MEEN 626 - Lubrication Theory: Syllabus FALL 16

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

References: Childs, D., **Turbomachinery Rotordynamics with Case Studies**, Minter Spring Publisher, 2013.
Szeri, A., **Fluid Film Lubrication**, Cambridge University Press, 2011.
Hamrock, B., **Fundamentals of Fluid Film Lubrication,** McGraw-Hill, Inc., 1994.

San Andrés, L., Introduction to Pump Rotordynamics (26 p.), Hydrodynamic fluid film bearings and their effect on the stability of rotating machinery (35 p.), Annular pressure seals and hydrostatic bearings (36 p.) **von Karman Institute - RTO Lecture Series, RTO-MP-AVT-143, DESIGN AND ANALYSIS OF HIGH SPEED PUMPS**

- 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).

Childs: Turbomachinery Rotordynamics, **JoT**: ASME Journal Of Tribology, **JLT**: ASME Journal Of Lubrication Technology, **TribTrans**: STLE Tribology Transactions, **TurbSymp**: Proceedings of the TAMU Turbomachinery Symposium, **AIAA:** Journal of Propulsion & Power, **JEGT:** Journal of Eng Gas Turbines & Power, **S&D D:** Shock and Vibration Digest.

W	(Dates)	Lecture Material (subject to revision)	Notes	Reading Assignment
1	08/29 09/02	**Introduction** Tribology Needs for the 2000's. Performance Objective. Lubrication principles: types of bearings. The basics of a rotordynamic analysis. The fundamental equations of lubrication	**Intro 1**	Pinkus, 1987, JoT, pp.1-20.
2	09/05 09/09	**Classical Lubrication:** Laminar Flow Fluid Film Bearings. The Reynolds Equation. Magnitude of fluid inertia effects. Boundary conditions and the notion of liquid cavitation. **1-Dimensional bearings:** Evaluation of pressure field and forces for slider, Rayleigh-step bearings and simple dampers.	**2** **2- App**	Szeri, 1987, JoT, pp. 21-35. San Andrés, 1989, JoT, pp. 391-393
3	09/12-15	Students attend to Turbomachinery/Pump Symposia, Houston		Must register in advance
4	09/19 09/23	**1-Dimensional bearings:** Evaluation of pressure field and forces for ideal tilting pad bearings. **Kinematics of motion in cylindrical journal bearings** Reynolds equation for journal bearings. Fixed & rotating coordinates. Pure squeeze film vector. Impedance formulation.	**3**	Lund, 1987, JoT, pp. 37-41
5	09/26	**Static load performance of plain journal bearings (JB):** Long and short JB models. Pressure and forces for short JBs. Equilibrium condition, attitude angle and Sommerfeld Number.	**4**	Klitt & Lund, 1986, JoT, pp. 421-425
	09/28	**Dynamics of rigid rotor-fluid film bearing system** Eqns. of motion. The concept of force coefficients. Stability and synchronous response. Effect of cross-coupled stiffness. **Other Bearing geometries**	**5** **5a**	Childs, Chp 3, pp. 132-183
6	10/03 – 10/05	**Liquid Cavitation in fluid film bearings:** Physical concepts and a universal calculation model. Air entrainment in dynamically loaded bearings.	**6**	Braun, MJ, 2010, JET772 Diaz & LSA, 2001, JEGTP, pp. 1-7
	10/07	**EXAM I (Friday)**		
7	10/10	**Thermohydrodynamic 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.)	**7**	San Andrés, 2012, IMECE2012-87713
7	10/14	**Turbulence in Fluid Film Bearings** Basic concepts. Hirs' bulk-flow model for turbulent flows. Friction factors. Fluid inertia effects and importance in design. **Group PROJECT proposal due on F 10/14**	**8**	Hirs, 1973, JLT, pp. 137-146.
8	10/17 10/21	**Fluid inertia and turbulence in fluid film bearings on** When fluid inertia effects are important. Bulk-flow model for inertial flows. **Group PROJECT approved by F 10/21**	**9**	Hashimoto, 1988, JoT, pp. 539-47,
9	10/24 10/28	**Thermohydrodynamic Bulk-Flow Models:** The bulk-flow equations for analysis of turbulent flow bearings & seals. Importance of thermal effects in process fluid applications. A CFD method for solution of the bulk-flow equations.	**10**	Launder, 1977, JLT, pp. 330-338
10	10/31 11/04	**Applications of oil seals in turbomachinery Floating ring seals and long seals. Gas seals:** Stiffness principle. Effect of eccentricity. Seals as load support elements. Rotordynamic effects	**11**	Childs & Vance., 1997, TurbSymp, pp.201, 220.
11	11/07 11/11	**Annular pressure (damper) seals and hydrostatic bearings** Stiffness principle. Effect of eccentricity. **Seals** as load support elements. Rotordynamic effects. **Hydrostatic bearings**: stiffness principle. Effect of fluid compressibility. Force coefficients	**12**	Chupp et al., 2006, AIAA JPP Childs, Chp 4, pp. 227-284 Delgado & LSA, JoT, 2012
12	11/14 11/16	**Squeeze Film Dampers:** Modeling, design and operation issues. Unbalance response of rigid rotor on SFDs. Air ingestion. Differences in performance between Dampers with oil cavitation and air entrapped.	**13**	Zeidan, et al., 1996, TurbSymp, pp.169-188. Diaz & LSA, 2003, JoT, pp. 325 Adiletta, 2002, S&V D
	11/18	**EXAM II (F 11/18)**	**14**	Diaz & LSA, 1999, TribTrans

W	(Dates)	Lecture Material (subject to revision)	Notes	Reading Assignment
13	11/21 11/23	**Experimental methods and analyses for identification of bearing force coefficients.** Examples of applications	**14**	**Nov 24-25 Thanksgiving**
14	11/28 12/02	**Gas film lubrication and gas bearings for microturbomachinery** review of the state of art **An overview of tilting pad bearings –** Dos' and don'ts	**15** **16**	
15	12/05	**Group Project** Technical report due **12/05**		
		Monday 12/05: Group Project presentations - (10 minutes max).		
16	12/13	**NO Final exam T 12/13 10:30-12:30**		

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Method of Class Teaching:

- Description of material to be covered, provide reading assignments and homework, announce seminars or events of importance, deadlines, etc.
- Lecture material using 95% overheads. Stop each 15 minutes to provide (5 min.) discussion topics for students.
- At end of class, request students to fill **One Minute Paper** to establish their degree of understanding and address to questions or issues still unanswered.
- Provide closure to lecture and advance preview of upcoming material.

MEEN 626 LUBRICATION THEORY — POLICIES

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 C**lass 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/). 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	

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
hydrotrcM: process fluid, laminar/turbulent flow hydrostatic bearings, annular seals and tilting pad bearings.

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** (10 minute group oral presentation). 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.
n)

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

	Computational or analytical subject	Experimental subject
CHECK	Title page: name of students and abstract	Idem
MARKS	Table of contents	Idem
	Problem definition: well established objective	Idem
	Review of pertinent past literature	Idem
	Analysis with highlights in derivation of equations governing the model	Description of test rig and expected results
	Discussion of numerical method of solution	Procedure to perform experiments
	Results: discussion of calculations (predictions), comparison with analytical or existing results in the literature	Results: discussion of measurements, comparison with analytical or existing results in the literature
	Discussion on consistency, accuracy, and convergence of numerical solution	Discussion of uncertainty of test data
	Conclusions and recommendations What was learned? How to improve?	Idem
	Bibliography (References)	Idem – USE ASME style format
	List of source file with sample input and output (Electronic files)	Test data in tabular form (Electronic files)
	Other evaluation criteria [(-:poor, + : good, ++ : very good, +++: excellent) .	At least 8+'s required for 90 + grade
	Quality of oral presentation	
	Report neatness and organization	
	Level of difficulty	
	(Percent) Completion of stated objective(s)	

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
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)
San Andrés, L., Introduction to Pump Rotordynamics (26 p.), Hydrodynamic fluid film bearings and their effect on the stability of rotating machinery (35 p.), Annular pressure seals and hydrostatic bearings (36 p.) **von Karman Institute - RTO Lecture Series, RTO-MP-AVT-143, DESIGN AND ANALYSIS OF HIGH SPEED PUMPS**,

Notes	Content
0	**Introduction to Hydrodynamic Lubrication** The basic laws of friction. Fluid Film Bearings. Basic Operational Principles. Hydrodynamic and Hydrostatic Bearing Configurations. Example of rotordynamic study. Performance objectives. **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** Reynolds equation for cylindrical journal bearings. Kinematics of motion and film thickness. Distinction between fixed and rotating coordinates. The pure squeeze velocity vector. Examples of journal motion. 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** Equations of motion of a rigid rotor. The concept of force coefficients. Derivation of stiffness and damping coefficients for the short bearing. Stability analysis and the effect of cross-coupled stiffness. Effect of rotor flexibility on stability and imbalance response. Includes a section on **practical (used) bearing configurations** and recommendations. **Appendix Physical interpretation of dynamic forces for circular centered whirl** MATHCAD program for evaluation 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** The nature of turbulence. Turbulence equations in thin film flows. Turbulence flow models. The bulk-flow model of turbulence, Hirs' and Moody's friction factors. MATHCAD program for prediction of turbulent friction factors.

9	**Fluid inertia and turbulence in fluid film bearings** 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).
10	**A thermohydrodynamic bulk-flow model for fluid film bearings** The complete set of bulk-flow equations for the analysis of turbulent flow fluid film bearings. Importance of thermal effects in process fluid applications. A control volume method for solution of bulk-flow equations.
11	**Floating ring oil seals for compressors and Long (laminar flow) oil seals.** 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 annular pressure seals.
12	**(a) Annular pressure (damper) seals (22p)** 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 **(b) Hydrostatic journal bearings (18p)** 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.
13	**Squeeze Film Dampers (SFDs)** 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 http://rotorlab.tamu.edu MATHCAD code: predicts imbalance response of rigid rotor supported on short length SFDs, fluid inertia effects included.
14	**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.
15	**Gas film lubrication (59 p)** Introduction to gas bearings: slider and radial rigid bearings – limits of operation. A little about foil bearings **Gas Bearings for oil-free MTM** Appraisal of the art. Technical Presentation to IFToMM Rotordynamics Conference, Seoul, Korea (Sept, 2010)
16	**Analysis of tilting pad bearings** The fundaments of analysis – Incomplete document. Presentation. **Appendix A primer to tilting pad bearings** (old but still useful material)

17

Selected Technical papers (reading assignments)

Hirs, G.G., 1973, "A Bulk-Flow Theory for Turbulence in Lubricant Films," ASME Journal of Lubrication Technology, pp. 137-146.

Launder, B.E., and M. Leschziner, 1978, "Flow in Finite-Width, Thrust Bearings Including Fluid Inertia Effects," ASME Journal of Lubrication Technology, Vol. 100, pp. 330-338.

Allaire, P., and R.D. Flack, 1981, "Design of Journal Bearings for Rotating Machinery," Proceedings of the 10th Turbomachinery Symposium, pp. 25-45.

Klitt, P., and J.W. Lund, 1986, "Calculation of the Dynamic Coefficients of a Journal Bearing Using a Variational Approach," ASME Journal of Tribology, Vol. 108, pp. 421-425

Pinkus, O., 1987, "The Reynolds Centennial: A Brief History of the Theory of Lubrication," ASME Journal of Tribology, Vol. 109, pp. 1-20.

Szeri, A., 1987, "Some Extensions of the Lubrication Theory of Osborne Reynolds," ASME Journal of Tribology, Vol. 109, pp. 21-36.

Lund, J.W., 1987, "Review of the Concept of Dynamic Coefficients for Fluid Film Journal Bearings", ASME Journal of Tribology, Vol. 109, pp. 37-41.

Hashimoto, S., S. Wada, and M. Sumitomo, 1988, "The Effects of Fluid Inertia Forces on the Dynamic Behavior of Short Journal Bearings in Superlaminar Regime," ASME Journal of Tribology, Vol. 110, pp. 539-547.

San Andrés, L., 1989, "Approximate Design of Statically Loaded Cylindrical Journal Bearings", ASME Journal of Tribology, Vol. 111, pp. 391-393.

San Andrés, L., 1990, "Turbulent Hybrid Bearings With Fluid Inertia Effects," ASME Journal of Tribology, Vol. 112, pp. 699-707.

Zeidan, F., and B. Herbage, 1991, "Fluid Film Bearing Fundamentals and Failure," Proceedings of the 20th Turbomachinery Symposium, pp. 161-186.

Zeidan, F., L. San Andrés, and J.M. Vance, 1996, "Design and Application of Squeeze Film Dampers in Rotating Machinery," Proc. of the 25th Turbomachinery Symposium, pp. 169-188.

Childs, D.W. and Vance, J.M., 1997, "Annular Gas Seals and Rotordynamics of Compressors and Turbines," Proceedings of the 26th Turbomachinery Symposium, pp. 201–220, September.

Diaz, S., and L. San Andrés, 1999, "A Method for Identification of Bearing Force Coefficients and its Application to a Squeeze Film Damper with a Bubbly Lubricant," STLE Tribology Transactions, Vol. 42, 4, pp. 739-746.

Diaz, S.E., and San Andrés, L., 2001, "Air Entrainment Versus Lubricant Vaporization in Squeeze Film Dampers: An Experimental Assessment of Their Fundamental Differences," ASME Journal of Engineering for Gas Turbines and Power, Vol. 123, pp. 1-7.

Della Pietra, L., and Adiletta, G., 2002, "The Squeeze Film Damper over Four Decades of Investigations. Part I: Characteristics and Operating Features," Shock and Vibration Digest, Vol. 34, No. 1, pp. 3-26.

Adiletta, G., and Della Pietra, L., 2002, "The Squeeze Film Damper over Four Decades of Investigations. Part II: Rootordynamic Analysis with Rigid and Flexible Rotors," Shock and Vibration Digest, Vol. 34, No. 2, pp. 97-126.

Diaz, S.E., and San Andrés, L., 2003, "Flow Visualization and Forces from a Squeeze Film Damper Operaing with Natural Air Entrainment," ASME Journal of Tribology, Vol. 125, pp. 325-333.

Tiwari, R., Lees, A.W., and Friswell, M.I., 2004, "Identification of Dynamic Bearing Parameters: A Review," The Shock and Vibration Digest, Vol. 36, No. 2, pp. 99-124.

Tiwari, R., Manikandan, S., and Dwivedy, S.K. , 2005, "A Review of the Experimental Estimation of the Dynamic Parameters of Seals," The Shock and Vibration Digest, Vol. 37, No. 4, pp. 261–284.

Chupp, R.E., Hendricks, R.C., Lattime, S.B., and Steinetz, B., 2006, "Sealing in Turbomachinery," AIAA J. Propulsion and Power, Vol. 22, 2, pp. 313-349.

Braun, M.J, and Hannon, W.M, 2010, "Cavitation formation and modeling for fluid film bearings: a review," Proc.

18	**Other References with Useful Information** (paper copy only, ask your course instructor) **Tribological Design Data Guide, Part 1: Bearings**, 1995, The Institution of Mechanical Engineers, Tribology Group, UK. **Tribological Design Data Guide, Part 2: Lubrication,** 1995, The Institution of Mechanical Engineers, Tribology Group, UK.

Recommended Tribology Journals

	Impact factor	2015 or last 5 years
Journal of Tribology	1.236	(Transactions of the ASME). Published quarterly by the American Society of Mechanical Engineers, 22 Law Drive, Box 2300, Fairfield, NJ 07007-2300, USA.
Journal of Eng Gas Turbines Power	1.095	(Transactions of the ASME)
Tribology Transactions	1.418	(Journal of the Society of Tribologists and Lubrication Engineers). Published quarterly by STLE, 840 Busse Highway, Park Ridge, Illinois, USA
Wear	2.323	Published by Elsevier Science B.V. Sequoia SA, PO Box 851, 1001 Lausanne, Switzerland. ISSN 0043-1648
Tribology Letters	1.758	
Tribology International	2.352	Published bimonthly by Butterworth Heinemann, Linacre House, Jordan Hill, Oxford, OX2 8DP.
Journal of Engineering Tribology	0.631	(Proceedings of the Institution of Mechanical Engineers, Part J). Published quarterly by Mechanical Engineering Publications Ltd.
Lubrication Engineering	0.53	(STLE magazine). Published monthly by STLE

Recommended reference books

Szeri, A., 2011, Fluid Film Lubrication, Cambridge University Press
Flitney, R., 2007, Seals and Sealing Handbook, 5th Ed., Elsevier BH.
Stahley, J.S, 2005, Dry Gas Seals Handbook, PennWell Corp.

Khonsari, M. and E.R. Booser, 2001, Applied Tribology, John Wiley Pubs.
Hamrock, B.J., 1994, Fundamentals of Fluid Film Lubrication, McGraw-Hill Book Co., Singapore
Williams, J.A., 1994, Engineering Tribology, Oxford University Press, New York

Szeri, A., Tribology, 1980, McGraw Hill Co., Taylor & Francis (reprint).

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

Hutchings, I. M., 1992, Tribology: Friction and Wear of Engineering Materials, Edward Arnold Ltd.
Pinkus, O., 1990, Thermal Aspects of Fuid Film Tribology, ASME Press.
Arnell, R. D., Davies, P. R., Halling, J. and Whomes, T. L., 1991, Tribology, Principles and Design Applications, Macmillan Education Ltd.

Johnson, K. L., 1985, Contact Mechanics, Cambridge University Press.
Landsdown, A. R. and Price, A. L., 1986, Materials to Resist Wear, Pergamon.

Neale, M.J., 1993, Tribology Handbook: Lubrication; Bearings; Drives and Seals, Butterworth Heinemann.
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 fundaments) 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**
Foil Gas Bearings: **http://www.neuros.com/** **http://www.miti.cc/** **http://www.rddynamics.com/**

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.