987, JoT, pp. 21-35. San Andrés, 1989, JoT, pp. 391-393</td>
</tr>
<tr>
<td>3 09/12-15</td>
<td>Students attend to Turbomachinery/Pump Symposia, Houston</td>
<td></td>
<td>Must register in advance</td>
</tr>
<tr>
<td>10/07</td>
<td>EXAM I (Friday)</td>
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</tr>
<tr>
<td>7 10/10</td>
<td><strong>Thermohydrodynamic analysis of finite length fluid film bearings including fluid inertia</strong> (analytical perturbation methods and evaluation of dynamic force coefficients in finite length bearings. Finite Element models: basic equations and their solution.)</td>
<td>7</td>
<td>San Andrés, 2012, IMECE2012-87713</td>
</tr>
<tr>
<td>8 10/17 10/21</td>
<td><strong>Fluid inertia and turbulence in fluid film bearings</strong> When fluid inertia effects are important. Bulk-flow model for inertial flows. <strong>Group PROJECT approved by F 10/21</strong></td>
<td>9</td>
<td>Hashimoto, 1988, JoT, pp. 539-47.</td>
</tr>
<tr>
<td>11/18</td>
<td>EXAM II (F 11/18)</td>
<td>14</td>
<td>Diaz &amp; LSA, 1999, TribTrans</td>
</tr>
</tbody>
</table>
Experimental methods and analyses for identification of bearing force coefficients. Examples of applications

Gas film lubrication and gas bearings for microturbomachinery review of the state of art

An overview of tilting pad bearings – Dos’ and don’ts

Monday 12/05: Group Project presentations - (10 minutes max).

MEEN 626 LUBRICATION THEORY

Group homework will be assigned. Homework is good practice for the exams, and more importantly to acquire practical experience solving actual industrial problems! One homework per group should be handed for grading. The grade is the same for all group members unless special circumstances arise. No late homework will be accepted. Note that homework assignments make 40% of your total grade.

The way to learn how to work problems is to work problems. Use the answer (if given or known) only to determine that your strategy, procedure, and numerical computations are correct. Working backwards from the answer will not teach you the engineering method, or the principles involved in the solution of the problem.

Weekly advance reading assignments are listed in the Class Syllabus (pages 2-3). Quizzes most times cover understanding of this material. The lectures broaden the coverage of the class notes and provide examples/insights of analysis. There are significant amounts of subject material mentioned in the lectures that are not in the class notes.

Individual (pop) quizzes (10 minutes) will be given (almost) weekly, graded and returned in class the following week. Quizzes account for 10% of your total grade (added bonus). Material for quizzes includes answering simple questions with physical relevance and/or detailing your level of comprehension about reading assignments.

The class notes are not a complete reference for this course. Attendance and attention to the lectures is therefore mandatory for success. There will be no excuses for missing quizzes or homework (except for University excused absences). Solutions to quizzes and homework problems will be often delivered electronically.

About Lecture notes and MATHCAD© programs: The lectures, handouts and MATHCAD© worksheets used in this course are copyrighted. By “handouts,” I mean all materials generated for this class, which include but are not limited to syllabi, lecture notes, computer programs, quizzes, exams, lab problems, in-class materials, review sheets, and additional problem sets. Because these materials are copyrighted, you do not have the right to copy or modify the handouts, unless I expressly grant permission.

**About plagiarism:** As commonly defined, plagiarism consists of passing off as one’s own ideas, words, writings, etc., which belong to another. In accordance with this definition, you are committing plagiarism if you copy the work of another person and turn it in as your own, even if you should have the permission of that person. Plagiarism is one of the worst academic sins, for the plagiarist destroys the trust among colleagues without which research cannot be safely communicated. If you have any questions regarding plagiarism, please consult the latest issue of the TAMU Student Rules, section “Scholastic Dishonesty.”

**Americans with Disabilities Act (ADA) Policy Statement**
The Americans with Disabilities Act (ADA) is a federal anti-discrimination statute that provides comprehensive civil rights protection for persons with disabilities. Among other things, this legislation requires that all students with disabilities be guaranteed a learning environment that provides for reasonable accommodation of their disabilities. If you believe you have a disability requiring an accommodation, please contact the Department of Student Life, Services for Students with Disabilities, in Room 126 of the Koldus Building or call 845-1637.

**Academic Integrity Statement**

Aggie Honor Code: *"An Aggie does not lie, cheat, or steal, or tolerate those who do."*

It is the responsibility of students and instructors to help maintain scholastic integrity at the university by refusing to participate in or tolerate scholastic dishonesty ([Student Rule 20. Scholastic Dishonesty, http://student-rules.tamu.edu). New procedures and policies have been adopted effective September 1, 2004. Details are available through the Office of the Aggie Honor System ([http://www.tamu.edu/aggiehonor/](http://www.tamu.edu/aggiehonor/)). An excerpt from the Philosophy & Rationale section states: "Apathy or acquiescence in the presence of academic dishonesty is not a neutral act -- failure to confront and deter it will reinforce, perpetuate, and enlarge the scope of such misconduct. Academic dishonesty is the most corrosive force in the academic life of a university."

**About Office Hours:**
The purpose of office hours is to encourage individual interaction between the student and the instructor. The instructor is available to discuss not only questions related to the course, but other issues where I can help you as a professional engineer and educator. Please take advantage of office hours. To utilize this time efficiently, students should prepare by organizing questions in advance. Students should seek help in developing clear procedures for solution of problems and to improve their understanding of class materials. I will not solve problems for you. Instead, I will help you learn an engineering method for problem solving.

I am willing to help you at times other than office hours without an appointment; however, just like you, I have responsibilities other than MEEN 626 and must budget certain times to meet those responsibilities. So please do not be offended if I am in the office but cannot meet with you.

**The use of e-mails** for communication with your instructor is acceptable. I usually receive three types of messages:

a) a request to schedule a meeting at other times than office hours,
b) questions related to the impending homework or reading assignment,
c) questions related to the study material for an exam.

I reply promptly to all messages (usually within the next working hour if I am in town). If I cannot be found in my Campus Office, please call 862-4744. I spend most of my time at the Turbomachinery Laboratory (FM2818 and George Bush).

**When will the instructor be absent? Schedule for make up classes**

This Fall I have scheduled attending to several technical Conferences. There will be no class on the dates noted below. Make up recitations for the lost classes will be scheduled within a week and be conducted at nighttime (6 to 8 p.m.). The instructor will announce the exact date and meeting place.

| September 22-25 | Houston, Turbomachinery/Pump Symposium | Students are encouraged to attend the event. |
| October 14-18   | Doha, Qatar, Middle Eastern Turbomachinery Symposium | |

MEEN 626 FALL 2016  L. San Andrés
**Numerical Demonstrations**

The instructor has developed a number of MATHCAD© worksheets and FORTRAN programs to help you gain understanding in the analysis of fluid film bearings and rotordynamics. Among these programs you will find the following:

- Calculation of dynamic force coefficients and threshold speed of instability of a rigid rotor supported on short journal bearings.
- Dynamic response of flexible rotor supported on short journal bearings. Demonstration of motion of system to impact and imbalance excitation.
- Dynamic response of rigid rotor supported on open ends squeeze film dampers. Demonstration of multiple valued response to imbalance.
- Calculation of dynamic force coefficients and threshold speed of instability for multiple pad bearings and pressure dam journal bearings.

**Other computer programs** available for prediction of steady state and rotordynamic force performance of the following types of bearings:
- **thrust**: incompressible fluid film tapered thrust bearings
- **spiral**: gas spiral grooved face seals and thrust bearings
- **fempresdambear**: incompressible fluid film radial pad bearings
- **hydrotcM**: process fluid, laminar/turbulent flow hydrostatic bearings, annular seals and tilting pad bearings.

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**MEEN 626 - LUBRICATION THEORY - CLASS PROJECT**

Individual or group (4 students maximum) projects are acceptable. The purpose of the class project is to develop your ability to **INDEPENDENTLY**:

- select a well defined, though limited, TOPIC,
- clearly identifying the problem to be solved,
- locate and read related material,
- derive equations or preparing test apparatus,
- write related software or perform controlled tests,
- make computer runs and sum results in tables or graphs, or organizing test data,
- compare results to analytical predictions or published test data,
- write a well organized and neat technical report.

Do not expect your instructor to give you a topic, or derive or solve equations for you. This is your project! However, I will help you locate related material and give advice. Your project may be related to your professional expertise and/or current research interests, if applicable.

You must submit a ONE page proposal for the project by **October 14**. Do not initiate any work w/o consulting the class instructor or obtaining his approval by **October 21**. Most times proposals are poorly written, do not establish a clear need nor have objectives to accomplish. Students must realize that an objective is different from a task. Expected results or deliverables conclude a good proposal.

The project need not be typed but should have the following parts:

- Title page: name of student and abstract.
- Table of contents.
- Problem definition: establish objective.
- Review of pertinent past literature.
- Analysis with highlights in derivation of equations governing the model, or description of test rig and expected results,
- Discussion of numerical method of solution, or procedure to perform experiments,
- Results: discussion of calculations or measurements, comparison with analytical or existing results in the literature.
- Discussion on consistency, accuracy, and convergence of numerical or analytical approximation, or Discussion of uncertainty of test data,
- Conclusions and recommendations
- Bibliography.
- List of source file with sample input and output, or test data in tabular form.

E-mail a copy of your program, test results and technical report to LSanAndres@tamu.edu. Instructor will e-mail you later in the semester a document describing the preparation of sound technical reports.
The project should be completed, a technical report delivered on Monday, December 5, and presented on December 5.

Project grade (30\% of total grade) will be based on originality, neatness, quality of results, level of difficulty, and correctness of approach and results. **Suggested (suitable) topics for a group project are:**

a) Develop a code for the analysis of externally pressurized gas bearings.
b) Develop a code for the design of gas thrust pad bearings.
c) Develop a code for the analysis of finite length journal bearings with a mass conservation cavitation model.
d) Develop a code for the analysis of gas face-seals.
e) Perform imbalance response measurements on a rotor supported in a squeeze film damper.
f) Perform imbalance response measurements on a floating ring journal bearing rotor kit.
g) Perform imbalance response measurements on a rotor supported on flexure-pivot tilting pad bearings.
h) Perform imbalance response measurements on a rotor supported on gas film bearings.
i) Demonstrate experimentally streamlines (recirculation) in viscous fluid journal bearing.
j) Develop a code for imbalance response or transient response of a MDOF system with squeeze film dampers.
k) Analysis of dynamic response and stability characteristics of a flexible rotor supported in fluid film bearings.
l) Modify a rotor-bearing system and perform experiments to record (measure) oil-whirl and oil-whip.
m) Any other ideas or problems related to your research, professional experience or interests, with instructor’s prior approval.

**REMEMBER:** the objective of the project is for you to obtain depth in a particular aspect of lubrication theory. The project should NOT be purely numerical or purely experimental. A code will aid you to predict bearing/seal performance and to explain the findings. Tests will deliver bearing/seal performance and the results will serve to explain behavior.

### A typical grading sheet for a MEEN 626 project follows:

Student Names:
Project Title:
Abstract forwarded/approved:  
GRADE: / 100

<table>
<thead>
<tr>
<th><strong>Computational or analytical subject</strong></th>
<th><strong>Experimental subject</strong></th>
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<tbody>
<tr>
<td>CHECK</td>
<td>Title page: name of students and abstract</td>
</tr>
<tr>
<td>MARKS</td>
<td>Table of contents</td>
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<tr>
<td></td>
<td>Problem definition: well established objective</td>
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<tr>
<td></td>
<td>Review of pertinent past literature</td>
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<td>Discussion of numerical method of solution</td>
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<td>Results: discussion of calculations (predictions), comparison with analytical or existing results in the literature</td>
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<td></td>
<td>Discussion on consistency, accuracy, and convergence of numerical solution</td>
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<td></td>
<td>Conclusions and recommendations</td>
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<tr>
<td></td>
<td>What was learned? How to improve?</td>
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<tr>
<td></td>
<td>Bibliography (References)</td>
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<td></td>
<td>List of source file with sample input and output (Electronic files)</td>
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<td></td>
<td>Other evaluation criteria [ (-:poor, +: good, ++: very good, +++: excellent) ]</td>
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<tr>
<td></td>
<td>Quality of oral presentation</td>
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<td>Report neatness and organization</td>
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<td>Level of difficulty</td>
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<td>(Percent) Completion of stated objective(s)</td>
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</table>

Grading your class project is subjective and will depend greatly on the completion of the advanced objective and soundness of technical report (well written with accurate results). Uncertainty analysis required for experimental projects. Sensitivity analysis needed for computational projects. **The larger the group, the more comprehensive the project and report should be.**
# Index to Class Notes Fall 2016

Lectures notes 0-16 and appendices available as pdf files at [http://rotorlabtamu.edu/me626/default.htm](http://rotorlabtamu.edu/me626/default.htm)

**Reading Assignments**, listed as item 17, available as pdf (limited access). MATHCAD codes also available

**Lecturer Reference** (contains an expanded summary of most material learned in course)


<table>
<thead>
<tr>
<th>Notes</th>
<th>Content</th>
</tr>
</thead>
</table>
| 0     | **Introduction to Hydrodynamic Lubrication**  
**Appendix. Applications of Tribology in the 21st century**  
**Appendix. Microturbomachinery Applications** |
| 1     | **The fundamental assumptions and equations of lubrication theory**  
The fundamental assumption in Lubrication Theory. Derivation of thin film flow equations from Navier-Stokes equations. Importance of fluid inertia effects in thin film flows. Some fluid physical properties |
| 2     | **Classical Lubrication Theory**  
Derivation of Reynolds equation for laminar flow bearings. Boundary conditions and types of liquid cavitation.  
**Appendix:** One dimensional slider bearing, Rayleigh (step) bearing and circular plate squeeze film damper. A historical ASME landmark: The Kingsbury bearing. |
| 3     | **Kinematics of motion in cylindrical journal bearings**  
MATHCAD program for display of pressure field in short length journal bearings. |
| 4     | **Static load performance of plain journal bearings**  
The long and short bearing models. Pressure field and fluid film forces on short length journal bearings. Equilibrium condition, load capacity and the Sommerfeld number. Simple lumped parameter thermal analysis  
MATHCAD program for calculation of equilibrium eccentricity in a short length journal bearing. |
| 5     | **Dynamics of a simple rotor-fluid film bearing system**  
**Appendix. Physical interpretation of dynamic forces for circular centered whirl**  
MATHCAD program for calculation of force coefficients in short length bearings  
MATHCAD program for prediction of threshold speed of instability and imbalance response of a rigid rotor supported on laminar flow short length journal bearings (no fluid inertia).  
MATHCAD program for prediction of transient response of rigid rotor supported on short length journal bearings or SFDS. |
| 6     | **Liquid cavitation in fluid film bearings**  
Appropriate boundary conditions for a sound cavitation model. The basics of a universal cavitation model (algorithm). Includes a discussion on air ingestion and entrapment and the differences with oil cavitation (gaseous or vapor).  
MATHCAD program for calculation of pressure fields in 1-D bearing (Mass conservation model and Reynolds condition). |
| 7     | **Thermal analysis of finite length fluid film bearings including fluid inertia**  
(analytical perturbation methods and evaluation of dynamic force coefficients in finite length bearings. Finite Element models: basic equations and their solution.)  
FORTRAN program for prediction of static load and force coefficients in multiple pad bearings (distribution limited). |
| 8     | **Turbulence in Fluid Film Bearings**  
MATHCAD program for prediction of turbulent friction factors. |
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Topic</th>
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</thead>
<tbody>
<tr>
<td>9</td>
<td>Fluid inertia and turbulence in fluid film bearings</td>
</tr>
<tr>
<td></td>
<td>When fluid inertia effects are important. Bulk-flow model for inertial flows. Turbulence and inertia in short length journal bearings and open end dampers. MATHCAD program displays pressure fields (viscous + inertial) in superlaminar flow bearings and SFDs. MATHCAD predicts threshold speed of instability and imbalance response of a rigid rotor supported on turbulent flow short length journal bearings (no fluid inertia).</td>
</tr>
<tr>
<td>10</td>
<td>A thermohydrodynamic bulk-flow model for fluid film bearings</td>
</tr>
<tr>
<td>11</td>
<td>Floating ring oil seals for compressors and Long (laminar flow) oil seals.</td>
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<tr>
<td></td>
<td>Applications in compressors and pumps: reduce leakage, seal gas products and the source of rotordynamic instability. MATHCAD program predicts force coefficients in turbulent flow short length journal bearings.</td>
</tr>
<tr>
<td>12</td>
<td>(a) Annular pressure (damper) seals (22p)</td>
</tr>
<tr>
<td></td>
<td>The mechanism of centering stiffness in seals. Force coefficients for short-length pressure seals. Design of annular seals: swirl brakes, impact on rotordynamics. MATHCAD program for prediction of leakage and force coefficients for short length annular seal</td>
</tr>
<tr>
<td></td>
<td>(b) Hydrostatic journal bearings (18p)</td>
</tr>
<tr>
<td></td>
<td>Hydrostatic bearings in modern applications. The principle of hydrostatic lubrication. Effects of recess volume-fluid compressibility on force coefficients for operation at low and high frequencies. Applications of hydrostatic bearings MATHCAD program predicts frequency dependent force coefficients in 1-D hydrostatic bearings.</td>
</tr>
<tr>
<td>13</td>
<td>Squeeze Film Dampers (SFDs)</td>
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<tr>
<td></td>
<td>Appraisal of the art. Design considerations. Force Coefficients. Lubricant cavitation and air entrainment in SFDs. Response of a Rigid Rotor Supported on open-ended SFDs. (*) Digital video clips showing air entrainment in a SFD available at <a href="http://rotorlab.tamu.edu">http://rotorlab.tamu.edu</a> MATHCAD code: predicts imbalance response of rigid rotor supported on short length SFDs, fluid inertia effects included.</td>
</tr>
<tr>
<td>14</td>
<td>Experimental identification of bearing force coefficients includes paper on Instrumental Variable Filter method for bearing parameter identification. MATHCAD program implementing impedance and IVF methods for identification of parameters in a simple mechanical system.</td>
</tr>
<tr>
<td>15</td>
<td>Gas film lubrication (59 p)</td>
</tr>
<tr>
<td></td>
<td>Introduction to gas bearings: slider and radial rigid bearings – limits of operation. A little about foil bearings Gas Bearings for oil-free MTM</td>
</tr>
<tr>
<td></td>
<td>Appraisal of the art. Technical Presentation to IFToMM Rotordynamics Conference, Seoul, Korea (Sept, 2010)</td>
</tr>
<tr>
<td>16</td>
<td>Analysis of tilting pad bearings</td>
</tr>
<tr>
<td></td>
<td>The fundamentals of analysis – Incomplete document. Presentation. Appendix A primer to tilting pad bearings (old but still useful material)</td>
</tr>
</tbody>
</table>
Selected Technical papers (reading assignments)


Other References with Useful Information (paper copy only, ask your course instructor)


Recommended Tribology Journals

<table>
<thead>
<tr>
<th>Journal</th>
<th>Impact Factor</th>
<th>2015 or last 5 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Journal of Tribology</td>
<td>1.236</td>
<td>(Transactions of the ASME). Published quarterly by the American Society of Mechanical Engineers, 22 Law Drive, Box 2300, Fairfield, NJ 07007-2300, USA.</td>
</tr>
<tr>
<td>Journal of Eng Gas Turbines Power</td>
<td>1.095</td>
<td>(Transactions of the ASME)</td>
</tr>
<tr>
<td>Tribology Transactions</td>
<td>1.418</td>
<td>(Journal of the Society of Tribologists and Lubrication Engineers). Published quarterly by STLE, 840 Busse Highway, Park Ridge, Illinois, USA</td>
</tr>
<tr>
<td>Wear</td>
<td>2.323</td>
<td>Published by Elsevier Science B.V. Sequoia SA, PO Box 851, 1001 Lausanne, Switzerland. ISSN 0043-1648</td>
</tr>
<tr>
<td>Tribology Letters</td>
<td>1.758</td>
<td></td>
</tr>
<tr>
<td>Tribology International</td>
<td>2.352</td>
<td>Published bimonthly by Butterworth Heinemann, Linacre House, Jordan Hill, Oxford, OX2 8DP.</td>
</tr>
<tr>
<td>Lubrication Engineering</td>
<td>0.53</td>
<td>(STLE magazine). Published monthly by STLE</td>
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</tbody>
</table>

Recommended reference books

Szeri, A., 2011, Fluid Film Lubrication, Cambridge University Press


Moes, H., 2000, Lubrication and Beyond, U of Twente Press.

Pinkus, O., 1990, Thermal Aspects of Fluid Film Tribology, ASME Press.


Cameron, A., 1971, Basic Lubrication Theory, Longmans.

Recommended URL resources

MIT Open Course Tribology Advanced Fluid Mechanics
http://www.rotordynamics.org/ Search for Conference papers – good stuff!

Fluid film lubrication (the fundamentals) Wikipedia
Fluid film bearing manufacturers (nice pictures of cool products and applications)

- Lufkin-RMT Bearings
- Bearings+
- Kingsbury Bearings
- Waukesha Bearings
- Orion Bearings (John Crane)

NASA Oil-free turbomachinery Program

Air bearings: New Way Air Bearings

TRIBOLOGY SOFTWARE http://www.tribology-abc.com/calculators/window.htm

Disclaimer: Your lecturer does NOT endorse any of the commercial sites listed above. These are merely resources for students to see actual bearings and seals.