VU 325.100 Modal Analysis

Course Manual (in development)

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Abstract

The course is part of the module *Mechatonic Systems* in the bachelor's curriculum of mechanical engineering. Based on the example of linear, mechanic, multi degree of freedom systems the concept of modal analysis is explained. The content ranges from the required theory of multi degree of freedom systems: time and frequency domain representation, transfer functions, damping models, eigenvalue problem, and model order reduction by the use of modal coordinates, to the experimental determination of modal parameters of structures.

Contents

1 About this Course

The course focuses on the fundamentals of modal analysis, ranging from the theory of multi degree of freedom systems, over model order reduction to experimental techniques to determine modal parameters of mechanical structures. The course uses a team learning approach described in Section 6.

2 Learning Objectives

Upon completion of the course, students should be able to

- derive the free oscillation eigenvalue problem and interpret its results, i.e. model shapes and natural frequencies, as well as be familiar with the most important numerical solution methods,
- derive reduced order models for multi degree of freedom systems by using an appropriate modal basis,
- conduct harmonic response analyses of full and reduced systems, incorporating different damping methods, and be familiar with the concept of transfer functions.
- Describe the working principles of measurement equipment for experimental modal analysis, and to use such equipment in practice.
- Extract natural frequencies and mode shapes from measurement data by using various identification techniques, as well as compare experimentally determined modes to computational results based on appropriate criteria.

Additionally, students should improve their ability to

- work in teams,
- learn with and from other students, and
- present their findings in a clear and concise. manner

3 Prerequisites

As this course is embedded in the curriculum of *mechanical engineering* certain prerequisites are required. These include

- Basic knowledge in calculus, linear algebra, numerical methods
- Basic understanding of linear multi-degree-of-freedom systems
- Basic knowledge of mechanics

Experience in the Python scripting language is an advantage. Above prerequisites are covered, e.g. in the courses VO 104.299 Mathematics 2, VO 309.020 Mechanics of solid bodies 2, VU 317.530 Fundamentals in Programming, UE 317.516 Numerical Methods in Engineering, and VO 303.009 Measurement and vibration technology.

4 Organisation

The two parts of the course, theoretical basis and experimental application are jointly held by Florian Toth and Johann Wassermann, respectively. The first part of the course is using a *team learning approach* consisting of three learning cycles as detailed in Section 6. The second part of the course consists of lectures and lab experiments.

The final exam will take place at the end of the semester. The date will be announced in TISS.

5 Resources

The course content is contained in several textbooks, e.g. by Ewins [5] and Fu and He [6] which are available via the university library. The lecture notes of Arbenz [1] (available online) give an excellent (and very detailed) overview of solutions strategies for eigenvalue problems.

Slides of the overview lectures will be available via TUWEL after the lectures. Example problems will be distributed as Python code via TUWEL. No dedicated computer resources are provided for this course. The used Python distribution, anaconda (Python 3), is freely available for Windows, MacOS and Linux[1]. Students are encouraged to use their own laptops, however also the computers provided by TU.it around campus can be used. For presentations of pdf slides during workshops a laptop can be provided on request.

6 Teaching and Learning

The course uses a team learning approach similar to the one by Borglund [4]. The objective is to achieve a more natural and creative learning environment leading to a deeper and more long lasting understanding of the content. Additionally, it offers the possibility to develop some soft-skills like presentation techniques, and effective communication and collaboration. Participants will, therefore, be working in teams of 3–4 students. Each team will meet on a regular basis to engage with the course content and master the required tasks.

6.1 Overview Lecture

Each learning cycle will be stared by an overview lecture by Florian Toth. The overview lecture is intended to introduce the subject of the learning cycle. Additionally, the example problems that should be completed in the following teamwork phase are introduced. Attendance at the lecture is not mandatory, but of course recommended.

[1]anaconda by Continuum Analytics, `https://www.continuum.io/downloads`

6.2 Teamwork Phase

The teamwork phase offers the opportunity to discuss the content of the learning cycle, work on the example problems and the theory paper together. Work should be shared equally between team members. The different tasks will require you to, e.g. search for information, write programs, make presentations etc. It is perfectly OK to bring your individual skill into and competencies into the team, as long as everybody contributes in an active and meaningful way. However, you must make sure that everybody can account for most of the work done by the team members.

Each teamwork phase must contain at least one *team meeting* at which all member should be present. A *chairperson* and *secretary* should be appointed for each meeting. You are responsible to make sure that each team member takes up the position of *chairperson* or *secretary* at least once during one of the three meetings. The chairperson is responsible for keeping the meeting on track and to make sure everyone gets a say in the discussion. The secretary must write the minutes of the meeting, and post them in the forum of the TUWEL-course immediately after the meeting. The following can be used as an example:

```
Meeting minutes of 2017/03/12

Team:
The modal hammers

Present:
Burt Rutan (chairperson)
Edith Clarke (secretary)
Arthur Casagrande

Absent:
Julie Payette (recovering from accident)

Main discussion:
At this first meeting we first introduced ourselves to one another, and
briefly shared our experiences of group work. Afterwards, there was a
heated argument about the team name until we could all agree on
'The modal hammers'. We discussed the content of the overview lecture and
could resolve some points not everyone had understood. We then discussed
the distribution of work for the homework exercises and the theory paper.

Main Difficulty:
Where does the discretised system of equations come from?

Main Insight:
There are may ways to arrive at a system of coupled ODEs.

Next meeting:
We decided to have a follow-up meeting before the workshop
where we will:
```

```
- discuss the solution for the example problems 1 & 2 prepared by Burt &
  Arthur
- review the layout of the paper prepared by Edith
```

A lecture room will be available during the lecture time for holding the team meetings. A teacher will be present (on request) to answer questions. Please use this suggested time & location for the meeting.

6.3 Workshop

The learning cycle is concluded by a workshop at which the topic is summarised and discussed. The workshop will be chaired by Florian Toth. Selected team members will be asked to present the solutions to the example problems. The possibly different solutions or solution approaches should be discussed. Additionally, all teams will be asked to present the *main difficulty* and *main insight* encountered during the cycle. When you come to the workshop, please sit down together with your team members.

7 Distribution of Work

Many parts of the course must be completed in a team effort. In order to judge the contribution of each team member a statement *distribution of work* between the team members must be included in each submission. An example is given in the following:

```
Distribution of work for Exercise 1

Burt Rutan (python coding expert) programmed the functions for vector
iteration and Rayleigh quotient iteration.
Julie Payette (good friends with Burt) used Burt's functions to make
convergence studies comparing the different algorithms.
Arthur Casagrande (knew about plate modes) computed the natural
frequencies of the clamped plate and made plots of the mode shapes.
Edith Clarke (queen of power-point) collected the results and compiled
them into a presentation.

All team members participated equally in the discussion of the results
and prepared for the workshop together.
```

It is intended that work is shared between team members. Make sure that every team member can account for most of the work done by other team members (e.g. you can explain what the others did).

8 Grading

The total grade will be computed from the results obtained in the individual parts, theoretical basis and experimental application. The exact weighting of the individual parts

Participation in workshops & teamwork activities (20%) Points obtained at different occasions (workshop 1-5, meeting minutes, questions in class, ...) during the semester will be averaged.

Exercise submissions (40%) Each submission gives a maximum of 8 points.

Final test (40%) Points obtained on the individual written exam amount to a maximum of 40% of the course total.

Figure 1: Distribution of grades between the different parts of the coursework. Percentages of the total grade age given in "()".

is given in Fig. 1. In order to pass the course you must obtain more than 50% of the maximum points.

The individual written exam will be held at the end of the semester. For students missing the exam date due to important reasons (e.g. sickness) a replacement exam will be held in the following semester.

References

[1] Peter Arbenz. Solving Large Scale Eigenvalue Problems. lecture notes, 2016. URL `http://people.inf.ethz.ch/arbenz/ewp/Lnotes/lsevp.pdf`.

[2] Mike Ashby. *How to Write a Paper*. Engineering Department, University of Cambridge, Cambridge, 6 edition, April 2005.

[3] D. Borglund. Robust Eigenvalue Analysis Using the Structured Singular Value: The μ-p Flutter Method. *AIAA Journal*, 46(11):2806–2813, nov 2008.

[4] Dan Borglund. A case study of peer learning in higher aeronautical education. *European Journal of Engineering Education*, 32(1):35–42, 2007.

[5] D. J. Ewins. *Modal testing : theory, practice and application*. JOHN WILEY & SONS INC, 2 edition, 2009.

[6] Zhi-Fang Fu and Jimin He. *Modal Analysis*. BUTTERWORTH HEINEMANN, 2001.

[7] F. Toth and M. Kaltenbacher. Fully coupled linear modelling of incompressible free-surface flow, compressible air and flexible structures. *International Journal for Numerical Methods in Engineering*, 107(11):947–969, 2016.

[8] Florian Toth, Stefan Schoder, and Manfred Kaltenbacher. An infinite mapping layer for deep water waves. volume 17 of *PAMM*, pages 689–690. Wiley-Blackwell, dec 2017.