

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

DEPARTMENT OF MECHANICAL ENGINEERING

2.672 PROJECTS LABORATORY

LABORATORY MANUAL

**Fall Term
2013**

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2.672 Fall, 2013 SCHEDULE

FRIDAY AM SECTION 09:00-12:00

ADD DATE 10/4 - DROP DATE 11/22

1st Lab 9/6, 9/13, 9/27, 10/4

1st lab report due 10/11

2nd Lab 10/11, 10/18, 10/25, 11/1

2nd lab report due 11/8

3rd Lab 11/8, 11/15, 11/22

Oral Presentation 12/6, Class Time

Note: No class on 9/20 (Student holiday)
No class on 11/29 (Thanksgiving Week)

FRIDAY PM SECTION 14:00-17:00

ADD DATE 10/4 - DROP DATE 11/20

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2.672 - Staff

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Sections

Friday A.M. Section

Professor Wai Cheng

Friday P.M. Section

Professor Wai Cheng

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SECTION 1: 2.672 COURSE OUTLINE AND GRADING POLICY

2.672 Project Laboratory

PURPOSE: This course will provide experience in formulating, solving, and presenting solutions to engineering problems.

ORGANIZATION: Groups of two or three students will work together on three experiments. During the assigned time, a faculty member will be available in the laboratory and will assist with problems which arise. Since a significant purpose of the course is to allow you to learn problem solving techniques, the lab instructors *will provide guidance, but will not, in general, tell you what to do.*

A. Lab Work: Students are to be in the laboratory only at assigned times, unless by special permission. Attendance at the entire scheduled laboratory session is mandatory; *absence will be reflected in your final grade*; data must be reduced before leaving. Bring your calculators and relevant text books/notes to each class.

B) Reporting: One written report will be required from each student for each of the first two experiments. For the third experiment, the results will be presented orally as a coordinated effort of the group members.

WRITTEN REPORTS: It is anticipated that all written reports in a group will have data, calculations and figures which are similar, *but will have separately written texts.* If for any reason some figures, tables, appendices or other material are photocopied and shared, they should be initialed by the person who prepared the original. We want each of you to have the experience that accompanies writing a report but do not expect you to have different experimental results when you've run the same experiment. In general, each report should have enough detail so that the reader can reproduce your results. (See Section 3: Guide to 2.672 Report Writing.) In the last week of the first experiment, one hour will be spent in a brief workshop on report writing.

<p>Written reports are due by class time on the due day at the lab. The cover page should include your name, lab section, and the names of your lab partners. If you are late, deliver the report to the office of your instructor. Late reports will be penalized at the discretion of the instructor.</p>
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ORAL REPORTS: The results from your final experiment will be presented in an oral presentation by your group collectively. Oral presentations are an important part of communicating your results, so it should be a valuable experience. (See Section 4: Guide to 2.672 Oral Presentations.)

Grading Policy for 2.672

There will be 3 experiments. An independently written report by each student is required for the first two; an oral presentation by the group as a whole is required for the third experiment.

A letter grade (with pluses and minuses) will be given to each report. The final grade, however, is computed by assigning a number to each letter grade, and the following weighting is used.

1 st report (written)	25%
2 nd report (written)	25%
3rd report (Oral)	25%
Lab performance (participation, knowledge of the subject etc.)	25%

To encourage using the laboratory as learning environment, substantial weighting is assigned to the lab performance which is **subjectively** graded. ***It should be noted that much of this grade is based on the communication between you and your instructor in class.*** You should use the interaction to demonstrate your knowledge of the subject matter.

Late reports will be down graded. The downgrading is progressive as a function of the days past due. The grade discount is at the discretion of the instructor who will be grading the reports.

For the first two written reports, the grading will be based half on technical content and half on how well do you communicate in writing.

SECTION 2: 2.672 EXPERIMENTS

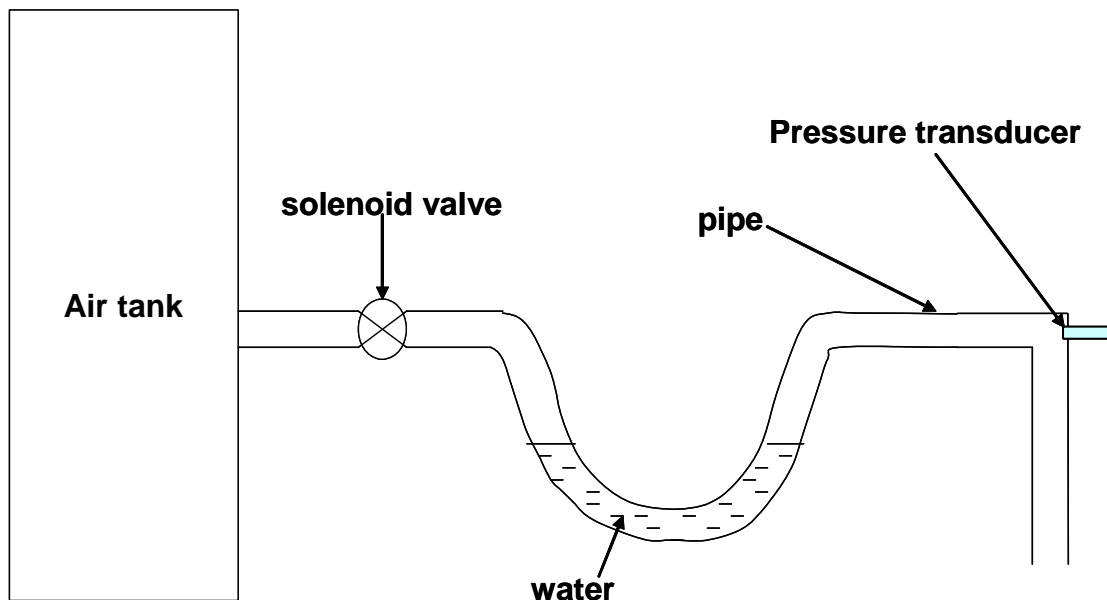
1. Pipe Clearing Fluid Transients

Introduction: When high pressure gas is suddenly admitted into a pipe containing liquid, such as a drain line in a power plant or chemical plant, the liquid is forced out by the gas at high velocity and hits the pipe bends. This clearing of the liquid from the pipe can give rise to impact forces for which the piping was not designed for. In this experiment we would like to see how large these forces are.

Experiment: A section of plastic pipe in which a measurable amount of water can be trapped has been set up in the laboratory. This water is driven out of the pipe by an air flow metered by a choked flow orifice of known diameter, which is that of the throat area of the solenoid valve used to switch on the flow. Make sure that the tank pressure is high enough (at least 1.9 bar absolute) to have a choked flow. The nominal orifice size is stated on the valve body. Due to the compact valve design, the discharge coefficient is significantly lower than 1. (If you have time, you can calibrate the discharge coefficient by discharging the tank; if you do not, you can assume a discharge coefficient of 0.5.) The mass flow rate through this orifice can then be calculated using formulas that are in your fluid mechanics text books under the section of compressible flow.

The pressure exerted by the slug of moving water is recorded by a pressure transducer on the pipe elbow. From the pressure, the force on the elbow may be deduced.

Report: Condensate is often trapped in low sections of pipe where drainage is imperfect. The transient that results when the liquid is forced out in these pipes can damage piping supports. We would like you to explain the mechanism of the phenomenon and come up with an estimate of the impact force due to such a transient. The methodology then can be used to conservatively size the piping supports for drain lines. We should be able to use this methodology to set a tolerable gas flow rate so that excessive forces on the pipes will be avoided. The amount of water trapped, the pipe size, and the gas flow rate, among other variables, must enter into this model.



2. Irradiation Sample Transfer Line Snubbing Section Behavior

The M.I.T. reactor is used to irradiate various isotope samples so that they can be used for medical treatment and research. These samples are packaged in a small cylinder and then inserted into a curved transfer line and lowered to the core of the reactor. (The curved line is to prevent personnel from radiation exposure at the point of insertion.) The sample is retrieved after a suitable interval. If the retrieval system fails, the sample drops to the bottom. To prevent such an accident from damaging the transfer line or the materials in the cylinder, a snug-fitting sleeve section has been installed in the bottom of the transfer line. The clearance between the cylinder and the tube in this section is small enough that air is trapped below the cylinder and is released slowly; this results in reduction in the speed of the cylinder.

This investigation has been commissioned to develop a methodology for designing the snubbing section. To verify the methodology, the experimental values of interest are:

- a) The cylinder impact velocity at the bottom of the transfer line, as a function of the cylinder mass.
- b) The time between entry and first bounce of capsule. This value is used to confirm your model. Then the “bounce distance” could be obtained from the model.
- c) The pressure of the air trapped in the line, both the peak value and the value when the cylinder has reached terminal velocity.

Note that results (a) and (b) are important to verify that your line design model is correct; (c) is just data for checking your theory. (The pressure is negligible compared to the materials yield strength.)

In the actual case, the air at the bottom of the tube is not at room temperature, but at a temperature of about 300°C. Also, the actual drop is one meter taller than the one in the lab. Thus, after confirming the validity of the model with the lab apparatus, the model must be used to predict results for the actual situation.

A simulated transfer line has been set up in the lab. The velocity of the cylinder before entering the snubbing section can be measured by determining the transit time of the cylinder as it passes a light sensor. Similarly, the velocity at impact may be obtained from the light sensor signal at the bottom of the tube. The pressure versus time behavior can be measured with the pressure transducer installed in the snubbing section. The mass of the cylinder can be altered by taking off the top and changing the mass of pellets inside.

A model for the motion of the sample in the snubbing section should be developed compared to the experiment. You have to formulate and solve the set of differential equations describing the dynamics of the system. (The terminal velocity is the steady state solution.) You may use MATLAB or write a simple program to simulate the dynamic behavior.

3. Transfer Line Dynamics

Introduction

We are concerned with modeling the transfer line used to transport a volatile and corrosive liquid from a high pressure storage tank to a tank car. (See the accompanying sketch.) The line is first hooked up and then, in normal operation, the valve (B) at the tank car is opened. After that, the one (A) at the storage tank is opened. If valve A is opened first, however, the resulting pressure surge might rupture the line. (*You should explain why there is a pressure surge.*) Therefore, the transfer line has to be sufficiently strong to withstand the transient that occurs if the valve at the storage tank is opened first.

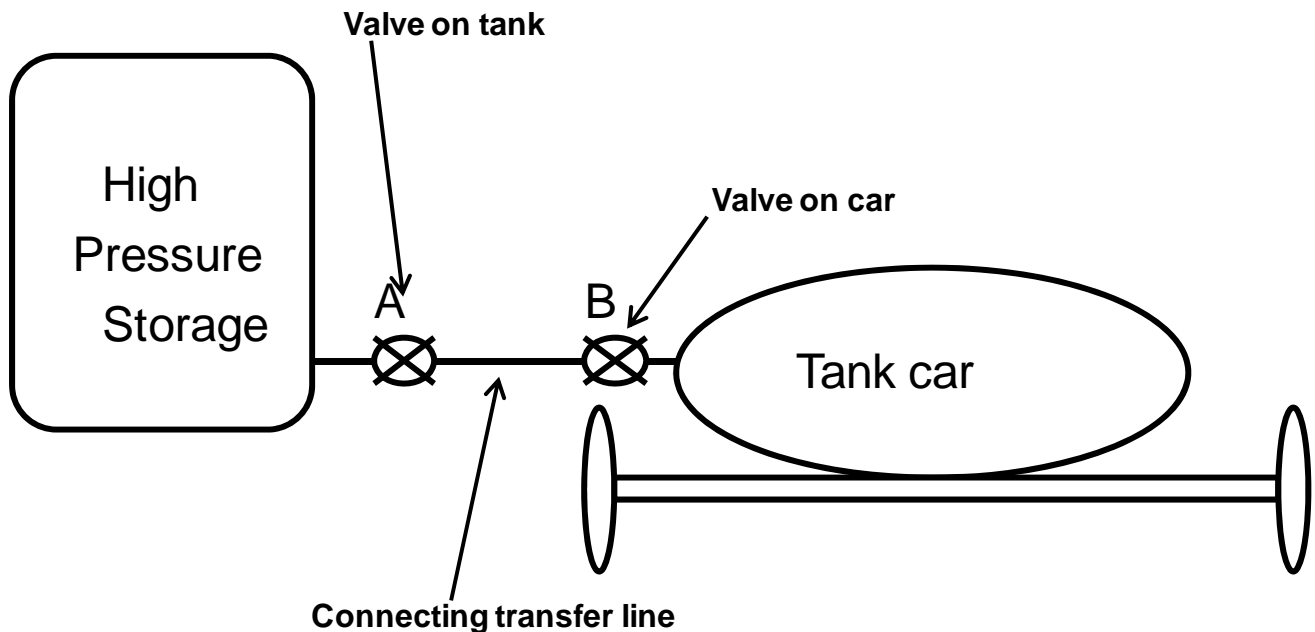
The particular problem we want to solve is: what is the peak pressure that occurs in the transfer line if the storage tank valve is opened first, and how does it depend on the line length, the driving pressure and the other parameters?

Experiment

A simulated storage tank containing water pressurized by air, and a transfer line system has been constructed. To start with, the transfer line will have only air in it. The storage tank valve is to be opened and the peak pressure determined at a point close to the tank car valve. You are to explain the nature of the pressure transient and to show how, and to what accuracy, you can calculate this pressure. An additional transfer line (of different length and with an extra “180° bend”) can be configured so that you can have another set of data.

Report

Your report is to be directed to the chief of the stress analysis section and state clearly how one should calculate the peak pressure.



4. The Effect of Thermal Stress on Heat Exchanger Tube Natural Frequencies

Typically a heat exchanger operates such that the tubes are at one temperature and the shell at another. This temperature mismatch can result in significant thermally induced stresses in the tubes. This investigation should establish the effect of these thermal stresses on the natural frequency of vibration of the heat-exchanger tubes.

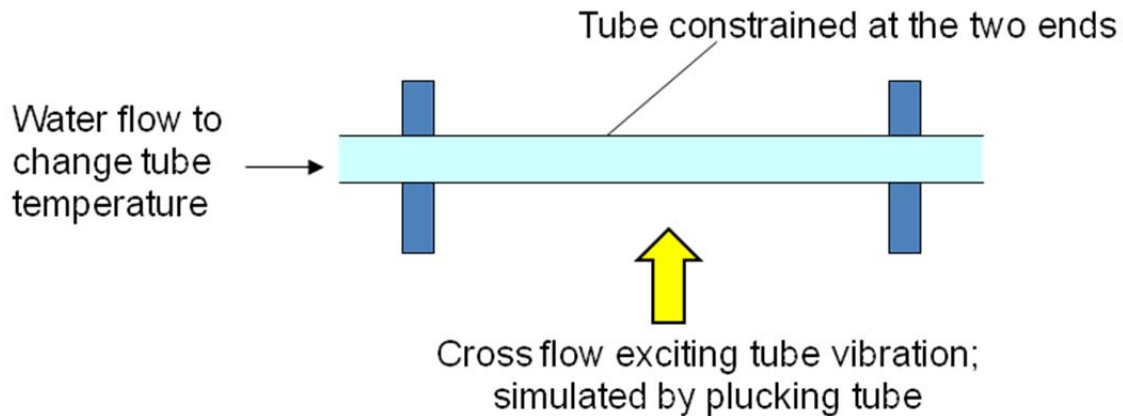
The frequency of vibration is important because the flow of the heat exchanger fluids *across* the tubes can excite vibration of the tubes. Adjoining tubes can hit, fret, and fail, or a tube can vibrate enough so that it is cut by the baffles. To prevent this from happening, the tube must be designed so that the natural frequency of the tube does not correspond to an important forcing frequency in the cross flow.

An apparatus has been constructed in the laboratory which allows the temperature of a tube to be varied while the length of the tube is maintained constant by a large outer pipe at room temperature. The tube is “preloaded” so at room temperature the tube is under tension. You can change the preload by loosening the end screws, heating up the inner tube to move the end plate out and inserting additional spacers between the end plate and the outer pipe.

Your job is to develop a theoretical model to calculate the natural frequency of the tube, including the effect of temperature and preloading. You should use the experimental results from the apparatus to guide the development of the model and to confirm in detail the accuracy of the model. The resulting model of the natural frequency of the tube would be used by a heat-exchanger designer who would also have a model to predict the characteristic frequency of flow-induced vibration--this latter part of the problem is not your responsibility.

Notes:

- ✓ The signal from the magnetic pick up is low. Need to set the a/d internal amplifier gain appropriately
- ✓ There is a 2.672 Matlab function “pwrspect” to calculate the power spectrum of the time domain signal



5. Proximity Heating Of Silicon Wafer

Lithography is a critical processing step in fabrication of advanced microcircuits. It transfers a circuitry layout from a photomask to a silicon wafer. A layer of photosensitive polymers (photoresist) is first spin-coated onto the silicon substrate. A lithography system then projects the image of the photomask onto the resist coating and creates a latent image in the resist. The photoresist in the exposed (or un-exposed) area is then removed by chemical etching

The latent image needs to be activated before the etching process. This is accomplished by setting the wafer temperature to around 180 C for a few seconds; etching quality control requires the temperature to be uniform to within 2 C over the entire wafer surface. A hot-plate heating technology is currently used. The wafer is first supported at ~2.5 cm away from the hot-plate surface. The wafer is then released and lowered quickly to a close proximity (of preset distance) of the hot plate. After a certain amount of heating time, the wafer is lifted away from the hot plate, picked up by a robot and then placed on a chilled plate to cool down.

It is important to reduce the wafer heating time in order to increase process throughput: the thermal activation time for the photo-resist only requires a few seconds at 180° C. You are hired as a consultant by a semiconductor equipment company to identify parameters that will affect the wafer heating rate, to establish a model that can accurately predict the transient wafer temperature, and to propose techniques to reduce the heating time and thus increase process throughput.

Specific questions to be addressed are:

- Are the steady state temperature differences between the hot plate and the wafer as a function of the gap size consistent with the theoretical model of the heat transfer processes?
- What does the heat-up time (either $(1-1/e)$ or 10-90% rise time) depend on? Is your theory consistent with the measurement?
- The smaller the gap, the faster is the heat up time. What determines the lower limit of the gap size?

Experiment

A simplified hot-plate heating experiment has been set up in the lab. A typical test run includes the following steps:

- Place small pieces of paper around the edge of the hot plate as spacers for setting the gap between the hot plate and the wafer. When you measure the thickness of the paper, do not squeeze it too much, since the wafer is not very heavy.
- Lower the test wafer onto the hot plate. The distance between the wafer and hot plate is determined by the paper thickness.
- Measure the plate temperature and the transient wafer temperature. Because of the low level signal (type K thermocouple response is $40 \mu\text{V}/^\circ\text{C}$), the amplified signal is noisy. You need to “eye-ball” average the signal.
- Cool the wafer by lifting the wafer away from the hot plate after the wafer temperature has reached a steady-state value. There is an air jet set up in the lab to cool the wafer.

The hot-plate temperature should be set between 120 C and 150 C. (The paper spacer will char if the temperature is too high. When the temperature is too low, the thermocouple signal is buried in the noise.) You should investigate experimentally the significant effect of wafer-plate distance on the wafer heating rate.

(Note: the thermal properties of silicon may be found on the web. The wafer is not doped; so the emissivity is low; ϵ is of the order of 0.01 to 0.05.)

The wafer thickness is 0.70 mm. Do not measure it, because using a caliper or micrometer on the wafer could crack it.

6. Irrigation System Pressure Surge

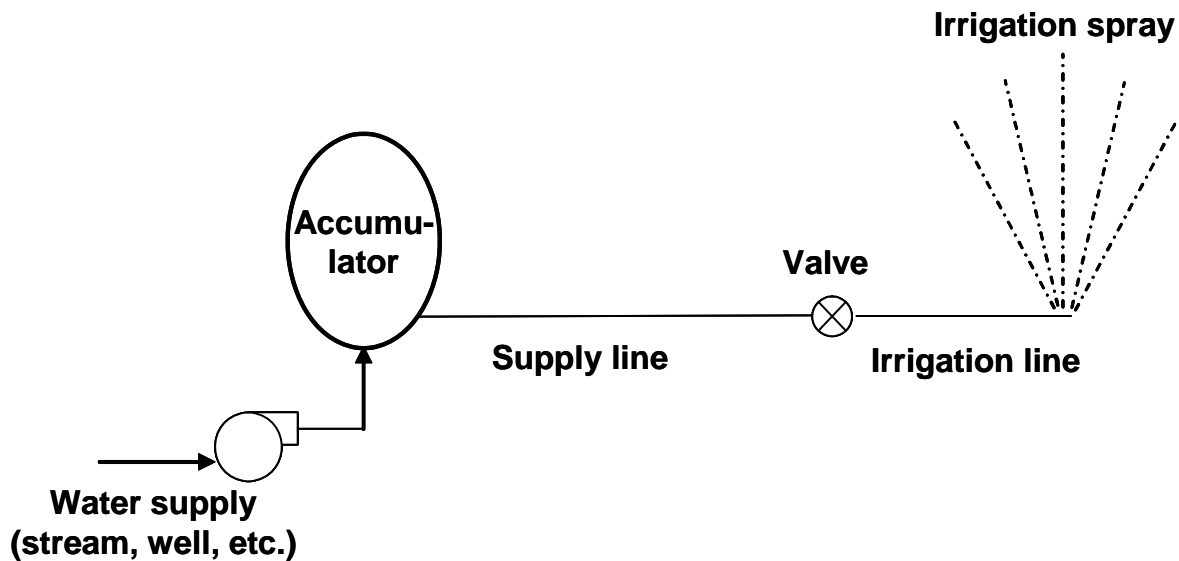
You work for Oxfam to supply low-cost irrigation systems for farms in the third world. The typical plumbing arrangement is shown in the figure below. Water from available sources (stream, well, etc.) is pressurized by a pump/accumulator system to feed the irrigation line, which supplies water to the water spray for the crops. (The accumulator is there just to maintain a steady fluid pressure to the supply line.) When the valve of the irrigation line is turned off quickly, a pressure surge is observed in the supply line. To minimize the cost of the system, the supply line typically consists of thin wall plastic tubing, and therefore the surge pressure is of concern.

Your job is to understand the factors contributing to the surge pressure, and how does this value scale with the system parameters (driving pressure, line length, etc.) The surge pressure depends on how fast the valve is closed off. Therefore, you should obtain the results by closing the valve consistently and aggressively (to assess the worst case).

The bench scale experiment was set up with a water supply pressurized by the shop air. Performing tests to a maximum pressure of 300KPa gauge would be adequate. In the set up, there are several supply lines with different lengths, diameters and materials.

The four lines which have been set up are summarized as follows:

Lines	Length (m)	ID (mm)	OD (mm)	Materials
A	8	12.50	15.88	Polyethylene
B	4	12.50	15.88	Polyethylene
C	4	25.40	28.58	Polyethylene
D	2	25.40	33.34	Polycarbonate



SECTION 3: A GUIDE TO 2.672 LAB REPORT WRITING

ELEMENTS OF A TECHNICAL PAPER

1. Title
2. Abstract
3. Introduction
4. Theoretical background
5. Apparatus and Procedure
6. Results and discussion
7. Conclusions
8. Nomenclature*
9. References
10. Appendices*

*Optional

Individual reporting

You share ideas, data and results with your group members. You need to write your own project report though.

Paper versus report

A report is usually for internal use: a document detailing the procedure and results of your project. A paper is for an external audience. As such, it should be succinct and right to the point. Routine details such as calibration of generic devices (e.g. pressure transducer or thermocouple) need not be described. ***Do not put any computer program listing in the paper.***

Focus on your contribution

You should focus on your ***contributions*** to the understanding and solution of your project problem. You developed a model to characterize the problem. It is a ***remarkable*** achievement. Although your model may not be perfect, it is an important tool to understand the essential physical processes. Write your paper to help people understand and solve real-world engineering problems. Do not write the paper focusing on how inaccurate your model is.

Writing style

In general, do not use “I”, “we”, “he”, or “she” in technical writing. Here are some examples.

Example 1. “This work develops an engineering model to assess wafer temperature in hot-plate photoresist processing.”

Example 2. “The experimental system consists of three major parts.”

Write directly, avoid words that are not useful; e.g. “in order to”, “the purpose of this experiment is to”, etc.

Number of significant digits

If you report a temperature of 100.002 C, it suggests that the temperature error is less than 0.001 C. You should present your results with the right number of significant digits to represent the accuracy of your experiments and model simulations.

TITLE

Title must include key words about the project and reveal the topic of the paper. The title is what attracts a reader to your work.

ABSTRACT

The abstract is a brief (approx. 150 – 200 words) condensation of the paper. ***Do not explain why the study is done in the abstract.*** That belongs to the introduction. Describe each of the following in one or two sentences.

- What was done
- How it was done
- Significant results

INTRODUCTION

- State context/background of study
- Articulate the need for the study
- Clearly define the problem (purpose of the investigation)
- Outline overall approach

THEORETICAL BACKGROUND (In the report or paper, use a more meaningful heading)

Physical explanation of phenomena

It is important to point out the pertinent physics governing the phenomena that you are studying. It helps to orient the readers, and give context to your theory and experiment.

Develop governing equations

- Assumptions: support them quantitatively, e.g., assume laminar flow - give Reynolds number.
- Describe the model development; give the major equations, but leave detailed algebra to the appendix. This part should be written as a mixture of equations and sentences and not just a list of equations.
- It is important to relate the theoretical background to your overall project.

APPARATUS AND PROCEDURE

Overview of Operation

- Refer to the schematic and explain the overall operation.
- Give dimensions of the apparatus. Point out the relationship between the laboratory device and the actual device.
- State what are being measured. Give detailed information of the transducers and measurement systems only if they are uncommon devices.

Conduct of the Experiment

- Brief description of the experimental procedure.
- List sets of experiments done.
- Give range of parameters that you have varied.

RESULTS AND DISCUSSIONS

Organize your results and discussions in coherent pieces so that the observed phenomena can be connected to your explanations and simulations.

- Present the results by referring to the figures. (Figures are much better than tables.)
- Describe the direct observations first (e.g., pressure as a function of time) - ***point out and explain the features in the observation in terms of physical laws.***
- Describe how the results change when you vary the parameters of the experiment.

- > magnitude of change (goes up/down, by how much)
- > scaling (e.g., peak pressure proportional to the driving pressure, etc.).
- If appropriate, point out what is the most sensitive parameter?

Discussions

- See if theoretical results produce the same features as the direct observations of the experiment (e.g., pressure versus time curve).
- Plot theoretical curve on the same graph as the experimental points.
- Explain the differences
- . Present model applications and engineering design if required.

CONCLUSIONS

- Brief summary of your finding
- Pronounce your judgment here
 - What are the key parameters governing the phenomena that you are studying?
 - How good is your model? What does it capture?
- Implications of your conclusions: how your results would apply to your original objective

APPENDICES

Appendices are for details that your reader may not need in order to follow the overall picture of the paper, but they are required to support the validity of your work.

The appendix section, however, has often been misused in 2.672 as a “dumping” area for equations and data tables. That is not appropriate. There should be text description on the equations and tables.

FIGURES AND GRAPHS

Refer to figures to explain procedures and theory. Graphs are much more informative than data tables because trends can be identified much more easily.

Figures and graphs should be labeled well enough to allow them to stand alone as documents.

- Results should be presented in graphical form whenever possible.
- All figures and graphs should be referred to in text before their appearance. They should all be numbered.

Graphs

1. Caption should be short but informative. It should include what is being graphed and any additional information needed to interpret the graph.
2. Axes should be labeled (for quantities with dimensions, units are required).
3. Use symbols for data points and lines for theoretical predictions.
4. Each curve should be marked clearly and distinctly.

SECTION 4: GUIDE TO ORAL PRESENTATION

GENERAL PRINCIPLES OF TECHNICAL PRESENTATIONS

Thomas R. McDonough (MIT '66)

1. REHEARSAL

- Timing - very important
- Rehearse a speech 10% shorter than the allotted time, since most people speak longer than they expect. If you exceed allotted time, end quickly.
- Rehearse beginning and end especially thoroughly. Don't memorize the speech word-for-word. Have a friend critique the rehearsal. Try out the equipment and lighting beforehand.

2. ERROR CORRECTION

Ignore the trivial errors of grammar and pronunciation. Don't apologize for errors. (Don't say "excuse me.") Apologizing just draws attention to errors.

3. EYES

- A. Look at audience, not ceiling or floor
- B. Use visual aids
- C. Bring in an example of the hardware, if practical.

4. VOICE

- A. *Volume* Speak up.
Very important, unless there is a public-address system
Speak much louder than a conversational tone
- B. *Quality* Don't use a boring monotone.
Speak slowly and clearly.

5. LANGUAGE

- A. *English:* fool everyone into thinking you're well educated. Use the best grammar, enunciation and vocabulary. Avoid:
'noises' (uh, you know, sort of, kind of, like, ok)
'you' (e.g., 'your electron' should be 'the electron')
'thing' (e.g., 'this thing' should be 'this device')
'gonna' (say 'going to')
- Slang:* A large percentage of technical audiences speaks English as a second language, and *many* cannot understand slang. Students with strong regional or foreign accents must: put a little . pause . between . each . word. For non technical or interdisciplinary audience: avoid most jargon; define terms carefully.
- B. *Body Language* Don't stand stiffly
Don't move spasmodically
Do use symbolic gestures

6. ORGANIZATION

- A. Have three distinct parts:
 - Beginning* (motivation, history, abstract). Tell us: why should anyone care?
 - Middle* (body): have a logical order: Tell the story chronologically or start with the simple and work up to the complex.
 - End:* (summary, conclusion, future directions)
- B. Keep notes brief. When possible, use visual aids instead of notes. As often as possible, keep notes down and out of sight.

7. ENTHUSIASM (Incredibly important!)

From a cover story on Apple/NeXT founder, Steve Jobs, in "Business Week," 10/24/88: "Of course, Jobs has a powerful weapon with which to wage these uphill battles: his aura and the notice it attracts. Unsolicited, (Billionaire H. Ross Perot bought 16% of NeXT for \$20 million after seeing Jobs's infectious enthusiasm on a TV documentary about entrepreneurs. 'I'd be glad to dramatically increase it, too,' Perot says."

2.672 ORAL PRESENTATION

As indicated in the course outline, the report for the third lab will be in the form of an oral presentation. In addition to your participation in the oral presentation, you will also be required to hand in, as a group, a copy of the viewgraphs used in the oral presentation

PREPARATION OF VIEWGRAPHS

Each group is expected to prepare their own viewgraphs, which **YOU** will make from the original figures. Responsibility for preparation of figures and procuring the viewgraphs will be a group decision. If you want to use computer projected visuals, you have to make arrangement for that yourselves. A good quality paper copy of these figures should also be made and presented to your section instructor at the time of the presentation.

TIME AND LOCATION OF ORAL PRESENTATIONS

Presentations will be held during normal class time. A specific schedule of the presentation (i.e., the time each group presents) will be posted the week prior to the presentation.

Each laboratory group will have a total of 30 minutes for the oral presentation.

+

Breakdown: 24 minutes for the presentation
6 minutes for questions

Total 30 minutes

PREPARING THE ORAL PRESENTATION

Division of Labor

Be careful that the work is relatively evenly divided among all members of the group. We suggest, but not strongly, the following division of material.

Group of Two Students (12 minutes per student)

- | | |
|-------------|---|
| 1st Student | a) Introduction - including overview work
b) Experimental Apparatus, Procedure and Results |
| 2nd Student | c) Theoretical Model and Results
d) Comparison of Theory and Experiment
e) Discussion and Conclusions |

Students will share answering of questions.

Group of Three Students (8 minutes per student)

- | | |
|-------------|--|
| 1st Student | a) Introduction - including overview of work
b) Experimental Apparatus, Procedure and Results |
| 2nd Student | c) Theoretical Model and Results |
| 3rd Student | (d) Discussion and Conclusions |

SECTION 5: SOFTWARE SUPPORT FOR 2.672 PROJECTS

The 2.672 lab uses the ME computer network system under Window NT. You'll log in under a group name and a default password for your lab group (assigned by your instructor). Change the password after you log in the first time. Then you can access the files by logging in on any ME computers.

Computer software packages have been installed in the lab computers for data acquisition, data processing, and word processing. **You should start these programs by double-clicking their icons in the window.** Then, the default directory will be your home directory. The following is a brief overview of these packages.

1. **Labview:** There are several icons here: CHART, WAVEFORM and VBENCH. **CHART is the package we use the most;** it is a general data logging program and displays the data on the fly. You can select which segment of the data you want to store afterwards. WAVEFORM acquires data in the usual way but you cannot display the data until the whole set is taken. VBENCH is a data acquisition virtual bench, which provides simulated oscilloscope, signal generators etc.
2. **Matlab:** Data processing, data plotting, and numerical simulation software. It has built-in programs for solving differential equations, curve fitting, and signal analysis.
3. **Microsoft Word:** Word processing software
4. **Microsoft Excel:** Spreadsheet software
5. **Microsoft Powerpoint:** Presentation software

MATLAB FOR 2.672

This is a short introduction to the MATLAB software. The idea is to enable you to use MATLAB quickly. Refer to the MATLAB REFERENCE MANUAL for more sophisticated operations.

TO USE MATLAB - **click the MATLAB icon**. It will set up your directory as default for you so that you can access your files.

CONCEPTS

- o MATLAB is a giant calculator which remembers the values of all the variables you have calculated.
- The command you type in is executed every time you hit a carriage return (CR). Use the **up-and-down arrow keys to recall previous commands**.
- Sometimes you **do not want the intermediate results** to be printed (e.g., when you are calculating the values of a thousand numbers). To do this, **end the command with semi-colon**, before the CR.
- For a very long command that you cannot finish in one line, the line can be continued to the next by using the ellipsis consisting of **three dots...**, before the CR.

- o One can store a set of commands in a script file and recall it to be used. More of this later in the section **SCRIPT FILES**. (Using a script file is preferred if you have to do any serious calculations because then you have a record of all the commands you put in, and you can edit them and redo the command sequence easily.)

- o If you want to clear your "calculator," use the command **CLEAR**. You can clear a specific variable by **CLEAR variable_name**.

- o **Variables in MATLAB are case sensitive!!!** If you prefer, you could adapt the convention of using lower-case characters for scalars and upper-case characters for vectors and matrices.

- o MATLAB stands for MATRIX LABORATORY; therefore, the basic representation of information is in terms of matrices. A number, or scalar, is a 1x1 matrix. In 2.672, we mostly deal with vectors (e.g., an array of data). Because the software is matrix-based, there can be quite a bit of confusion if you are not careful. For example, if x is a 5x1 matrix (i.e., a column vector of 5 elements), $X*X$ is illegal. On the other hand $X*X'$ (X' stands for the transpose of X) will give you a scalar.

- o You can always click the **HELP** icon to search for information within MATLAB.

BASIC OPERATIONS

- o The **operators +,-,*,/,^** have the usual meaning. (The last one is to raise power.)
 - operation between a scalar (s) and a matrix (A) is straight forward; e.g. $s*A$ means that every element of A is multiply by s .
 - For operations between matrices (vectors are special case of matrices: a row vector of n elements is a $n \times 1$ matrix; a column vector is a $1 \times n$ matrix), you have to be careful that the dimensions match, or you will get error messages.
 - Division means multiplication by the inverse matrix. As such, there are two different symbols: the right division, e.g. $A/B = A*B^{-1}$, and the left division, e.g. $C \setminus D = C^{-1}*D$.
 - In most of the applications, we want to do element-by-element operation. To do this, **precede the operator by a dot**. e.g. If $X=[1,2,3]$ and $Y=[2,4,6]$. Then $X*Y$ is illegal, but $X.*Y=[2,8,18]$. Use $X.^2$ to obtain the square of the elements of X in the above example.

- o **Complex numbers** - Numbers can be complex. When you first start MATLAB, (or after a CLEAR command,) the symbols i and j are given the value of $\sqrt{-1}$. Thus you can enter complex numbers such as $x=4+5*i$. (In this case, because you are entering a pure number instead of an expression, you do not have to use the multiplication sign, thus $x=4+5i$ or $x=4+5j$ are valid.) (Think about applications when you have to do

complex transfer functions.) If you have used i and j for some other things, you can recreate them by setting $i=\text{sqrt}(-1)$ etc.

- o **To access the elements of a vector** - For vector X (does not matter whether it is a column or row vector), $X(n)$ is the n^{th} element of X .
- o **To access the elements of a matrix** - For matrix A , $A(m,n)$ refers to the element in the m^{th} row and the n^{th} column.
- o The **range operator (:)** - It is convenient to be able to refer to a range of elements. The colon symbol does that. e.g. for a vector X , $V=X(3:5)$ is a vector (row or column vector, corresponding to that of X) of length 3, with $V(1)=X(3)$, $V(2)=X(4)$, $V(3)=X(5)$. Similarly for a matrix A , $A(2,7:9)$ refers to the second row, and elements $A(2,7)$, $A(2,8)$, $A(2,9)$.
- o An extremely useful expression is the **range operator without range specification**. Then, it refers to the **whole range**. For example $A(:,3)$ refers to the third column of the matrix A , and $B(2,:)$ refers to the second row of A .
- o There are a lot of other useful operations such as **looping**, **logical test**, etc. which are not described in here. Refer to the manual or the on-line HELP if you need to use them. To learn about looping, type **HELP FOR**; to learn about logic test, type **HELP IF**.

BUILD-IN FUNCTIONS

There are many build-in functions, such as all the standard ones (\sin , \cos , \tan , \exp , sqrt etc.) and many special ones, such as quad (to integrate a function by quadrature). In addition, we have put in several build-in functions for the 2.672 lab, such as **steam_p** (to evaluate the saturated thermodynamic properties of water for an input pressure) and **fitplot** (to fit a polynomial of n^{th} degree to data and plot the data as points and the fit as line). See the MATLAB REFERENCE MANUAL for listing of build-in functions, or click the HELP icon for on-line listing. A short listing of the 2.672 build-in functions can be found at the end of this write-up.

ENTERING NUMBERS BY HAND

- o **Scalar**. Entering a **scalar** is obvious, e.g., $s=5$.
- o **Row Vector**. To enter a **row vector**, start off with the left square bracket and end with the right square bracket. For example, $X=[1,2,3,4,5]$ is a 1×5 vector. If it is a very long vector, use the ... line continuation method.
- o **Column Vector**. To enter a **column vector**, the method is similar to the row vector, except that the elements are separated by semi-colons instead of commas. For example, $Y=[2;4;6;8]$ is a 4×1 vector. Another way to do this is to use the transpose operator; i.e., enter as $Y=[2,4,6,8]'$.
- o **Range Operator**. The **range operator (:)** is very useful for entering numbers. For example: $X=[1:5]$ is the vector $[1,2,3,4,5]$. Even more useful, is the range with increment specification, i.e., **start:increment:end**. For example, $Y=[0:0.2:1]$ is the vector $[0,0.2,0.4,0.6,0.8,1.0]$. The latter construction is very useful if you want to specify a range to calculate a function (e.g., the range of frequency to calculate the transfer function).
- o **Matrix**. Entering the values of the **elements of a matrix** can best be illustrated by an example.

$$X=[1,2,3 \\ 4,5,6]$$

is the 2×3 matrix. Alternatively, you can enter it as $X=[1,2,3;4,5,6]$, with the rows separated by the semicolon. Note that the construction is consistent with that of the row and column vectors.

IMPORTING DATA FILES FROM THE DATA ACQUISITION SYSTEM

In the data acquisition package, choose to **save the data in the matlab format**. Give it a file name, for example xyz (**THE FIRST CHARACTER OF THE FILENAME SHOULD BE NON-NUMERIC**; do not use any extension, because the default extension is **.m**). Then go to the MATLAB window and type in the filename as a command; in this case, it is xyz. The data will be imported. The data will also be plotted. Use the command **whos** to find out what are the data variable names.

Often you want to **pick off values from the plot**. The following command reads off n points on the plot and puts the coordinates into arrays x and y.

[x,y]=ginput(n)

You have to enter a value for n. For example, if you enter [x,y]=ginput(4), a cross-hair will appear on the figure of the plot. Use the mouse to locate the cross-hair on your curve. Clicking the mouse will enter the coordinate of the cross-hair into x and y. Repeat the process four times to finish the command and get four pair of coordinates in the arrays x and y. Note that the process does not terminate until all n points are done. (To kill the process, use **ctl-c**.)

To access the variables in the acquired data, use the function **getdata** which can be downloaded from the 2.672 web page. After you download it to your working directory, type **help getdata** to learn how to use the function.

PLOTTING

The strategy is to create the plot (using auto-scaling) first, and to rescale the axes if necessary, add titles, axes labels etc. later. The plot appears in another window called "Figure 1" (and "Figure 2" etc. if you have more than one plot). **To print the graph**, go to this window and click the **file** icon. See later for option to import the graph to Microsoft Word document.

The **plot** command creates a 2D plot of vectors or matrices. Use **plot(X, Y)** to plot vector X versus vector Y. If X or Y is a matrix, the vector is plotted versus the rows or columns of the matrix, whichever line up.

plot(Y) plots the columns of Y versus their index. If Y is complex, **plot(Y)** is equivalent to **plot(real(Y),imag(Y))**. In all other uses of **plot**, the imaginary part is ignored.

Various line types and plot symbols may be obtained with **plot(X,Y,S)** where S is a character enclosed in '' selecting the plot style as follows:

.	point	-	solid line
o	circle	:	dotted line
x	x-mark	-.	dash-dot line
+	plus	--	dashed line
*	star		

For example, **plot(X,Y,'o')** plots a circle symbol at each data point, and **plot(X,Y,'-')** connects the data points with a solid line.

plot(X1,Y1,S1,X2,Y2,S2,X3,Y3,S3,...) combines the plots defined by the (X,Y,S) triples, where the X's and Y's are vectors or matrices and the S's are strings. X1,Y1,S1 are for the first plot; X2,Y2,S2 are for the second; etc.

Now that you have the plot, you can make it look nice by the following commands:

To **re-scale the axis**, use the command **axis([xmin, xmax, ymin, ymax])**. Note that the [] is necessary because the argument to the function **AXIS** is actually a 1x4 vector. You may use the functions **xlim** and **ylim** to set the x and y axis limits respectively.

To add axes labels and title, use **xlabel('text')**, **ylabel('text')** and **title('text')**.

Use **gtext**('text') to add text any where on the graph. A cross-hair will show up. Use the mouse to move it to position and click.

To create a log-log plot, substitute the command **plot** (...) by **logplot** (...). Similar substitutions are used for **semilogx**, and **semilogy**.

See the manual or use the **HELP** icon for more advance topics such as multiple plots on a page (**SUBPLOT**), overlaid plots (**HOLD**), and freezing the axes scales etc. You can also use the edit manual to make the lines thicker etc.

FITPLOT - Many times, one has to fit a curve to data points. This procedure is done by a 2.672 built-in function.

$C = \text{fitplot}(X, Y, n)$ fits a nth degree polynomial to the data, and plot the data points as circles and the fit as a solid line. The fit coefficients are put in the vector **C** in order of descending powers. For example $C = \text{fitplot}(X, Y, 1)$ would do a linear fit, with $y = C(1)*x + C(2)$.

Often you have to look at the exponential decay coefficient of **y** as a function of **t**. The command:

$C = \text{fitplot}(T, \text{LOG}(Y), 1)$

will do the trick. The decay coefficient is then equal to **C(1)**.

TO IMPORT GRAPHS TO MICROSOFT WORD DOCUMENT

If you want your graph to appear as a picture in the Word document, first create the graph in Matlab, and copy it using the edit menu. Then the graph is copied onto the clipboard as a Window metafile ready to be pasted onto a Word document.

SCRIPT FILES

These are files containing commands that you can recall to reuse again and again. These files have to have the file extension **.m**.

To create them, click the **file** icon, follow by the **new** icon, and then follow by the **M_file** icon. Then the **Matlab editor** will come up, and you can type in your commands. Afterwards hit the **file** icon; follow by the **save as** icon. You'll be asked for the filename etc. Save the file with extension **.m**. After successfully saving what you have typed in the file, the program will return to the editor. Then click the **file** icon again, and click **exit**.

To edit a previous file, click the file icon; follow by the open m file icon. Then the procedure is as in the above.

There are two kinds of script files:

The **command script files**--This is a collection of commands. To invoke them in a **MATLAB** session, type in the filename of the script file (without extension, because the default extension is **.m**). Then all the commands in the file will be inserted and executed.

Hints- (a) It is useful to document your script file with comments. Anything starting with a % symbol is a comment. The comment could either start at the beginning or anywhere in a line.
(b) Usually, you don't want the intermediate results to be displayed. End the commands with ; in the script file.

The **function subroutine script files** - These are files that you can call within a **MATLAB** command as a function. The filename in which the function subroutine is stored must be the same as the function name (i.e., **name** in the following), with the extension **.m**. The first line of these files must be:

FUNCTION **output** = name(**argument1**, **argument2**, ...)

where **output** is the name of the scalar, vector or matrix containing the output of the function evaluation, **name** is the name you give to the function, and **argument1**,... are the arguments passed down from the calling program.

Note that the names given to **output** and all the **arguments** are "dummy variable names"; i.e., you can think of them as if they take on the names of the variables used in the calling program during execution. Note also that all the internal variables are not saved and are released after the functional call.

As an example, the following is the fitplot program in **fitplot.m**.

```
function c=fitplot(x,y,n)
% fit n th degree polynomial to input vectors x,y
% fit coefficients output in c, fit is c(1)*x^n+...+c(n)*x^n+c(n+1)
% then plot the input vector pairs as points and the fit as line
c=[]; %Zero out output vector c
c=polyfit(x,y,n); %Call the built-in function polyfit to do the least square fit
x1=min(x); %Get the minimum and maximum of the input array x
x2=max(x);
xout=[x1:(x2-x1)/99:x2]; %Generate the x and y values for the plot, note that these values
yout=polyval(c,xout); %are not passed back to the calling program, but are released
%after exit
plot(x,y,'o',xout,yout,'-'); %Plot the input data as points and fit values as line
```

INTEGRATION OF ORDINARY DIFFERENTIAL EQUATIONS (ODE)

The steps in integrating ordinary differential equations are: (These steps will be made clearer with an example.)

1. Rewrite the higher order ordinary differential equation as a set of first-order differential equations. This can be easily done by renaming the derivatives as other new variables. Say the variables are y_1, y_2, \dots , and the independent variable is t .
2. Write a function subroutine m file to evaluate the derivatives, i.e., $dy_1/dt, dy_2/dt, \dots$
3. Call the built-in ode solver **ode23** which stands for solving ode by 2nd and 3rd order Runge Kutta method.

The calling format is : **[t,y] = ode23('ydot', [t0,tfinal], y0)**.

t is the output vector containing the independent variable (t) in the course of the integration

y is the solution matrix. Each column corresponds to the components Y_1, Y_2, \dots . The rows are the values evaluated at time points contained in **T**.

ydot is the name of the function m file (i.e. the filename is **ydot.m**) containing the formula for evaluation of the derivatives. Note that ydot is enclosed in quotes. The ydot.m file may look like this:

```
dydt = function ydot(t,Y);
dydt(1) = expression; % which can contain t and components of Y
dydt(2)=..... etc. % In these expressions, dydt are the derivatives of
% y(1),y(2)...Note that dydt must be a column vector
```

t0 is the initial time

tfinal is the final time (the end of the integration)

y0 is the initial condition column vector

The above procedure can best be illustrated with an example. Consider the solution to the mass/spring/damper system released from an initial position x_0 from the equilibrium position. The ode is:

$$m \frac{d^2 x}{dt^2} + b \frac{dx}{dt} + kx = 0$$

with initial condition $x(0)=x_0$ and $dx/dt(0)=0$. (Note that in solving the problem numerically, we have to put in numerical values for the parameters. Let's use $m = 1, b = 2, k = 3, x_0 = 4, t_0 = 0, t_{\text{final}} = 5$ as an example. These values are purely arbitrary here. Note that in real problems, **you have to use a consistent set of units for numerical values.**) The equation can be reduced to two first order ode by defining $v=dx/dt$, then

$$\begin{aligned} dx/dt &= v, \text{ and} \\ dv/dt &= -(bv+kx)/m \end{aligned}$$

To use the ode function, we have to put the equations in vector form. We'll use $y=[x,v]'$ and $dy/dt=[dx/dt, dv/dt]'$. (Note that Matlab requires them to be both column vectors.) Then we write the m file containing the derivative formulae. Let's call it **ydot.m**. (You could call it anything you like, as long as everything is consistent). **ydot.m** would look like the following:

```
function dydt=ydot(t,y); %Note that dydt is a dummy variable to pass back the derivatives values
x=y(1); %It is convenient to copy the components of the vector to scalars with
v=y(2); %meaningful names to make it easier for typing in the formula and
%for debugging

m=1; b=2; k=3; %The equation for the derivatives

dxdt=v;
dvdt=-(b*v+k*x)/m; %In this example, t is not used
dydt(1)=dxdt; %Putting back the derivatives into the vector array of derivatives
dydt(2)=dvdt;
dydt=dydt'; %Rotate the row vector to a column vector for the ode routine
```

Then in the MATLAB main window, use the command:

```
[t,y] = ode23('ydot', [0, 5], [4,0]'); % [0, 5] is [t0, tfinal]; [4,0]' is [x(0), v(0)]'
```

will give you at the time points in the array t, the values of x and v in the first and second column of y.

Note that a ; is used at the end of the command to prevent displaying all the values of the variables in the course of integration.

You could plot the results of each by **plot(t,y(:,1))** for x and **plot(t,y(:,2))** for v. (**plot(t,y)** would plot them both in the same graph, but it is better to plot them individually using the subplot command because in general, they may have very different scales. To get drastically different values on the same graph, rescale them to new variables first)

HINT: Very often, you have to pass values to and from the ode routine. This process can be facilitated by using the **global** command to define global variables. Type help **global** to learn how to use it.

Notes on ode23

The basis for the 'matching' kind of ordinary differential equation solvers such as the **ode23** is as follows. Using the above example, when the initial conditions of the above system are known, the state of the system at every next time step, $x(t+\Delta t)$ and $v(t+\Delta t)$, can be predicted from its current state, $x(t)$, $v(t)$ and their derivatives.

$$\begin{aligned} dx/dt &= v(t) \\ dv/dt &= a(t), \text{ where} \\ a(t) &= -(b(t)*v(t)+k*x(t))/m, \end{aligned}$$

The time-marching solution process can be illustrated by a first-order-accuracy numerical scheme,

$$\begin{aligned} x(t+\Delta t) &= x(t)+v(t)*\Delta t, \text{ and} \\ v(t+\Delta t) &= v(t)+a(t)*\Delta t. \end{aligned}$$

In **ode23**, the above time-marching solution is obtained with a higher order of accuracy. It is based on the second- and third-order Runge-Kutta method. See a numerical analysis text book for detailed description of the algorithm.

LIST OF MATLAB APPLICATION PROGRAMS FOR 2.672 PROJECTS

The following Matlab programs have been prepared for 2.672 projects. These programs can be run in the Matlab main window or be called in script files.

Detailed information about these programs can be obtained in the Matlab main window by entering

***help function name* <return>**

The **m** files for these programs are also available for your personal use via download from the 2.672 web page. You may copy them for your own use outside the lab.

Function Name	Description
fitplot	Fit a n^{th} degree polynomial to the data, plot the data points as circles and the fit a solid line
ginput	Matlab intrinsic function for getting the coordinates of points on a graph with a cursor
getdata	Loads data from the 2.672 chart program to designated variables
pwspect	Transform data from the time domain to the frequency domain, and find an oscillation frequency. The peak location in the power spectrum is printed.
powerfit	Least square fit of data using linear combination of powers. A particular use is to fit a straight line with a forced fit through the origin
steam_p	Calculate the thermophysical properties of saturated water for a given temperature; output saturation pressure and properties
steam_t	Calculate the thermophysical properties of saturated water for a given pressure; output saturation temperature and properties