RESEARCH MASTER IN FLUID DYNAMICS

(former VKI Diploma Course)

(level master after master)

COURSE SYLLABUS

2012- 2013

von Karman Institute for Fluid Dynamics

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TABLE OF CONTENTS

INTRODUCTION

The von Karman Institute for Fluid Dynamics (VKI), founded by Professor Theodore von Karman in 1956, is an international association with the following aims:

- To promote the training of scientists and engineers from the NATO countries in the field of fluid dynamics,
- To contribute to the dissemination of knowledge in the field of fluid dynamics,
- To undertake, to instigate and to promote studies and research in the field of theoretical, experimental and computational fluid dynamics.

The educational and research programs of the Institute are organised within the following areas of specialisation:

- Aeronautics and Aerospace,
- Environmental and Applied Fluid Dynamics,
- Turbomachinery and Propulsion.

The VKI operates a comprehensive range of experimental and computational facilities covering virtually all aspects of the above fields. Necessary support is provided by facility engineers, electronic and photographic laboratories, a computing centre, a technical library, a computer-aided drawing/design office and well-equipped workshops.

One of the main programs offered by the Institute is the one-year post-graduate “Research Master in Fluid Dynamics” at the level “Master after Master” (former VKI Diploma Course). Approximately thirty-five engineers and scientists drawn from ten or more countries attend this program. They are offered a wide selection of specialised courses on various aspects of fluid dynamics and are given the opportunity to perform personal research projects under close guidance by members of the faculty. The projects may be experimental, theoretical, or computational in nature. Thus, the VKI Research Master in Fluid Dynamics Course complements, rather than duplicates, the teaching programs of universities.

This brochure presents pertinent information regarding the VKI Research Master in Fluid Dynamics Course. Admission and diploma requirements are reviewed first. Then the course syllabus for the current academic year is presented. A description of research activities provides an indication of the diverse possibilities for the individual research project. The major facilities available for the research project are described and a list of the faculty members is included.

Further information on the VKI Research Master in Fluid Dynamics Course may be obtained by writing to:

The Director
von Karman Institute for Fluid Dynamics
Chaussée de Waterloo, 72
B - 1640 Rhode-Saint-Genèse
See the VKI on the Internet : http://www.vki.ac.be
or by e-mail : secretariat@vki.ac.be

REGULATIONS OF THE RESEARCH MASTER PROGRAM

Present regulations define the jury, admission conditions, educational organization, evaluation processes, conditions to receive the diploma, relation between staff and students and the way complaints and conflicts will be handled for the Research Master (RM) in Fluid Dynamics at the von Karman Institute. It also describes the organizations involved in Quality Assurance.

Any change/update of the regulations is the prerogative of the Educational Council and must be submitted to the Board of Directors for approval.

Chapter I Admission requirements

Admission to the VKI RM program is decided by the faculty of the department in which the student wants to continue his/her studies on the basis of a file prepared by the student. Admission requirements are:

- A five-year engineering or science degree (3-year B.Sc. + 2-year M.Sc.) from a European university or a M.Sc. from an American, Canadian or Turkish University.
- A working knowledge of the English language. Students that did not obtain their degree from a university with lectures in English have to deliver a proof of having studied in English or an English language test-result from an international organization. There is no test required for students from the European Economical Union (EEU) or students that have successfully followed courses in English of minimum 15 ECTS equivalent. Derogations from these rules can be granted by the heads of departments on the basis of a judgement of the application file.
- Endorsement of the applicant by an RTO National Delegate. Citizenship of one of the NATO countries is imposed by the financing organization. Non-NATO nationals residing in NATO countries will be considered for admission if they are recommended by the RTO National Delegate of their country of residence on the ground that their attendance at VKI would be beneficial to that country.
- Recommendations by 3 professors from a university where the candidate has studied previously.

There is no tuition fee for students from the countries financing the VKI.

Chapter II Study program

The VKI Master after Master program comprises a balanced combination of lectures and individual research. All teaching activities are in English.

Each student will select one of the following areas of specialization offered by VKI: Aeronautics and Aerospace, Environmental and Applied Fluid Dynamics or Turbomachinery and Propulsion department.

The study program and project are defined during a first meeting of the students with the faculty of the department of his/her choice. A minimum total study load of 60.5 ECTS (30.5 ECTS course work and 30 ECTS project) is required. The selection is based on the detailed description of the general and optional courses, defined and made available before the start of each academic year. The student can add optional courses as determined by his or her needs.

The outcome is the definition of the official study program of each student, written down in a document (one copy for the student, one for the supervisor and one for the VKI secretariat). The study program of all students is submitted for approval to the faculty at the first faculty meeting following its definition. Later changes are possible only in function of the project evolution and with the agreement of the complete faculty of the department.

Students who have a job can spread the program over two years. The yearly program is defined in agreement with the Educational Committee taking into account the other (professional) activities of the student. They have to satisfy all requirements in terms of evaluation teams and public presentations.

Except on the days shown as holidays on the calendar, the Institute will be open from Monday to Friday. Normal working hours are from 8.10 to 12.15, and from 13.00 to 16.55. All students are requested to be present at VKI during these hours, unless prior arrangements are made with their supervisor. A detailed schedule for courses and laboratory sessions will be announced before the start of every trimester.

Students may also have access to their desk or to the computer centre during nights, weekends, or other holiday periods. For safety reasons, students are not allowed to be alone in the laboratories outside normal working hours. The presence of at least another researcher or technician is required. Furthermore all safety instructions, given by the VKI Safety Officer and the Laboratory Industrial Engineer must be rigorously respected. Under no circumstances students are authorized to operate large facilities or noise-producing facilities outside the normal working hours.

Chapter III Master thesis

In addition to the courses, each student is required to carry out a Master's Thesis project. It consists of an independent research project. It must exhibit originality and be more than a routine test or computation. Originality is understood to mean a contribution to the field, e.g., the study of a new phenomenon, the interpretation of the results of an experiment, modeling a complex flow, or a significant modification or development of a new computational method or experimental technique. A list of possible projects is published at the start of the academic year. A final selection by the student must be made before October 30.

A full time faculty member will be indicated as supervisor. In some cases, the faculty supervisor will be assisted by a researcher (a post-doctoral researcher, a Ph.D. candidate or a research engineer) working in a field that is related to the student's Master Thesis project. They will assist the student in a more detailed definition of the project, identify problems to solve, define goals, and assists the students in defining the approaches, tools and test cases.

The student should also report on progress at regular intervals as defined by the supervisor, and also report to him unexpected problems. If the student is carrying out an experimental project, the supervisor will organize the contacts with the department's Industrial Engineer, responsible for the technical aspects of the work and for the technical coordination with other VKI services (metal and wood workshops, electronic and photo labs, etc.).

The supervisor is also responsible for the establishment of the Project Evaluation Team (PET) within the first month of the year. In addition to the supervisor, the team will have at least one faculty member from the two other departments. They are selected for their interest in and knowledge of the research subject. The PET supervises the evolution of the project and is the main evaluating body.

Chapter IV Exams

Examinations are organized for each course and will take place between two and three weeks after the last lecture. The examination procedure (oral/written, open book / closed book…) must be announced to the students at the start of the course.

The detailed time schedule of examinations must be announced at least two weeks before the exam takes place. Any changes must be announced sufficiently in advance and take into account the other work load of students and professors.

If for a serious and exceptional reason a student does not participate in an exam, he should contact the examiner who will fix a new date in common agreement. If this agreement cannot be reached the Ombudsperson should be requested to start mediation.

An examiner who, for circumstances beyond his own control, cannot take the exam will inform the Ombudsperson immediately and define a new time table in common agreement with the students involved or organize a written exam on the time scheduled in the original time table.

In case an examiner does not appear within 30 minutes after the fixed time, the student should immediately inform the Ombudsperson who will fix a new time schedule where the preferences of the student have priority.

The examiner can split the evaluation in a formal exam and exercise. The way of examining and the weight of the different components must be communicated to the student at the start of the course.

Test exams may be organized to allow the student familiarizing with the VKI examination technique and criteria. The student has the right to repeat the test exam if he wishes to do so or may request to consider the score as final. In the latter case he will not be examined again on the same content. If partial evaluations of large courses are organized, the final grade will be the average of the partial results weighted by the respective course hours

Within 2 weeks after the exam, the grades must be communicated to the student and to the secretariat, who will store them in a safe place. The secretariat will acknowledge in writing having received the grades. The further handling of the grades is under the supervision of the Dean of Faculty.

Grades of less than 50% are considered unsatisfactory and a repeat exam will be organized within four weeks of the publication of the initial results. The student can do the exam maximum two times and this possibility to repeat an exam replaces the exams that are traditionally organized on September. At this second exam, a maximum mark of only 60% can be awarded. In case the exam consists of different parts with different examiners, this 50% passing rule and the 60% rule applies to the global results of all exams and exercises.

Oral exams are public. The public cannot intervene during the exam. The copies of the written exam can be consulted after being corrected. In critical cases the student or professor may request the presence of a second professor to be indicated by the Dean of Faculty. A professor cannot participate in an exam of a relative up to the forth degree.

Chapter V Master thesis evaluation

A special evaluation procedure is put forward for the Master Thesis project and the general course “Presentation, Reporting and Management”.

At the end of the first trimester, each student will present to the PET a progress report. He will describe his understanding of the problem and proposed solution method, together with a summary of the work already accomplished on the project; i.e. the results of the literature search, time schedule and planning. A thorough discussion with the PET members will help the student to ensure that the proposed solution is realistic and that the pathway to a successful conclusion has been defined.

A second presentation will be made to the PET at the end of the second trimester. Again, a thorough appraisal of the progress will be made including recommendations for future work. A report relative to the literature survey associated with the research project will also be presented. A **“PET bibliography grade”** will be assigned to this report by the faculty members of the PET as part of the course “Presenting, Reporting and Research Management”.

A first public presentation of 15 minutes duration and 5 minutes discussion is made towards the end of March to practice in the art of public speaking; no grade is assigned.

The complete Master Project report (one paper and electronic copy) must be submitted at the date specified at the start of the academic year. The word “complete” means that the text and figures will be as close as possible to a final report. All chapters must be included, but updates to incorporate last minute data or calculations can be made before graduation day.

This report must describe completely the research, including definition of the problem, methodology, results and their uncertainty, their analysis, conclusions and recommendations for future work. It must contain all information necessary to repeat the experiments and calculations in order to reproduce the same results. Therefore it must include a full description of the hardware or software developed during the stay at VKI, if any, and its use. In particular, mechanical drawings of hardware should be included in appendix, or alternatively the VKI Design Office drawing number must be indicated in the text, to fully specify the hardware. These requirements apply only if the same information is not given in a previous VKI report, which has then to be referenced.

A detailed presentation of the project to the PET will be made in mid-June, followed by a full and careful assessment of the work. As a result of the final evaluation session, the team members may propose optional or mandatory changes to the report. The latter concern the language and organization of the report, missing information or further explanations, and must be carried out before graduation day. The PET will assign a **“PET report grade”** based on the quality of the report that has been delivered at the due date. Requested modifications will not results in a change of the **”PET report grade”**.

The PET will also assign a **“PET project grade”** based on the team’s overall assessment of the work during the year, with special consideration of the student’s contribution to the result, The analytical approach, creativity in finding a solution, mastering of the techniques used, understanding of the physics and validation of results are the main evaluation criteria.

The overall grade is the average of the grades given by the faculty members of the PET.

A second public presentation of 20 minutes duration followed by 10 minutes for questions and discussions will be made in late June. A **“Faculty presentation grade”** will be assigned by each member of the faculty together with a **“Faculty project grade”** on the basis of the results presented in the public presentation.

Weighted with the **“PET project grade**” the **“Faculty project grade** defines the final overall project grade. The weight ratio is 23 for the **“PET project grade”** and 7 for the **“Faculty project grade”.**

The **“PET bibliography grade”** and the **“PET report grade”** together with the **“Faculty presentation grade”** will constitute the final grade for the Presentation, Reporting and Research Management (PRM) course (total of 5ECTS). The **“Faculty presentation grade”** and the **“PET report grade”** have both a weight 2 versus a weight of 1 for the “**PET bibliography grade**”. This weighting is illustrated on following Table.

Definition of PRM and Project grades

	Evaluation based on	**PRM grade (ECTS)**	**Proj. grade (ECTS)**
PET Eastern meeting (Faculty members of Ev. Team)	**PET bibliography grade**	1	
PET meeting of June (Faculty members of Ev. Team)	**PET report grade**	2	
	PET project grade		23
Public presentation June (All faculty members)	**Faculty presentation grade**	2	
	Faculty project grade		7
	TOTAL	**5**	**30**

Deliberations of the PET are confidential. Only the results and conclusions are communicated to the student. The supervisor is encouraged to communicate to the students the arguments that have lead to the grading without revealing the secret of the deliberation.

The dates of the evaluation meetings and public presentations of the Master Thesis are fixed at the start of each trimester.

If because of circumstances beyond the student's control (sickness, major equipment failure or non availability of important equipment) the project cannot be finished within the schedule, the jury may agree to postpone the deadlines for the report and presentations.

Chapter VI Complaints

The student can within a period of five days after the exam took place or the results have been communicated to the student complain in writing to the Ombudsperson about any irregularity in the way the courses are given or the exam has been organized. Only complaints relating to not respecting the administrative rules described in the student information booklet or to an erroneous transmission of the information to the secretariat are receivable. The quote that was given to the student by the examiner or decision taken by the Project Evaluation Team can not be the object of a complaint. The examiner will be available during five days following the announcement of the results for explanations about the grade and to discuss any possible material errors in the communication or transmission of results.

The Ombudsperson will examine the complaint together with the official student representative and they will communicate their decision in writing to the student within 5 days after receiving the complaint. In conflicts of larger importance or when the student does not agree with the decision of the Ombudsperson, the problem will be presented to the whole faculty at the next faculty meeting. After gaining advice of an independent external expert in educational matters and hearing of the student, the faculty will take a motivated decision and communicate it to the student.

The same procedure applies for matters related to the master thesis (i.e decisions of the PET)

The Ombudsperson is nominated at the start of the academic year for a one year period by the educational committee. The name, telephone number and Email address of the Ombudsperson are during the whole year announced ad valves and on the Intranet. He handles all complaints on educational matters. He negotiates a settlement by agreement between all parties involved and communicates it to the Educational Committee.

The ombudsperson has access to all information related to education and will be consulted when modifying present regulations. He/she must respect the confidential character of the information he receives and is obliged to discretion.

Chapter VII Jury

The jury is composed of all the full time faculty members and is presided by the Dean of Faculty. The Dean can be replaced by a faculty member for some specific matters. The youngest faculty member present is the secretary of the jury.

The jury can take valid decisions if a minimum of 60% of the faculty members are present. Faculty members that are absent cannot be replaced. The decisions of the jury are adopted by a majority of the votes cast. Each member of the jury has one vote. The jury can define additional rules if it feels needed.

The jury verifies that the student satisfies all legal conditions and those defined by the regulations, and that the study load is in agreement with the required number of ECTS in the student's study program. The diploma "Master after Master" will be awarded on the basis of the results of the exams.

A professor cannot participate in the deliberation of a relative up to the forth degree.

Deliberations and votes of the jury are confidential. Only the results and conclusions are made public.

Chapter VIII Diploma

The diploma will be awarded to the student who obtained a grade of 50% or higher in each course of his study program and achieved an average result of 60% or more in both the course work and the research project. The overall course grade is the average of the individual course grades weighted by the corresponding ECTS. The overall grade for the year is a weighted average of the course work and the research project in proportion to the respective ECTS.

Students that did not obtain a grade above 50% in all courses will be the object of a deliberation and vote by the jury. A majority of 60% of the votes cast is required to attribute the diploma in those cases.

The secretariat provides the detailed results of all the exams and Master Thesis evaluation and the averaged values to the members of the jury in form that facilitates the deliberation. The averages are weighted by the corresponding ECTS. Students not satisfying the diploma requirements mentioned before are highlighted.

Students with results of 80% or more in each category (courses and project) will receive the diploma with honors. The jury may in exceptional cases deviate from this rule if a small shortcoming on courses is compensated by a high grade for the project. Such a decision requires a more than two thirds majority of the votes and must be motivated. The top two students will be awarded the von Karman Prize and the Belgian Government Prize, respectively. Recognition can also be made for excellence in experimental and numerical work (these prizes cannot be cumulated with the von Karman or Belgian Government prize), and for excellence in project presentation.

The decisions of the jury are final and announced ad valves.

Each student receives a copy of a summary sheet listing all course and Master Thesis project grades; this sheet is referred to as a “transcript of grades”. The results of the deliberation are written in the official VKI register of diplomas and signed by all the members of the jury.

Complaints related to erroneous transmission of results or erroneous calculations can be considered if received before the official diploma ceremony. Any correction requires a decision of the jury.

Complaints related to a non-respect of the regulations must be submitted to the Ombudsperson within a period of five days after the decision of the jury has been communicated. In cases where the Ombudsperson considers the complaint justified and of sufficient importance, he can call for a new meeting of the jury to reconsider the decision. The latter will be officially communicated to the student.

Chapter IX Fraud

Fraud must be reported together with any available proof to the Dean of Faculty as soon as it is detected. The student will be interrogated by the members of the Educational Committee in presence of the Ombudsperson and the examiner. The student will have the possibility to be assisted by a third person for his defense. The Educational Committee will communicate its conclusions in a written report to the jury and to the student. The student has the right to continue the exams during this period.

Based on this report the jury will take a decision. If detected before the deliberation the jury may refuse the student of further participation in the educational program. If detected after the deliberation the jury may take correcting measures on previous decision concerning the diploma.

Chapter X Class Representative

The VKI encourages the students to select a representative to facilitate the planning of social activities (particularly those taking place at the VKI or under the sponsorship of the VKI) as well as to provide a formal mechanism by which problems may be brought to the attention of the Direction and the Ombudsperson in order to improve the quality of life at the VKI. This representative will be member of the Educational Committee and as such have the possibility to discuss policies, which may improve the educational.

There is also a representative per department who reports to the Heads of department about any problem related to the department.

Chapter XI Quality Assurance

Internal quality assurance

The education at VKI is subject to several systematic evaluations. Besides the permanent concern of the faculty about educational quality, there are also following organizations for a more structured monitoring of the quality of the education provided at VKI.

The Educational committee is responsible for the active promotion of teaching competences within the VKI and makes a systematic evaluation of the quality of the teaching activities. The purpose is an optimization of the education process by measuring the student's perception about the quality of the education. Participation in these evaluations is mandatory for the VKI students. Specific criteria are: quality of lecturing, availability and quality of didactic material, evaluation method, respect of course and examination schedule, supervision of Master Thesis Project. The committee organizes remediation when educational problems are detected.

The Educational Council is the main responsible for the educational program at the von Karman Institute. More specifically:

- it defines a long term vision on education and research,
- defines the curriculum of the study and verifies the load,
- updates the rules for the examination,
- makes proposals about major new investments in equipment.

The Educational Council is composed of the VKI faculty members, representatives of the VKI students and alumni, and representatives of the administration and industry with activities related to fluid dynamics. The external members are selected on the basis of their experience and knowledge of the field.

The Educational Council is organized in three sections, corresponding to the three departments. Each of them is responsible for the educational matters that are specific for the respective departments. The meeting of the sections is normally followed by a plenary session of the complete Educational Council for matters concerning the whole institute as there are common and optional courses, course load, evaluation procedures, etc.

A more detailed description of the responsibilities and activities of the Educational Council and Educational Committee are provided in the document **"Internal Quality Assurance at VKI"**

External quality assurance

Following are independent organizations evaluating the VKI performance in terms of education and research

The Technical Advisory Committee (TAC), composed of senior professors and heads of large research centres is established by NATO-RTO was formed at the invitation of the NATO Council (C-R (83) 30 dated 25 July 1983) to make a yearly assessment of the importance for NATO and NATO countries of the von Karman Institute's activities conducted in accordance with its Charter. At this occasion the VKI management and faculty members present the results of the past activities, the new orientations in research, a five year development and investment plan and the expected impact on the VKI educational programs. The outcome is an evaluation report to NATO.

The NATO Ad Hoc Committee, composed of representative of the ambassadors at NATO, evaluates the VKI activities in terms of education, research and service to the financing countries on the basis of an extensive report of activities. The committee makes recommendations to the financing countries.

The VKI Research Master in Fluid Dynamics has been accredited as a Master after Master program by the NVAO.

FINANCIAL ASPECTS

TUITION FEES

Tuition is free for citizens of the following NATO countries which contribute to the operating budget of the VKI:

Belgium	Iceland	Spain
Czech Republic	Italy	Turkey
France	Luxembourg	
Germany	Norway	
Hungary	Portugal	

as well as for citizens of the nine new NATO countries : Albania, Bulgaria, Croatia, Estonia, Latvia, Lithuania, Slovakia, Slovenia and Romania.

Information on tuition fees applicable to citizens of other countries may be obtained by writing to the Director.

COST- OF- LIVING FELLOWSHIP

Grants are available to citizens of the above-listed countries who have been accepted to the Research Master in Fluid Dynamics and have demonstrated no other means of support.

COURSE PROGRAM 2012-2013

Attendees to the VKI Research Master in Fluid Dynamics Course follow a series of lectures entitled "Theoretical and Experimental Fluid Dynamics" described on the next pages and then make a selection among the three areas of specialisation shown in Figure 1. Further specialisation in certain fields is also possible. The final program of courses for each attendee is formulated, following discussions with the supervisor.

An essential aspect of the VKI Research Master in Fluid Dynamics Course is the independent research project.

The detailed program is presented on the next pages.

1. GENERAL COURSES

DIFFERENTIAL EQUATIONS OF FLUID DYNAMICS (DEFM - 1.25 ECTS)
J.-M. BUCHLIN

This is a formal course, organized as a refresher to assure that all students have the basic knowledge to follow the other courses.

Learning objectives
Students should master the basic laws of fluid dynamics valid for all applications i.e. the universal conservation equations, stress tensor and heat flux vector, the Newton-Navier viscous stresses, the Fourier law and their range of validity.
The relative importance of the different terms in the Navier-Stokes equations, their mathematical properties and impact of boundary conditions should be understood.
The shortcomings of the limiting cases (incompressible, inviscid flows, Stokes flow, flows with low viscosity, unsteady flows) should be known.
The student should also master the use of the similarity parameters (Strouhal, Mach, Reynolds, Prandtl numbers, etc.) and understand their limitations.

Course notes
- A Review of the Differential Equations of Fluid Dynamics, J.M. Buchlin, VKI-CN 195.

Literature
- Bibliography in VKI-CN 195.

Evaluation
The learning outcome is verified by a written (open book) exam. Criteria are the understanding of the basic equations and the capacity to apply them in practical cases. Memorization of the equations is not required and the VKI-CN-195 can be used to copy complex equations if needed.

INTRODUCTION TO MEASUREMENT TECHNIQUES IN FLUID DYNAMICS (IMT - 2.5 ECTS)
FACULTY

The course, mandatory to both numerical and experimental options, consists of lectures (70%) and “hands-on” laboratory sessions (30%) and provides an insight into different fundamental measurement techniques for fluid dynamics. Each technique is presented by a faculty member who is experienced in it.

Learning objectives
At the end of this course students should be able to select the appropriate measurement technique (Pressure probes and transducers, temperature measurements inclusive infrared thermography, Laser velocimetry and optical density and spectroscopic measurement techniques, hot wire anemometry, flow visualization) to solve a given experimental problem. He/she should be able to implement the technique, understand its limitations and be able to estimate its accuracy.

Course notes
- Measurement Techniques in Fluid Dynamics – An Introduction, Third revised edition, VKI, 1991, 383 pgs.

Literature
Extended bibliography in Course notes.

Evaluation
The objectives are verified by a single open book exam organized by the course responsible based upon the questions he receives from the other lecturers. The student has to propose a solution for some practical measurement problems within a limited amount of time. The open book evaluation technique is selected because it is the closest to the real world application where the scientist has to select and apply the most appropriate technique to solve a problem.
Evaluation criteria are the student's ability to select the best technique, to define the measurement chain and corresponding data processing procedure, to provide a critical evaluation of the application limits and a correct estimation of the accuracy. The weighting of the questions is proportional with the number of lecture hours for each part and indicated on the questions.

PRESENTING, REPORTING AND RESEARCH MANAGEMENT

(PRM – 5.0 ECTS)
FACULTY

This course intends to teach the skills that are needed for a successful completion of research projects in the domain of fluid dynamics and is considered as one of the specificities of the VKI training program.

Learning objectives
The learning outcome of this course is :

- the methodology to conduct research, in particular the techniques and skills that are required for the problem definition, the preparation of research proposals, planning and budgeting, time management, how to keep track of end-goals and progress of the project.
- the methodology for the selection of instrumentation or numerical techniques and test facilities, safety, product and quality assurance.
- the skills for reporting and presentation of results.

Students should also understand techniques for project breakdown, the organization and conduct of project reviews, the risk and documentation management.
Students should be able to talk about the field of specialization of the project in a multidisciplinary working-environment. They should be able to function as a member of an international team working on a large projects or complex facility. They should master the technical and scientific terminology in their field of specialization and be able to report on technical or scientific subjects orally, in writing and in graphics.

Course notes

- Quality Assurance – An introduction, B. Delcourt, (PowerPoint slides)
- Quality Assurance – Concepts, B. Delcourt, (PowerPoint slides)
- Managing Product Assurance, B. Delcourt, (PowerPoint slides)
- Project Management and Planning, M. Carbonaro, (PowerPoint slides)
- Selected examples using computerized Project Management Tools, M. Carbonaro, (PowerPoint slides & live demo)
- Bibliographical search (PowerPoint slides by M. Riethmuller)
- Reporting and Presenting (PowerPoint slides by M. Riethmuller)
- Manuals of reporting.

Literature

- On line tutorials by Microsoft and Open Proj.
- Getting the Message Across, in SCIENTIAE, April/June 1979, pgs. 16-22
- A Guide to Presenting Technical Information Effective Graphic Communication, Matthews, Clifford, John Wiley & Sons, June 2000
- Webb sites indicated on the PowerPoint slides.

Evaluation

The evaluation is done by the Project Evaluation Team composed of minimum 3 professors (at least one of each department), measuring how the theory has been applied in the Master Thesis project. It is based on a bibliographic report prepared by the student about his research topic.
Criteria are the quality of the project definition, planning and execution discussed during 3 meetings at different steps of the project. Other criteria are the quality of the written project report (content and clarity of reporting).
The skills of presenting the results are evaluated during 2 public presentations to the total faculty and fellow students.

Students following a **numerical option** follow also:

NUMERICAL METHODS IN FLUID DYNAMICS (NMFD – 4.25 ECTS)
H. DECONINCK

This course consists of two parts: one at introductory level (NMFD1) and one at advanced level (NMFD2). The reason for splitting the course into two parts is as follows: the first part is mandatory for all students having selected the numerical option, while the second part is mandatory for the students of the AR and TU department who follow the numerical option, but not for the EA students. Indeed, the second part (NMFD2) has a strong component oriented towards hyperbolic conservation laws (essential for compressible flow) and is therefore less important for students of the EA department because they are mostly interested in incompressible flows.

Learning objectives

NMFD1 **(**NMFD1 – 1.25 ECTS)
H. DECONINCK

The first part (NMFD1) has similar objectives as the “Introduction to Computational Fluid Dynamics Lecture Series” but is oriented towards students that will make a numerical project, hence it is more oriented towards future development of CFD methods rather than the application of CFD codes and using existing CFD tools. Hence, this course aims to give the broad view that prepares for making the best choice of algorithms and methods to accomplish a specific flow simulation and prepares the student for a more specialized numerical study (either independently or in other CFD courses, or by following NMFD2).
At the end of NMFD1 the student should have an understanding of the basic principles of Computational Fluid Dynamics (CFD), how the equations for incompressible and compressible flows (introduced in previous mandatory course DEFM) are numerically modeled and how the different formulations (implicit/explicit) influence accuracy and stability. He/she should know the fundamental differences between convection/propagation and diffusion with respect to their numerical treatment. He/she will understand the principles of discretization methods based on functional (Finite Elements, Spectral methods) and pointwise or cell-averaged (Finite Differences, Finite Volumes) representation of the discrete solution. He/she will acquire a global view on the formulations used to obtain the discrete system of equations like strong differential form (for finite differences), weak formulation, integral conservation law, method of weighted residuals (for finite elements) and the consequences for boundary conditions (weak, strong).
He/she will understand the concepts of consistency, stability and convergence of discrete solutons, linked by the Lax-Wendroff theorem and master the stability theory for the Method of Lines (stability of Ordinary Differential Equations in time obtained after semi-discretization in space). Finally he will learn the particularities of the treatment of incompressible flow with respect to the solenoidal constraint for the velocity and pressure stabilization (by staggered grid formulation or using different finite element spaces for velocity and pressure).

NMFD2 (NMFD2 – 3.0 ECTS)
H. DECONINCK

The second part is a natural continuation of the first part, but goes much more in detail. At the end of the course the student should be able to follow the global CFD literature, choose an algorithm and develop independently a CFD method for a particular application. The following objectives should be reached for a successful completion of this course:

- master the theory of Partial Differential Equations, including the classification of PDEs based on the theory of characteristics. Master the specific properties of hyperbolic, elliptic and parabolic equations and the link with initial versus boundary value problem and diffusion versus propagation. Understand the concept of well-posedness with respect to boundary and initial conditions (Hadamard). Have a detailed understanding of the theory of hyperbolic conservation laws including weak solutions, jump relations, concept of mathematical entropy condition, boundary conditions.
- know the main discretization techniques based on finite difference, finite volume, finite element and spectral methods, including a discussion of the relationship between the various methods.
- have a deep understanding of the concepts of consistency, stability and convergence, stability theory (von Neumann analysis), Lax-Wendroff theorem, equivalent differential equation of a scheme, concepts of artificial dissipation and upwinding and the relation between both.
- master the principles of monotone schemes for hyperbolic conservation laws based of TVD and positivity (LED) conditions.
- be familiar with the classical finite difference and stabilized finite element schemes (SUPG, GLS) for hyperbolic and parabolic problems. Be familiar with classical time integration schemes (explicit and implicit) and their stability properties.
- have a good understanding of the boundary value problems, with emphasis on iterative methods for solving linear systems, including relaxation methods (SOR, Gauss-Seidel), conjugategradient like (Krylov subspace) methods and multigrid methods.

Course notes

- Introduction to CFD, G. Degrez, VKI-CN 153
- Overview of Grid generation Methods, H. Deconinck, VKI-CN 146
- Numerical Techniques for Solving Partial Differential Equations, H. Deconinck, VKI-CN 142
- Numerical Methods in Fluid Dynamics 2, Exercises, H. Deconinck, VKI-CN 182
- Numerical Methods in Fluid Dynamics 2, Solutions to exercises, H. Deconinck, VKI-CN 183.

Literature

- Numerical Solution of Time-Dependent Advection-.Diffusion-Reaction Equations, W. Hundsdorf and J.G. Verwer, Springer Series in Computational Mathematics, 2003.
- Fundamentals of Computational Fluid Dynamics, Springer Verlag H. Lomax Thomas H. Pulliam David W. Zingg.
- Difference Methods for Initial-Value Problems, Robert D. Richtmyer, K. W. Morton.
- Numerical Computation of Internal and External Flows, Ch. Hirsch,Butterworth-Heinemann.
- Numerical Methods for Conservation Laws (Paperback), Randall J. LeVeque, Birkhauser.
- Finite Element Methods for Flow Problems, J Donea, Antonio Huerta, John Wiley.

Evaluation

Evaluation of the first part (NMFD1) is by a written exam in 2 parts: a closed book exam with questions about theory (weight 50%) and an open book exam with practical exercises (weight 50%) (4 hours in total).
The evaluation of the second part (NMFD2) is made by a written open book exam consisting of exercises which require both a good understanding of the theory and the capacity to set up, analyze and solve a CFD problem.

2. SPECIALIZATION IN AERONAUTICS/AEROSPACE

The aim of this series of courses is to provide the student with an overall appreciation of the role of aerodynamics in aeronautics/aerospace, as well as providing the required background to study a particular topic in greater depth. The common part of the program is designed to achieve the first objective. It comprises courses devoted to some areas of flight dynamics as well as courses dealing with the theory of inviscid and viscous flows for the different speed regimes. At the end of these courses, the attendee should be aware of the problems and methods encountered in aeronautical aerodynamics and re-entry aerothermodynamics. He should also understand the compromises and trade-offs that are necessary for any aircraft, missile or spacecraft design. After completion of this general program, the attendee can select more specialized courses in either high speed or low speed aerodynamics within the experimental or numerical approach.

Students with a good background in aeronautics may replace one or more of the general course by some optional courses.

2.1 General Courses in Aeronautics/Aerospace

AIRCRAFT PERFORMANCE, STABILITY AND CONTROL

(APSC - 2.0 ECTS)
M. CARBONARO

The course consists of formal lectures on flight mechanics, but also includes computerized demonstrations and exercises.

Learning objectives

At the end of this course students should have a good knowledge of the basic concepts of flight mechanics such as: lift and drag characteristics of airborne vehicles, their relation to the power required for flight and general performance for horizontal, climbing, gliding or accelerated flight.
The student should be able to predict the velocity-flight envelope of a propeller-driven and of a jet-driven aircraft, as well as ceilings, climb rate, range and endurance. The student should also be able to understand and explain aspects of maneuvering performance and of aircraft stability and control.

Course notes

- Introduction to Aircraft Performance, Stability and Control, M. Carbonaro, (PowerPoint slides).

Literature

- Introduction to Flight, John Anderson, McGraw-Hill Science/Engineering/Math; 6th edition, October 25, 2007.
- Theory of Wing Sections: Including a Summary of Airfoil Data, Ira H. Abbott and A. E. von Doenhoff, Dover Publications, 31. December 1960.

Evaluation

The exam is based on an individual open book design problem or exercise consisting of predicting performances of a given aircraft, followed by a closed book written exam based on a list of 28 questions covering all the course subjects. (weight is 50% for each).

INVISCID AERODYNAMICS IN AERONAUTICS

(IAAI - 4 ECTS)
B. BOTTIN

This course is oriented towards the students without background in classical aerodynamics.
There are two parts, one covering incompressible and one covering compressible flow. At the end of these courses the student should understand the physics of incompressible and compressible flows and be capable of using these theories in the interpretation of wind tunnel experiments or CFD simulations. Depending on the students background he may be dispensed of following one or both parts of the basic course. In that case he should select optional courses in agreement with the faculty of the AR department.

A. INCOMPRESSIBLE INVISCID FLOWS

(IAAI - 2.5 ECTS)
B. BOTTIN

This tutorial course gives insight into the characteristics of lifting airfoils in two-dimensional flows.

Learning objectives

The student should have a firm physical understanding of the methodology used for incompressible flow analyses (superposition principle, the relation between circulation and lift).
The student should also understand the limitations and possibilities of linearized theories for thin airfoils and three dimensional wings. He/she should be able to use these methods to solve typical problems encountered during the design phase of aerodynamic surfaces. A good understanding of the underlying principles of numerical panel methods for wing sections (2D and 3D) and the ability to use state of the art software to analyze practical cases is also required.

Course notes

- Inviscid Aerodynamics in Aeronautics / Incompressible Case (partial notes), B. Bottin, VKICN 173

Literature

- *Theoretical aerodynamics*. Milne-Thomson, L.M., Mc-Millan, 1948. Also Dover, New York, 1973. {VKI reference number: 08.126}
- *Hydrodynamics in theory and application*. Robertson, J.M., Prentice-Hall, Englewood Cliffs, 1965. {VKI reference number: 08.311}
- *Fundamentals of aerodynamics*. Anderson, J.D.Jr., 3rd Edition. McGraw-Hill, New York, 2001. {VKI reference number: 08.456}
- A. *Low-speed aerodynamics from wing theory to panel methods*. 2nd Edition. Katz, J. & Plotkin, Cambridge University Press, Cambridge, 2001. {VKI reference number: 08.624}

Evaluation

The evaluation consists of two open book exercises and an oral interview. The former allows verifying that the student is capable of applying the techniques, the latter allows verifying that the student has understood the theoretical basis and its limitations.
The first exercise is a mid-course homework (weighting 4/20). The final evaluation is based on the individual solution of a complete problem (open book) by the student and an oral interview about the proposed solution (weighting 16/20).
The total weight of this first incompressible part is 62%.

B. COMPRESSIBLE INVISCID FLOWS (IAAC - 1.5 ECTS)
H. DECONINCK
T. MAGIN

Learning objectives
At the end of the course the student should master the classical theory of compressible flow including oblique shock theory, Prandtl-Meyer expansion theory, numerical method of characteristics (MOC), shock/expansion method, and small disturbance theory applied to supersonic wing and slender bodies. He/she should be able to apply this uderstanding in the practice of external aerodynamical engineering: for example to interprete physical data (e.g. Schlieren pictures from a supersonic wind tunnel or iso-plots from CFD, or to carry out a simple design of a supersonic nozzle, or to estimate the lift and drag of a supersonic wing.

Course notes
- Inviscid Compressible Aerodynamics, G. Degrez, IVK-CN 145.

Literature
- Gas Dynamics, Maurice Joseph Zucrow, Joe D. Hoffman
- Compressible Fluid Dynamics, Philip A. Thompson
- Supersonic Flow and Shock Waves (Applied Mathematical Sciences)
  Richard Courant, K.O. Friedrichs.

Evaluation
The exam consists of oral questions about the theory and a small exercise/project (e.g. using the MOC to design a 2D nozzle). The ratio is 2/3 for the theoretical questions (1.0 ECTS) and 1/3 for the exercise (0.5 ECTS) giving in total 1.5 ECTS.

TWO DIMENTIONAL BOUNDARY LAYERS (2DBL – 4.0 ECTS)
G. DEGREZ

The detailed description is given in the section **Optional Courses for all departments**.

The attendees to the Aeronautics/Aerospace program will specialize in one of the following two subgroups :

- **Experimental option**
- **Numerical option**

2.2 Courses Experimental Option

LOW SPEED WIND TUNNELS ANALYSIS AND DESIGN (WTAD - 1 ECTS)
B. BOTTIN

The detailed description is given in the section **Optional Courses for all departments**.

COMPUTATIONAL FLUID DYNAMICS LABORATORY (CFD Lab-1.5 ECTS)
P. RAMBAUD

The purpose of this activity is to acquaint experimentalists with the basic use of CFD tools for investigating fluid flow problems.

Learning objectives
Students should be able to compute a simple flow (e.g. one of the flows investigated experimentally in the measurement technique labs) using either by an in-house or a commercial CFD package. Issues to become familiar with include amongst other: the influence of the discretization scheme on the computational results, the iterative convergence and grid sesitivity.

Course notes
Not applicable

Literature
- Computational fluid dynamics - An introduction, edited by Wendt, J.F., ed. Springer, 3rd edition, 2009, isbn-13 978-3-540-85055-7, A von Karman Institute Book.

Evaluation
Evaluations are based on a written report, presenting/discussing the simulation results of the ERCOFTAC database test cases. Criteria are the student's capability: to define the calculation domain and the quality of the grid, to generate the correct boundary conditions based on available data, to evaluate the influence of the RANS one and two equation turbulence models and wall treatments, to investigate the influence of the order of numerical discretization and grid refinement (grid dependency) on convergence and accuracy, to evaluate, acceleration techniques and convergence criteria.

INTRODUCTION TO COMPUTATIONAL FLUID DYNAMICS LS
(ICFD - 1.25 ECTS)

The detailed description is given in the section **Optional Courses for all departments**.

<u>ADVANCED MEASUREMENT TECHNIQUES LABORATORIES</u>

(MT Labs 1.5 – 6.0 ECTS)

Detailed description is given in the section **Optional Courses for all departments.** Students following the experimental option have to choose all four sections of this course.

2.3 <u>Courses Numerical Option</u>

<u>NUMERICAL METHODS IN FLUID DYNAMICS, PART 2</u> (NMFD2 - 3 ECTS)

H. DECONINCK

The detailed description is given in the section **General Courses.**

<u>COMPUTATIONAL METHODS FOR COMPRESSIBLE FLOWS</u>

(CMCF – 4.0 ECTS)

Both parts of this course, theory and Lab sessions, are mandatory for the numerical option in Aeronautics and aerospace, and fully described in the **Optional Courses for all departments**.

<u>ADVANCED MEASUREMENT TECHNIQUES LABORATORIES</u>

(MT Labs 1.5 – 6.0 ECTS)

Detailed description is given in the section **Optional Courses for all departments.** Students following the numerical option have to choose minimum one of the four sections of this course.

2.4 <u>Optional Courses in Aeronautics/Aerospace</u>

Students should take an equivalent of minimum 2 ECTS of following optional courses, depending on the project.

A. <u>For all options</u>

<u>PHYSICAL GAS DYNAMICS</u> (PHYSGD – 4 ECTS)

T. MAGIN/ D. GIORDANO

The detailed description is given in the section **Optional Courses for all departments.**

<u>BOUNDARY LAYERS AND FLOW SEPARATION IN THREE DIMENSIONS</u>

(3DBL - 1.25 ECTS)

G. DEGREZ

The detailed description is given in the section **Optional Courses for all departments.**

INTRODUCTION TO AEROACOUSTICS (ACOUS - 1 ECTS)

C. SCHRAM

The detailed description is given in the section **Optional Courses for all departments**.

TRANSONIC AERODYNAMICS (TRANS - 1 ECTS)

O.CHAZOT

This is a basic course on the typical features of transonic flows.

Learning objectives

After successful completion of this course the students should be aware of the specific problems of transonic flows over airfoils and bodies and master the transonic small disturbance technique and similarity rules, as well as the solution techniques for the transonic full potential and small disturbance equations. They should also understand the conditions for shock-free supercritical flows, law of stabilization around M = 1 and specificities of the drag at transonic speeds.

Course notes

- Elements of Transonic Aerodynamics G. Degrez, VKI-CN 194.
- Hand written notes by O. Chazot

Literature

- Elements of Gasdynamics, H.W. Liepmann and A. Roshko, GALCIT Aeronautical series, John Wiley, 1957.
- Bibliography of VKI-CN 194.

Evaluation

Evaluation consists of a (closed book) written exam measuring the understanding of typical transonic flow problems. The evaluation criteria are the correct description of basic transonic flow phenomenology by reading Schlieren pictures and the understanding of theoretical results together with classical applications.

HYPERSONIC AERODYNAMICS (HYP - 2 ECTS)

O. CHAZOT

This course describes the main features of hypersonic flows and aerothermodynamics. It will be merged with the PWT course starting from the academic year 2010-2011.

Learning objectives

The objective of this course is to assure that the student has a good understanding of the specificities of inviscid and viscous hypersonic flows such as: Newtonian flow, shock expansion, tangent wedge and tangent cone, similarity rules, small disturbance theory, and strong and weak viscous interactions. The student must have a good insight into the physics of the hypersonic boundary layers and the consequences of the high temperature (i.e. dissociation, nonequilibrium, etc.). He/she should also be familiar with the classical hypersonic literature, be able to select the appropriate experimental techniques and capable to interpret the results of high enthalpy flow experiments.

Course notes

- Hypersonic Aerodynamics, R. Korkegi VKI-CN 9
- Fundamentals of Hypersonic Flow – Aerothermodynamics, D. Fletcher, VKI CN 190
- Hand written notes, O. Chazot.

Literature

- Hypersonic and High temperature gasdynamics, Anderson J.D., MCGraw-Hill, 1989.
- Introduction to physical Gasdynamics, W.G. Vincenti & C.H. Kruger, John Wiley and sons, 1965.

Evaluation

A closed book oral exam (weight 50%) evaluates the understanding of the basic hypersonic theory. The second part of the evaluation is based on a three page synthesis report including comments about a reference publication in hypersonic aerothermodynamics selected from a list provided at the end of the course period. Evaluation criteria are the understanding of major features of hypersonic flow, the competence to develop ground testing strategies and to extrapolate the measurements to real reentry flows.

B. For the Experimental option

DESIGN AND OPERATION OF PLASMA WIND TUNNELS (PWT – 1.0 ECTS)

The detailed description is given in the section **Optional Courses for all departments**.

LOW SPEED WIND TUNNEL TEST TECHNIQUES (WTTT - 1 ECTS)

B. BOTTIN
M. CARBONARO

The detailed description is given in the section **Optional Courses for all departments**.

DATA ACQUISITION AND PROCESSING (DAP - 2 ECTS)

G. PANIAGUA
P. RAMBAUD
C. SCHRAM

The detailed description is given in the section **Optional Courses for all departments**.

C. For the Numerical option

COMPUTATIONAL METHODS FOR COMPRESSIBLE FLOWS

(CMCF - 1.5 to 4 ECTS)

H. DECONINCK
T. MAGIN

A full description of this course is given in the **Optional Courses for all departments.**

3. SPECIALIZATION IN ENVIRONMENTAL AND APPLIED FLUID DYNAMICS

The objective of these lectures is to train attendees in handling and solving the wide variety of problems that may occur in environmental and industrial fluid dynamics. The main objective is to acquire a good insight into both fundamental and applied fluid dynamics. The teaching is closely related to the research activities carried out by staff members of the Department.

Each course member will make a selection with his supervisor among the courses below in function of his/her project.

3.1 General courses in Environmental and Applied Fluid Dynamics

METHODOLOGY OF APPLIED FLUID DYNAMICS (MAFD - 5 ECTS)
EA FACULTY

The objective of this course is to train students in dealing with industrial fluid dynamics problems. It is a combination of tutorial courses, providing insight into typical industrial fluid dynamic problems and solution techniques, and exercises in methodology. Sessions are organized for treating samples followed by four exercises on real problems; each of them takes four successive sessions; one to introduce the problem to the students, two for the students to work on it under supervision of a professor and one for the debriefing and comments.

Learning objectives

After completing the course, the student should be able to analyze a problem and make a complete research proposal. He/She must have the skills needed to perform a good analysis and diagnosis on the types of engineering and research problems which he/she may be faced with during his or her professional career, and devise ways to solve them.

To achieve this objective the student must be able to apply efficiently the systematic methodology which is taught in the course, i.e.

- to identify and diagnosis of the fluid dynamic aspects of industrial problems
- to determine the type of relevant solution to apply,
- to select the most convenient (numerical or experimental) modeling of the situation
- to estimate the resources in terms of required manpower and technical facilities
- to establish a research program
- to establish a time schedule and estimate a cost
- to put together a contract proposal.

In addition to these competences, the student must also have a good knowledge of typical problems and have an insight into the possible solution methods. For this purpose he/she must have an insight into: Fundamentals of Aeroacoustics; Aerodynamics of Cylinders; Fundamentals of Boundary layer theory; Fundamental and Applied Heat transfer; External compressible flows; Macroscopic Balances; Dimensional analysis and Model Theory; Blockage in Wind tunnels; Internal Compressible flows; Pollutant dispersal in the atmosphere; Introduction to Two-phase flows; Optics & laser; Incompressible internal flows; Transport Phenomena in Liquid Sprays; Flow induced oscillations; Wind Tunnel Design; Flow-acoustic coupling in solid rocket motors; Applied research in Coating Processes.

Course notes

- Syllabus of MAFD course,
- Flow charts of systematic procedure,
- Slides associated to exercises and seminars,
- Risk analysis and vapor cloud dispersion, various technical data sheet for exercises JM Buchlin, VKI-CN 131 volume 1 & 2 .

Literature

- Workbook of atmospheric dispersion estimates, D. Bruce Turner, US department of Health, Education and Welfare 1969

Evaluation

The evaluation is based on proposed investigation methodology to a typical problem elaborated by small groups of 2 to 3students supervised by a faculty member. A first part is a written report prepared by each group, containing a complete industrial proposal. Evaluation criteria are: clarity and conciseness of the report, completeness of the technical description, time schedule and estimation of cost in terms of manpower, adequacy of the proposed investigation.

A second part is based on an internal technical report, intended to the research institute supervisor. Evaluation criteria are: the motivation for selecting a given investigation methodology, the appropriateness of it, the demonstration that the technical proposal is feasible and that delays and cost are realistically estimated.

A grade is given by the supervisor.

The second part consists of an oral presentation of the problem and research proposal by each group, followed by questions from the faculty. An individual oral examination is then made with all the faculty members of the department who agree on a common grade. Evaluation criteria are relevancy and sound founding of the proposed technical investigation (correct measurement technique or adequate numerical solution) and capability of the student to justify his/her choices and explain his/her approach to the problem.

The final grade for MAFD is a weighted average of the written reports (40%) and oral examination (60%) grades.

INDUSTRIAL DESIGN EXERCISE (IDE - 3.5 ECTS)

EA FACULTY

The objective of the industrial design exercise is to solve, within a limited amount of time, a realistic industrial problem related to fluid dynamics in a manner fitting the purpose. It is the follow-up of the MAFD course. The subject of the exercise is selected in relation to the options and the research project in which the students are already involved.

Learning objectives

The main objective is to allow the student getting better acquainted with the methodology techniques that he has been taught in the course of MAFD by putting them into practice.

The student must be able to propose a complete solution for a typical research problem of fluid dynamics taking into account the context of a complex industrial engineering system. He/She must be able to select an adequate methodology and solve the problem in the allocated time.

Course notes

- Same as MAFD course notes.

Literature

Add-hoc, depending on assigned exercise, different for each student.

Evaluation

The first part of the evaluation is based on a written report describing the proposed solution of the industrial problem assigned to an individual student. Evaluation is by the supervising faculty member. Criteria are:

- the quality of the report (clarity, conciseness, structure, completeness)
- the appropriateness of the selected solution,
- definition of the limits of application and estimation of uncertainty
- quality of proposal for future work that could be done if more time would be available
- presentation and discussion of the results, and conclusions

The second part is an oral presentation, given to all EA faculty members and EA research engineers followed by questions from the EA faculty. Evaluation criteria are the relevance and sound founding of the proposed technical solution (correct measurement technique or adequate numerical solution).

The final grade for IDE is a weighted average of report (50%) and presentation (50%) grades, the latter being an average of the grades given by each EA faculty member.

INTRODUCTION TO THE MECHANICS OF TURBULENCE

(TURB - 2.50 ECTS)

C. BENOCCI

J. VAN BEECK

The detailed description is given in the section **Optional Courses for all departments**.

DATA ACQUISITION AND PROCESSING (DAP - 2 ECTS)
G. PANIAGUA
P. RAMBAUD
C. SCHRAM

The detailed description is given in the section **Optional Courses for all departments**.

3.2 COURSES EXPERIMENTAL OPTION

ADVANCED MEASUREMENT TECHNIQUES LABORATORIES
(MT Labs - 6.0 ECTS)
J. VAN BEECK,J-M. BUCHLIN,M. RIETHMULLER, C. SCHRAM, O. CHAZOT

Detailed description is given in the section **Optional Courses for all departments.** Students following the experimental option have to choose minimum one of the four labs. The objective is to help them in the physical understanding of fluid mechanics.

3.3 COURSES NUMERICAL OPTION

NUMERICAL METHODS IN FLUID DYNAMICS (NMFD1 – 1.25 ECTS)
H. DECONINCK

The detailed description is given in the section **General Courses**

NUMERICAL SIMULATION OF INDUSTRIAL PROBLEMS 1
(NSIP1 - 2.75 ECTS)
J. VAN BEECK
C. BENOCCI

The purpose of the course is to familiarize the students with the solution of flow problems by applying a commercial flow solver, and to lead him/her to acquire the critical sense and physical feeling necessary to evaluate the numerical results. The course is composed of seminars in which the capabilities and the limitations of numerical simulation in industrial or environmental problems are discussed. A large part of this course consists of practical exercises whereby the numerical results are to be compared with own experimental results obtained during the MT labs.

Learning objectives
At the end of the course and exercises the student should
- master the best practice rules for CFD predictions
- be able to understand the different CFD models and approximations, which are a necessary part of this class of simulation,
- be able to make a critical evaluation of the numerical results, their uncertainty and to define the logical approach to improve them.

Course notes

- Numerical simulation of industrial flows – slides, C. Benocci, VKI-CN 181.
- User manual for Fluent flow solver
- User's Manual for STARCCM+ Flow solver

Literature

- Model Evaluation guidance and protocol document, Editors: Rex Britter and Michael Schatzmann, ISBN 3-00-018312-4, Copyright COST Office, 2007
- ERCOFTAC Special Interest Group on "Quality and Trust in Industrial CFD", Best Practice Guidelines, Editors: Michael Casey and Torsten Wintergeste, Fluid Dynamics Laboratory Sulzer Innotec, Version 1.0, January 2000, Copyright European Research Community On Flow, Turbulence And Combustion

Evaluation

The evaluation consists of a practical exercise in which the students can show their understanding and skills. Each group of 2-3 students (the same that make the MT labs) is assigned a practical problem. They are asked to apply a commercial flow solver to simulate one of the classical flow fields studied during the experimental measurement in the course MT labs.
The evaluation is based on the report in which the numerical results are compared with their own experimental results obtained during the MT labs. Evaluation criteria are: the critical analysis of the numerical results in terms on verification and validation, the discussion of uncertainty and the logics in the proposal for possible improvements.

NUMERICAL SIMULATION OF INDUSTRIAL PROBLEMS 2

(NSIP2 - 3.5 ECTS)
J. VAN BEECK
C. BENOCCI

This course is a higher level continuation of the course NSIP1 and is mandatory only for the numerical option. It consists mainly of a practical but complex exercises, in which the numerical results have to be compared with experimental ones, LES or DNS data from the literature.

Learning objectives

At the end of this project oriented course the students should be familiar with the simulation of complex flow problems using a general commercial flow solver, and have acquired the background, critical sense and physical feeling necessary to evaluate the numerical results. The main objective is the understanding of the models and the approximations, which are a necessary part of this class of simulation.

Course notes

- Numerical simulation of industrial flows – slides, C. Benocci, VKI-CN 181.
- User manual for Fluent flow solver
- User's Manual for STARCCM+ Flow solver

Literature

Idem as Numerical Simulation of Industrial Problems 1

Evaluation

Evaluation is based on an individual report on the practical exercise i.e the simulation with a RANS approach of a bench-mark case of the ERCOFTAC database. Criteria are the student's capability: to define the calculation domain and the quality of the grid, to generate the correct boundary conditions based on available data, to evaluate the influence of the RANS one and two equation turbulence models and wall treatments, to investigate the influence of the order of numerical discretization and grid refinement (grid dependency) on convergence and accuracy, to evaluate, acceleration techniques and convergence criteria. The evaluation is further based on the validation and critical analysis of the results in function of the parameters of the analysis and by an assessment of the origin of the differences between simulation and experimental or LES data.

4. SPECIALIZATION IN TURBOMACHINERY AND PROPULSION

The main objective of these specialized courses is to familiarize the students with the main theories and tools for the interpretation of numerical and experimental results and the design techniques for advanced turbomachinery components. The first part provides the basis for the more specialized studies in turbines or compressors in the second part of this course program. The formal lectures are completed with the aero-design of advanced turbomachinery components to put the learned lessons into practice. The targeted courses prepare the student for a position in a turbomachinery research center or the R&D department of a turbomachinery manufacturer.

4.1 GENERAL COURSES IN TURBOMACHINERY AND PROPULSION

FLOW IN TURBOMACHINES (FTM - 8.0 ECTS)

T. ARTS
G. PANIAGUA
T. VERSTRAETE

This basic course is mandatory for all Turbomachinery students (compressor and turbine specialization). The course starts with a detailed cycle analysis, a description of the component overall characteristics and a one dimensional flow analysis. It further provides a general description of the flow in Turbomachines using the S1/S2 model, based on the superposition of two 2D flows. It is the first step towards the understanding of the more complex 3D flows and the basis for the traditional turbomachinery design. Boundary layer issues and heat transfer are finally addressed at the end of this course.

Learning objectives

At the end of this course the student should have acquired the necessary knowledge and competences for the design of gas turbines and their turbomachinery components. He/she should have a good understanding of the thermodynamic principles governing the flow and master the analysis and design methods, specific for the turbomachinery components.
In particular he/she should have a good understanding of the thermodynamic cycles and the fundamentals of propulsion in addition to a good knowledge of turbopropulsion elements, the laws of similitude and the prediction correlations.
He/she should have an insight into the influence of the cycle characteristics on the performance of the individual turbomachinery components, the thermal efficiency of jet engines, gas turbines and steam turbine.
Starting from the engine specifications the student should be able to make a one dimensional layout of a jet engine, specify the cycle characteristics, and predict the performance and its changes with operating conditions. The student should also be able to implement these design requirements into an optimization strategy. This first part of the course is complemented by a description of more advanced cycles in a six hour seminar on “High Speed Propulsion” by Hon. Prof. F. Breugelmans. By this the

student should acquire a better insight into the different techniques used in propulsion systems.

The S1-S2 model is the basis of turbomachinery analysis and design. The correct use it for a more detailed layout of a multistage compressor or turbine (i.e. the prediction of the performance and the specification of blade shapes) and the understanding of its limitations are the objectives of the next and major part of the course. This results in 2 main and parallel courses related to respectively the meridional and blade to blade flow.
The main objective of the meridional flow study is to get a physical understanding of the theoretical relations on which the axi-symmetric flow model is based and to be able to apply them. The student must understand the influence of the design strategy (vortex law) on velocity triangles, degree of reaction, pressure, temperature and density gradients, efficiency and some basic aspects of manufacturing. The following more detailed aspects should also be understood: influence of radial enthalpy and entropy gradients, impact of streamwise curvature, relative motion and blade forces.
The main objective of the blade to blade flow study is a good understanding of the limitations of the experimental and numerical data for the turbomachinery blade design and a mastering of the analysis and design techniques. Students should be aware of the main differences between external flows and turbomachinery flows as there are: the impact of rotation, periodicity of the flow and unsteady blade row interaction. They should understand the limitations when using simplified numerical predictions or experimental data obtained in non rotating cascades. Students should also master the performance and loss prediction correlations in compressors and turbines, understand the physical phenomena occurring in turbomachines on which they are based (Secondary flows, impact of Reynolds- and Mach number on operating range, etc.) and be available to implement them in a design strategy. Students should also have a good knowledge of the numerical techniques that are at their disposal and of the modern design methods (inverse design and optimization methods) that presently the subject of intensive research.
At the end of the courses FTR and FTC the student should be able to make a first lay-out of a multistage compressor or turbine and predict the performance based on the S1-S2 model, the analytical relations and performance correlations.
The objective of a last part is to make students familiar with the specificities of the boundary layers in turbines and compressors, as there are: basic transition and turbulence modeling and their relation to stage interaction, heat transfer in turbines, film cooling and internal convection cooling.

Course notes

- Turbomachinery Cycles and Components, R. Denos, VKI-CN 163
- Thermodynamic Cycles in Turbomachinery, PowerPoint slides by G. Paniagua
- Turbomachinery Components, PowerPoint slides by G. Paniagua
- Meridional Flow in Axial Turbomachines, J. Chauvin, VKI-CN 99
- Flow in turbomachines and turbomachinery component characteristics, F.Breugelmans, VKI-CN 83
- Aerodynamic design of a gas turbine, McDonald, P.W., VKI-CN 95.
- Radial equilibrium in Turbomachines, T. Arts, (hand written notes)
- Boundary layers, R. Kiock, VKI-CN 118,
- Introduction to heat transfer phenomena in gas Turbines, T Arts, M. Lambert & , Rutherford, VKI-CN 127
- Blade to Blade flow in Turbomachinery, R.A. Van den Braembussche, VKI CN 172
- Compressor Cascade Flow and Losses, R.A. Van den Braembussche, PowerPoint slides
- Inverse Design Methods for Axial and Radial Turbomachines, R.A. Van den Braembussche, VKI Preprint 1994-35
-Fast Multidisciplinary Optimization of Turbomachinery Components, R.A. Van den Braembussche, VKI LS 2004-07 (part of)
- Hand written notes on introduction to numerical methods in Turbomachines, R.A. Van den Braembussche.

Literature

- Convective Heat and Mass Transfer, Kays & Crawford (Book)
- Boundary-Layer Theory, H. Schlichting, Springer, 8th edition, 2000, Corr. 2nd printing edition, 1 Oct 1999,
- Viscous Fluid Flow, Frank White, McGraw-Hill Science/Engineering/Math, 3rd Revised edition, 1 avril 2005
- Optimization and Computational Fluid Dynamics, Ed. D. Thevenin and G. Janiga, Springer Verlag, ISBN: 978-3-540-72152-9.
- Aerothermodynamics and Flow in Turbomachines, M.H. Vavra, R.E. Krieger Publishing Co., 159
- Aerodynamic Design of Axial compressors, NASA SP 36, Compressor and Turbine Research Division, NACA Lewis Research Center.

Evaluation

The evaluation is done by an oral exam for each of the three large parts of the course (open and closed book including exercises). The evaluation of the forth part (boundary layers) is incorporated into the second part. The weighting (3/20 for cycles, 7/20 for meridional flow, 3/20 for boundary layers and 7/20 for blade to blade flow) is proportional to the number of lecture hours and communicated to the students in advance. A test exam is planned early in the year for FTR and FTC, to familiarize the students with the VKI evaluation criteria and techniques. Students can decide to keep the points for the final grade or to repeat the exam at the end of the course.

The evaluation aims to measure the student’s knowledge of the flow phenomena, his/her capacity to apply the techniques and understanding of the consequences of the approximations that are involved. The ultimate test will be by a separate Design Exercise (2 or 5 ECTS depending if the student is following the numerical or experimental option).

More detailed evaluation criteria related to each part of the course are:

- the student’s understanding of the Joule cycle, his ability to explain the differences between the ideal cycle and the real one and to propose and justify possible improvements to the gasturbine lay-out and components.
- the student’s understanding of the different meridional flow concepts addressed during the teaching, his/her ability to select the appropriate design options, to propose solutions to the different problems and restriction of the design space. The understanding of the impact of boundary layers and heat transfer on the flow pattern and performance are also evaluated.
- the student’s understanding of the limitations of applicability of experimental and numerical data, its use in the design of compressors and turbines, its ability are the main evaluation criteria of the blade to blade part of the course.

DESIGN EXERCISE (DE - 5. ECTS)

T. ARTS
G. PANIAGUA
F. BREUGELMANS
J.F. BROUCKAERT

The objective of this individual exercise is to further familiarize with the turbomachinery design and analysis methods by applying them for the design of a complete turbomachinery component.

It is the final hands-on illustration/evaluation of the different basic and advanced turbomachinery lectures (FTM, ACC or ACT). The component (compressor or turbine) to be designed depends on the option chosen for specialization.

Students making a numerical project may decide to limit the design exercise the first part (2.0 ECTS) and complement their curriculum with the course “Numerical Methods for Fluid Dynamics, part2” described in the section **Optional Courses for all departments.**

Learning objectives

The student must be capable to define the aerodynamic path and to specify the blading in function of the design point, by means of the techniques specified in the courses. Only the overall boundary conditions (total inlet conditions, total pressure ratio, mass flow or power) of a turbine or (inlet conditions, mass flow and pressure ratio) for a compressor, are specified. Any other required input and design choice has to be defined and justified by the student.

The student should be able to address following successive steps of the design:
- global cycle analysis (compressor-turbine matching)
- 1D mean radius analysis of the turbine (selection/optimization of exit static conditions, degree of reaction, exit flow angles of vane and blade, rotational speed). Definition of the number of stages and cross sections (passage convergence or divergence).
- ISRE analysis. Selection of an exit vortex law for both vane and blade complying with the requirements on exit swirl, rotational speed, blade turning and cross section divergence.
- NISRE analysis. Selection of a loss model. Definition of profile, secondary and leakage losses. Effect of Mach and Reynolds number. Calculation of radial profiles of kinematic and thermodynamic radial gradients. Need to comply with requirements on exit swirl, rotational speed, blade turning and cross section divergence.
- Presentation, analysis and justification of final velocity triangles.

There is no pre-established software at the disposal for this part of the exercise. The main emphasis is put on a correct physical understanding of the implications of the choices made. The design has to be complemented by an off design performance prediction. Finally the student must be able to design/select the blades and analyzed them by Navier-Stokes solvers to confirm the local energy exchange and verify the optimality of the blade velocity distribution.

Course notes

All Turbomachinery course notes

Literature

Not applicable

Evaluation

The evaluation is based on a continuous assessment of the progress made throughout the exercise. Regular meetings with the evaluator are set-up to check the work in progress and to discuss the selection of the various design assumptions and choices that are made. Ultimately a detailed design report is provided in which the student justifies the additional assumptions he/she had to make and the methodology used. The evaluation is especially focusing on the consistency of the decisions and choices made for the design.

LABORATORY SESSIONS (TU Labs - 3.0 ECTS)
G. PANIAGUA

This course comprises a series of lab sessions that are defined to provide a better understanding of the flow physics and theories presented in the courses FTM, ACC and ACT.

Learning objectives

The student should demonstrate to master the following measurement techniques

- measurement of the steady flow in a cascades by pressure probes
- heat transfer and gas temperature measurements related to hot turbine blades.
- unsteady flow measurements during surge and stall by hot wire

For each technique he/she should

- understand the limitations and field of application,
- be able to select the appropriate data acquisition systems
- show the capability to develop data reduction techniques
- be able to estimate the accuracy
- show the capability to link the results to the physics of the problems,

Course notes

- Hands out for TU-labs, PowerPoint slides by G. Paniagua

Evaluation

The evaluation is based on the test report. The main criteria, specified in the hands out, are:

- completeness of the report
- quality of uncertainty analysis
- validation of the results by linking them with physical flow models
- dept in the interpretation of the flow data
- recognition of the design options in the measurement results.

4.2 Specialization on Turbines

ADVANCED COURSE IN TURBINES (ACT - 4.5 ECTS)
T. ARTS
G. PANIAGUA
C.H. SIEVERDING

This advanced course is the follow-up of the turbomachinery course FTM and followed only by students that have selected the turbine option. It provides a detailed overview of the advanced design and analysis methods for the different types of turbines. Honorary professors with a long experience and large expertise in this field play a non negligible role in this specialized teaching.

Learning objectives

At the end of this course the student should

- have a good knowledge of the evolution of the different architectures of turbomachines as prime mover in conversion and propulsion systems from 1900 to to-date as driven by a combination of the inventive spirit of gifted engineers, the gradual evolution of more and more complex experimental and analytical models and finally the irresistible progress of advanced numerical methods
- master in much more detail than taught in the FTM course, the design practice for turbine blades and stages, have a feeling for the hierarchy of importance of different design aspects and be able to judge what appears right or wrong in a turbine design.
- have a sound understanding of the basic physics of the complex flow through turbine bladings including aspects of transonic and supersonic flow, boundary layer transition and separation and three dimensional flows. They should know how to improve the turbine design by using this knowledge for an improved flow control.
- be able to evaluate the impact of the aerodynamics on the thermal aspects such as the appearance of condensation in last stages of steam turbines and the need of cooling of blades in the first stages of gas turbines and appreciate the effect of cooling systems and blade materials on turbine life time.
- understand the underlying physics and be able to make use of the art of bending the blades in tangential and/or axial direction to generate blade forces effecting the three-dimensional flow for improved flow control, in particular in the endwall regions.
- understand how the unsteady flows through the combination of most advanced time resolved experimental and numerical methods can help in improving both performance and life time of turbomachines.
- have insight in how the short and long term research efforts are of particular importance to the future development of more efficient turbomachines with the aim of reducing their impact on the environment and have a feeling for top priorities in research in a competitive environment

Course notes

- Rocket Engines: Turbomachinery, PowerPoint slides by G. Paniagua
- Contra-rotating Turbines Study, PowerPoint slides by G. Paniagua
- Unsteady flows in Turbines, G. Paniagua, VKI-CN 206
- Development of Steam and Gas Turbines and 1D stage Design and Analysis, C. Sieverding, VKI-CN 199
- Turbine Blade Design, C. Sieverding, VKI-CN 200
- Compressible flow theory, C. Sieverding, VKI-CN 201
- Transonic Gas Turbine Stages, C. Sieverding, VKI-CN 202
- Transonic Flow in Last Stage of Large Steam Turbines, C. Sieverding, VKI-CN 203
- Secondary Flows in Turbine Blade Passages, C. Sieverding, VKI-CN 204
- Full Three-dimensional Blade Design, C. Sieverding, VKI-CN 205
- Axial Performance Prediction Methods, C. Sieverding, VKI-CN 207
- Comparison of Axial Turbine Loss Correlations, C. Sieverding, VKI-CN 208

- Introduction to Heat transfer Phenomena in gas Turbines, T. Arts, VKI-CN 127

Literature

- Untersuchungen und Berechnung axialer Turbinenstufen, Dejc, E., Trojanovskij, B.M. & Naumann, W., Berlin : Verlag Technik, 1973.
- Thermische Turbomaschinen: Zweiter Band. Geänderte Betriebsbedingungen, Regelung, mechanische Probleme, Temperaturprobleme, Volume 2, Walter Traupel, Springer, 4th edition, 2000.

Evaluation

The evaluation consists of an individual oral (one hour) closed book exam covering 3 selected chapters of the six main chapters of the course (two imposed by the evaluator, one freely chosen by the student). The chapters imposed are communicated to the students at the end of the course.
The choice of the freely selected chapter is announced by the student at the beginning of the exam.
The evaluation criteria are the degree in which the student:

- masters the design methodology and his/her discernment of selecting the most appropriate solution, his/her knowledge of the most appropriate stage performance evaluation methods
- understand the basic physics of the flows in turbine bladings and their consequence on optimal blade designs
- understands and is able to apply the various means for reducing the impact of secondary and tip clearance flows on turbine performance.
- is able to estimate the impact of the selected solutions on the overall aero-thermal performance of the turbine stage(s).
- has a comprehension of the unsteady flow phenomena caused by blade row interaction and his/her appreciation of the importance of unsteady effects with respect to steady state stage performance data.

4.3 Specialization on Compressors

ADVANCED COURSE IN COMPRESSORS (ACC - 4.5 ECTS)

J.F. BROUCKAERT/ T. VERSTRAETE
F. BREUGELMANS
R. VAN DEN BRAEMBUSSCHE

This advanced course is the follow-up of the basic Turbomachinery course FTM and is followed only by students that have selected the compressor option. It provides a detailed overview of the advanced design and analysis methods for the different types of compressors. This course is composed of two parts corresponding to the main types of compressors.
The first part provides the theory and models that have been established for the detailed design and analysis of the different components of radial compressors.

The second one is similar to the first one but aims for an up to date understanding of the flow mechanisms governing advanced axial compressors (subsonic, transonic and supersonic).

Learning objectives

The learning objective of the first part is to make the student aware of the specificities of radial compressors. They should understand the role of radius change and flow separation on the transformation of energy and pressure rise, the mechanisms governing the flow in radial vaneless and vaned diffusers, return channels and volutes. The student should also understand the mutual interaction of these components. He should master the specific performance prediction models with special attention to range. He should understand the specificities of the secondary flow in radial turbomachines and its impact on stability (surge and stall). He/she should known the

specific problems related to the different fields of application (industry, power generation or aeronautics), and understand the impact of Reynolds number or gas composition on performance.

The objective of the second part is to provide the student a clear idea of the specificities of multistage, transonic and supersonic axial compressors and how the different operating conditions influence the design. The impact of flow unsteadiness, secondary flows and casing treatment, inlet distortion and erosion, on the stability (surge and stall) and advantages of variable geometry and bleeding should be understood. Students should master the design methodologies that are specific for high speed applications including the stage matching techniques. They should be aware of the differences between the aero and industrial applications and the impact of gas composition.

The students should also understand the problems that are specific for supersonic compressors such as: 3D shock losses and unique incidence and their impact on blade shape and range. They should also know the different design philosophies. The second part of the course makes extensive use of conference articles and journal papers to illustrate the topics that are discussed.

Course notes

- Centrifugal Compressors, Analysis & Design, R.A. Van den Braembussche, VKI CN 192.
- Flow and Loss Mechanisms in Volutes of Centrifugal Compressors and Pumps, R.A. Van den Braembussche, VKI Preprint 1996-55.
- Impeller Response to Downstream Pressure Distortion, R.A. Van den Braembussche, VKI Reprint 1995-45.
- Radial Impeller Design methodology, R.A. Van den Braembussche, VKI CN 162.
- Stability and Range in Centrifugal Compressors, R.A. Van den Braembussche, VKI Reprint 1996-51.
- Active Control of Surge and Acoustic Resonance in Centrifugal Compressors, R.A. Van den Braembussche, VKI Reprint 1996-13.
- Optimization of Radial Impeller Geometry, R.A. Van den Braembussche, RTO-VKI Lecture series on High Speed Pumps, ISBN: 978-92-837-0063-0, (part of).
- Centrifugal Compressors, R.A. Van den Braembussche, Powerpoint Slides.
- Collection of PowerPoint slides J.F. Brouckaert

- Mechanical Factors affecting Surge line, F. Breugelmans VKI-CN 96
- Off-design performance of axial compressors, J. Chauvin VKI-CN 100
- Transonic Compressor Cascades, H. Griepentrog, VKI-CN 73

<u>Literature</u>

- Extensive bibliography in CN 192
- Effect of Mach number on the Flow and Application of Compressibility Corrections in a Two-Dimensional Subsonic-Transonic Compressor Cascade having Varied Porous-wall Suction at the Trailing Edge, W.B. Briggs, NACA TN 2649
- Performance of Controlled Diffusion Blades, H. Starken, VKI-LS 1992-02 (part of)
- Loss Development in Transonic Compressor Cascades, H. Starken, VKI-LS 1998-03 (part of) - Investigation of the Axial Velocity Density Ratio in a High Turning Cascade, H. Starken, F. Breugelmans, P. Schimming, ASME 75-GT-25.
- Design of Compressor Blades Suitable for Transonic Axial-Flow Compressors, M.P. Boyce ASME 67-GT-47.
- A shock Loss Model for Supercritical Subsonic Flows in Transonic Axial Compressors, R.J. Dunker, AGARD …… paper 27
- The Cascade and Stator Section Performance of a 48_{o} Cambered DCA Airfoil – Comparison with 2D Flow Calculations in the Compressible Flow Regime, F. Breugelmans, VLI-LS 59
- Single Stage Experimental Evaluation of High Mach Number Compressible Rotor Blading, Part I Design of Rotor Blading, D.R. Steyler & L.H. Smith. NACA RM
- Design Methodology for Advance HP Compressor First Stages, M. Goutines, VKI_LS 1988-03, (pat of).
- Analysis of 3D Viscous Flow in Transonic Compressors, W.N. Dawes, VKI-LS February 1988)(part of)
- Fan and LP Compressor Design: General; Considerations, (slides), J. Lepine, VKI-LS 2003-06, (part of).
- LP Compressor Design, (slides), J. Lepine, VKI-LS 2003-06, (part of).
- Shock Structure Measured in a Transonic Fan Using Laser Anemometry, J. Wood et al. AGARD CP-401, paper 2.
- Transonic Investigation of an Axial-Flow Compressor Rotor with a Hub-tip ratio of 0.75 and Blades having NACA $A_{2}I_{8b}$ mean lines, NACA RM L57H08, P.T. Bernot & M. Savage.
- Single Stage Experimental Evaluation of High Mach Number Compressible Rotor Blading, Part 4 Performance of Rotor 2D, K.W. Krabacher & J.P. Gostelow.
- Axial Compressor Performance Predictions, AGARD (part of).
- Loss Sources and Magnitudes in Axial-Flow Compressors, C.C> Koch & L.H. Smith, ASME 75-WA/GT-6.
- A Design Point Correlation for Losses due to Part-Span Dampers on Transonic Rotors, W.B. Roberts, ASME Journal of Engrg. For Power, Vol. 101, pg. 415-421.
- An Off-Design Correlation of Part Span Damper Losses Through Transonic Axial Fan Rotors, W.B. Roberts et al., ASME 79-GT-6.
- Incidence Angle Rules in Supersonic Cascades, H. Starken, VKI-LS 1988-03 (part of).
- Shock Losses in Transonic and Supersonic Compressor Cascades, H.A. Schreiber, VKI-LS 1988-03, (part of).

- The Effect of Leading Edge Thickness on the Bow Shock in Transonic Rotors, F. Breugelmans, Squid Workshop, USNPGS Monterey, 1976.
- Cascade Wind Tunnel Tests on Blades Designed for Transonic and Supersonic Compressors, W. Heilmann et al., AGARD CP 34, paper 12.
- The compressor Blade Definition, F. Breugelmans, VKI-LS 59, (part of).

- The Cascade and Rotor Section Performance of a 9o57 Cambered DCA Blade, F. Breugelmans & H. Starken, VKI-LS 59, (part of).
- The Supersonic Compressor Stage, F. Breugelmans, VKI-LD 47 (part of).
- Variable Geometry in Supersonic Compressors, F. Breugelmans, VKI-LS 1988-03 (part of).
- Axial Supersonic Inlet Component, F. Breugelmans, VKI-LS 1988-03 (part of).
- Supersonic Throughflow Fan, C.L. Ball R.D. Moore, VKI-LS 1988-03 (part of)
- A Contribution to Supersonic Compressor Research, D. Bohn, VKI-LS 1974
- Design of Critical Compressor Stages, A. Wennerstrom, VKI-LS 1988-03 (part of).
- Supersonic Compressors, A. Wennerstrom, VKI-LS 1988-03 (part of).
- Airfoil Design for High Tip Speed Compressors, P.C. Tram et al., AGARD
- The Mach 2 Axial Compressor Stage, F. Breugelmans, ASME 75-gt-22.
- The Supersonic Axial Inlet Component in a Compressor, F. Breugelmans, ASME 75-GT-26.

Evaluation

Evaluation of the first part is done by a 3 to 4 hours oral exam. It starts with the design of a radial compressor by means of the VKI computerized design system, based on the theory that has been presented. This uncommon evaluation technique is used because it is the closest to the real world practice where designs are made by computerized systems and it allows concentrating on the student’s understanding of the physics of the flow. Evaluation criteria are the ability of the student to apply the information that has been presented in the course i.e. to discuss the different geometry changes that can be taken to improve the performance at design and off-design and to propose design changes that will allow achieving the required operating range. Important are the
student’s understanding of the interaction between the different components and how this can be used to reach the design targets. The weighting is proportional to the number of lecture hours (8/20).
The evaluation of the second part is by a closed book oral exam (weighting 6/20) where a series of small questions (see typical questions) should be answered followed by the presentation and discussion of a lecture prepared by the student on a specific topic (weighting 6/20). Criteria are the student’s understanding of the physics and his/her ability to effectively use the knowledge acquired in the courses in the advanced compressor design process.
The ultimate evaluation of the basic and advanced compressor courses will be by a separate design exercise (DE 2 or 5 ECTS).

4.4 Optional courses in the turbomachinery department

Students following the experimental option have to take following course:
INTRODUCTION TO COMPUTATIONAL FLUID DYNAMICS
(ICFD - 1.25 ECTS)
J. D. ANDERSON
The detailed description is given in the section **Optional Courses for all departments**.

Students selecting the **Numerical option** and making the reduced Design Exercise (1.5 ECTS) have to take following course:
NUMERICAL METHODS IN FLUID DYNAMICS, PART 2 (NMFD2 - 3 ECTS)
H. DECONINCK
The detailed description is given in the section **Optional Courses for all departments**.

5. OPTIONAL COURSES FOR ALL AREAS OF SPECIALIZATION

Following courses are optional and in function of their projects, students may select, in agreement with their supervisor, one or more optional courses available to all areas of specialization.

INTRODUCTION TO COMPUTATIONAL FLUID DYNAMICS LS

(ICFD - 1.25 ECTS)
J. ANDERSON

This one week course has the same objectives as the course on **“**Numerical Methods in Fluid Dynamics, part 1: Introduction” but is oriented to students that will follow the experimental option and hence will not continue with a more advanced CFD course. Emphasis is also put on the relation between the flow physics on the modeling.

Learning objectives

At the end of the course the student should have an understanding of the basic philosophy of Computational Fluid Dynamics (CFD). He/she should know how the equations for incompressible and compressible flows, explained in the theoretical courses, are numerically modeled and how the different formulations (implicit/explicit) influence accuracy and stability.
He/she should understand the CFD vocabulary.
This course is included in the VKI lectures series program and attracts every year between 30 and 40 external participants from industry and research centers.

Course notes

- Computational fluid dynamics - An introduction, Edited by Wendt, J.F., ed. Springer, 3rd edition, 2009, isbn-13 978-3-540-85055-7, A von Karman Institute Book.

Literature

References in the course notes.

Evaluation

The evaluation is done by an oral closed book exam.

ADVANCED MEASUREMENT TECHNIQUES LABORATORIES

(MT Labs – 6.0 ECTS)

J. VAN BEECK,J-M. BUCHLIN,M. RIETHMULLER, C. SCHRAM, O. CHAZOT

This course intends to provide the in-depth knowledge on typical measurement techniques to students who plan to use them in their project

Learning objectives

After conducting these laboratory experiments the student should have an in dept knowledge of and the skills required to apply following modern measurement techniques with application to fluid dynamics.

- Calibration of a three-component internal strain gauge balance and its use for force measurements on a typical aircraft/missile configuration,
- Laser Doppler velocimetry and its use to measure mean velocities and turbulence levels in a boundary layer flow,
- Hot wire anemometry and pressure probes to measure mean velocities and turbulence levels in a boundary layer flow,
- Infrared radiometry applied to heat transfer on a body in hypersonic flow.

In particular he/she should understand the limits of application, master the calibration, be able to perform the data reduction and be capable of estimating the accuracy.

Course notes

- Guidelines for the Measurement Techniques laboratories, J. Anthoine & O. Chazot, VKI-CN 191.

Literature

- Measurement Techniques in Fluid Dynamics – An Introduction, Third revised edition, VKI, 1991, 383 pgs.

Evaluation

Each group of students is asked to prepare a report about each lab and the evaluation is based on the grade given by the supervisor to this report. Emphasize is put a critical analysis of the results including uncertainty.

A second evaluation is by an individual oral examination of each student by a college of faculty members. Criteria are the understanding of the techniques, calibration and error estimation and their application to specific problems. The final grade is based on a weighted average of these grades (60% for oral examination and 40% for reports).

INTRODUCTION TO AEROACOUSTICS (ACOUS - 1 ECTS)
C. SCHRAM

The purpose of this course is to provide the students with some basic knowledge of physical acoustics and aero-acoustics. It is the intension to extend this course considerably in the near future in combination with the present evolution and research activities at the VKI.

Learning objectives
The students should understand the fundamentals of acoustics such as: units and assessment of noise, aerodynamic noise generation. They should understand 2D and 3D wave propagation and dissipation, Lighthill's formulation and vorticity formulation applied to jet noise, resonators and flow-acoustic coupling.

Course notes
- Introduction to Aeroacoustics, J. Anthoine, VKI-CN 176.

Literature
Bibliography in VKI-CN 176

Evaluation
The evaluation consists of a written exam focusing on practical questions and exercises involving the implementation of the theoretical aspects covered by the course.

INTRODUCTION TO THE MECHANICS OF TURBULENCE
(TURB - 2.50 ECTS)
C. BENOCCI
J. VAN BEECK

This is a formal course organized to assure that all students of the EA department have a basic understanding of the physics of the turbulence and its simulation by computational means. It is an optional course for the students of the other departments.

Learning objectives
At the end of this series of tutorials the student should have an insight into the mathematical tools for the statistical description of turbulence, including transition, turbulent stresses, kinetic energy equation, vortex dynamics in turbulent flows, correlations, spectral analysis, notions of homogeneous and isotropic turbulence. He/she should have an understanding of the basics of turbulence modeling and be able to select the appropriate model for each application and asses the capabilities and limitations of the chosen model.

Course notes

-.Concepts of Turbulence modeling, C. Benocci and D. Olivari, VKI-CN 158
- An Introduction to Mechanics of Turbulence, D. Olivari and C. Benocci, VKI-CN 157.
- Introduction to mechanics of turbulence: Spectral analysis of turbulent flows, , C. Benocci and J. Van Beeck, VKI-CN 168.
- Introduction to the Physics and Simulation of Turbulence, J.H. Ferziger, VKI-CN 156.

Literature

Bibliography in Course notes

Evaluation

Evaluation is by a written closed book exam measuring the objectives are reached i.e. a theoretical knowledge about the mechanics of turbulence and its modeling.

DATA ACQUISITION AND PROCESSING (DAP - 2 ECTS)

G. PANIAGUA
P. RAMBAUD
C. SCHRAM

The course teaches the basic techniques for acquiring experimental data under a digitized form and the numerical techniques for processing them. It consists of lectures and computerized demos.

Learning objectives

After successful completion of this course the student should understand the consequences of the measurement chain and numerical data processing techniques (digital filtering, numerical modeling of probe transfer function and digital compensation of signals …). In particular he/she should be aware of the restrictions and errors due to the discretization. He/she should also understand the advanced techniques for unsteady flow measurements (wavelets, POD decomposition, etc). The final objective is the student's capability to define and set-up the appropriate measurement chain for a specific problem and the knowledge and competence, needed to correctly perform the analysis of the results collected in the research project (TU students) or obtained in the laboratory sessions of the "**Advanced Experimental Techniques course (MT labs 1.5 ECTS)"**.

Course notes

- Data acquisition and processing, PowerPoint slides by G. Paniagua
- Measurement Techniques in Fluid Dynamics – An Introduction, Third revised edition, VKI, 1991, 383 pgs. (last chapter)
- Fundamentals of Data Acquisition and processing, R. Denos, VKI-CN 171.
- Introduction to Advanced Data Processing, Mike Bilka, VKI-CN 197

Literature
Bibliography in VKI-CN 171, VKI-CN 197

Evaluation
The evaluation is based on a written closed book exam measuring the understanding of the concepts explained during the courses (weight 16/20) and by a multiple choice test evaluating the understanding of the advanced data processing techniques for unsteady flows (4/20).

DESIGN AND OPERATION OF PLASMA WIND TUNNELS(PWT – 1.0 ECTS)

O. CHAZOT

This course the basic features of high enthalpy facilities and testing.

Learning objectives
At the end of this course the student should have a general knowledge of what is specific for plasma facilities and plasma reactors used for aerothermodynamic research. He/she should have a basic knowledge on:
- basic operations of high frequency generators
- the design of inductively coupled plasma torches
- characteristics of plasma flows
- operation of plasma wind tunnels
- application of aerothermodynamics testing in Plasmatron facilities

Course notes
- PowerPoint Slides on Plasma Windtunnel - Design Operation and Application

Literature
No good reference available (except in Russian)

Evaluation
Evaluation consists of a written (closed book) exam with theoretical questions on the course contents and the preliminary design and performance evaluation of a plasma wind tunnel. (50% weight each). The evaluation criteria concern the degree of understanding of plasma windtunnel operation, thermal plasma flow. features and typical associated measurement techniques.

NUMERICAL METHODS IN FLUID DYNAMICS, PART 2 (NMFD2 - 3 ECTS)
H. DECONINCK

Learning objectives

This second part is a natural continuation of the first part, but goes much more in detail. At the end of the course the student should be able to follow the global CFD literature, choose an algorithm and develop independently a CFD method for a particular application. The following objectives should be reached for a successful completion of this course:

- master the theory of Partial Differential Equations, including the classification of PDEs based on the theory of characteristics. Master the specific properties of hyperbolic, elliptic and parabolic equations and the link with initial versus boundary value problem and diffusion versus propagation. Understand the concept of well-posedness with respect to boundary and initial conditions (Hadamard). Have a detailed understanding of the theory of hyperbolic conservation laws including weak solutions, jump relations, concept of mathematical entropy condition, boundary conditions.
- know the main discretization techniques based on finite difference, finite volume, finite element and spectral methods, including a discussion of the relationship between the various methods.
- have a deep understanding of the concepts of consistency, stability and convergence, stability theory (von Neumann analysis), Lax-Wendroff theorem, equivalent differential equation of a scheme, concepts of artificial dissipation and upwinding and the relation between both.
- master the principles of monotone schemes for hyperbolic conservation laws based of TVD and positivity (LED) conditions.
- be familiar with the classical finite difference and stabilized finite element schemes (SUPG, GLS) for hyperbolic and parabolic problems. Be familiar with classical time integration schemes (explicit and implicit) and their stability properties.
- have a good understanding of the boundary value problems, with emphasis on iterative methods for solving linear systems, including relaxation methods (SOR, Gauss-Seidel), conjugategradient like (Krylov subspace) methods and multigrid methods.

Course notes

- Numerical Techniques for Solving Partial Differential Equations, H. Deconinck, VKI-CN 142.
- Numerical Methods in Fluid Dynamics 2, Exercises, H. Deconinck, VKI-CN 182
- Numerical Methods in Fluid Dynamics 2, Solutions to exercises, H. Deconinck, VKI-CN 183

Literature

- Numerical Solution of Time-Dependent Advection-.Diffusion-Reaction Equations, W. Hundsdorf and J.G. Verwer, Springer Series in Computational Mathematics, 2003.
- Fundamentals of Computational Fluid Dynamics, H. Lomax Thomas H. Pulliam David W. Zingg, Springer Verlag
- Difference Methods for Initial-Value Problems, Robert D. Richtmyer, K. W. Morton,
- Numerical Computation of Internal and External Flows, Ch. Hirsch,Butterworth-Heinemann,
- Numerical Methods for Conservation Laws (Paperback), Randall J. LeVeque, Birkhauser, - Finite Element Methods for Flow Problems, J Donea, Antonio Huerta, John Wiley

Evaluation

The evaluation of NMFD2 is made by a written open book exam consisting of exercises which require both a good understanding of the theory and the capacity to set up, analyze and solve a CFD problem.

COMPUTATIONAL METHODS FOR INCOMPRESSIBLE FLOWS

(CMIF - 1.5 to 4.0 ECTS)
P. RAMBAUD

The course consists of lectures (1.5 ECTS) and exercises (2.5 ECTS). Students may choose to attend only the lectures.

A. Lectures (1.5 ECTS)

Learning objectives

The student must master the different discretization methods applied to the steady convection diffusion equation, with emphasis on monotonicity and accuracy. This includes finite difference, upwind finite volume schemes (including monotone schemes like MUSCL TVD) and SUPG finite element schemes.
They should understand the incompressibility condition and the role of the pressure in incompressible flows. They should also be able to solve problems governed by the full
incompressible Navier-Stokes equations and master:

- the projection method, including the different ways of coupling the velocity and pressure field (SIMPLE, SIMPLEC, SIMPLER, PISO),
- the different ways to stabilize the pressure (Brezzi-Babuska condition),
- staggered grid approaches for finite differences and non collocated finite element methods in u-v-p formulation,
- finite volume methods based on the artificial compressibility method and Lagrangian Augmented.

They should have a basic knowledge of:
- turbulence models for incompressible solvers (with focus on k-epsilon and Large Eddy Simulation),
- multiphase models for incompressible solver (with focus on VOF).

Course notes
- Computational Methods for Incompressible Flows, PowerPoint slides by P. Rambaud

Literature
Computational methods for fluid dynamics, Ferziger, J.H.; Peric, M., 3rd Edition Springer, 2002,

Evaluation
Evaluation is done through a written exam trying to measure the theoretical understanding of the
different techniques.

B. Exercises (2.5 ECTS)
The exercises consist of short problems to illustrate the theory.

Learning objectives
The students should be able to use a commercial code and an open source code to solve a specific problem by means of the different techniques presented in the lecture part. Modifications of the open source code written in Matlab will be required.

Course notes
- MatLab program to be modified

Literature
- Computational methods for fluid dynamics, Ferziger, J.H.; Peric, M., 3rd Edition Springer, 2002

Evaluation
Evaluation is done through a report showing the sensibilities of the solutions and potential benefits from modifications implemented in the solvers.

COMPUTATIONAL METHODS FOR COMPRESSIBLE FLOWS

(CMCF - 1.5 to 4.0 ECTS)
H. DECONINCK
T. MAGIN

The course consists of lectures (1.5 ECTS) and exercises (2.5 ECTS). Students may choose to attend only the lectures. This is a specialized course oriented towards the development of new advanced algorithms and software for compressible flow with application to both aeronautics and turbomachines. The student is supposed to have completed the NMFD1 and NMFD2 courses before starting this one.

A. Lectures (1.5 ECTS)

Learning objectives

A successful completion of this course requests that the student has an in depth knowledge of the modern explicit and implicit Finite-Difference, Finite Volume and Finite Element techniques for the solution of compressible Euler and Navier-Stokes equations, including:

- Finite Volume methods on structured and unstructured grids,
- the mixed fourth/second order artificial diffusion scheme of Jameson, Schmidt and Turkel,
- upwind schemes based on Godunov's method (Riemann solvers), including Flux Difference (Roe, Liu) and Flux Vector Splitting (Steger-Warming, van Leer) schemes,
- second order high resolution TVD and LED schemes combined with central and upwind discretization based on MUSCL reconstruction, flux limiting using classical limiters,
- multidimensional upwind Residual Distribution methods on unstructured grids.
- stabilized (continuous) Least Squares Galerkin Finite Element methods, SUPG stabilization, shock capturing stabilization,
- basics of Discontinuous Galerkin Finite Element methods for compressible flow and the link with Finite Volume Methods.
- explicit time integration based on multi-stage schemes,
- implicit time integration methods, Newton and quasi-Newton methods combined with iterative solvers including relaxation methods (SGS), multigrid methods, Krylov subspace methods.

Specificities of external flows (airfoils) and internal flows (nozzles, turbo-machinery cascades) should be understood.

Course notes

- Computational Methods for Compressible Flow, H. Deconinck, VKI-CN 147

Literature

- Finite Volume Methods for Hyperbolic Problems, , Cambridge University press. Randall J LeVeque
- Numerical Methods for Conservation Laws (Paperback), Randall J. LeVeque, Birkhauser
- Numerical Computation of Internal and External Flows, Ch. Hirsch, Butterworth-Heinemann
- Riemann Solvers and Numerical Methods for Fluid Dynamics: A Practical Introduction, Eleuterio F. Toro, Springer

Evaluation

The evaluation is based on an oral exam with questions, verifying the theoretical knowledge, and the explanation of an original paper from literature (given to the students a few days before the exam). Weight is 2/3 for the oral questions and 1/3 for the literature paper.

B. Exercise - project (2.5 ECTS)

For a CFD course at this advanced level it is essential to be able to convert the theory into a working computer code. Students with a good background (e.g. programming experience in a previous master's thesis) can be allowed to skip this part. This is evaluated at the beginning of the year when the course program is fixed.

Learning objectives

Completing the programming exercise serves two purposes: first, it completes the process of mastering the theory because understanding a CFD algorithm in all its facets can only be obtained by programming and testing the method in a working program. For example, use of memory, speed of the algorithms, complexity of programming (e.g. implicit versus explicit) are important elements which the student will acquire through the programming exercise. Second, the principles of incremental programming and debugging will be acquired by students who are inexperienced in programming. This experience is then further developed in the masters project.

Course notes

Not applicable

Literature

See theory

Evaluation

Attendees have to submit a detailed report on the results. The evaluation is based on an oral discussion of the project report describing the outcome of the program, supplemented with theoretical questions about the methods that have been implemented.

TWO-DIMENSIONAL BOUNDARY LAYERS (2DBL – 4.0 ECTS)

G. DEGREZ

This is the basic boundary layer course for AR students

Learning objectives

At the end of this course, the student should have a good knowledge of the different boundary layer concepts together with the equations and master the solution techniques for incompressible and compressible boundary layers. In particular he/.she should:

- know the Blasius' solution for flat plate flow, Falkner-Skan self-similar flows,
- understand the influence of pressure gradient,

- know the criteria for instability and transition (Orr-Sommerfeld equation, initial instability and growth of 3D perturbations, turbulent spots; by-pass mechanisms, receptivity) for laminar boundary layers.
- have a physical understanding of the turbulent boundary layers, know the Reynolds-averaged turbulent boundary layer equations and turbulence models.
- understand the concept of integral methods and the effect of boundary layers on outer flowviscous/inviscid interaction.

Course notes

- Laminar Boundary Layers, G. Degrez, VKI-CN 143
- 2D Boundary layers – Transition and turbulent Flows, G. Degrez, VKI-CN 143 Part II, (Draft)

Literature

- Modeling & Computation of Boundary-Layer Flows: Laminar, Turbulent & Transitional Boundary Layers in Incompressible Flows. Solutions Manual & Computer Programs, Cebeci, T. & Cousteix, J., Springer, 1st edition, June 15, 2001.

Evaluation

Evaluation is based on 3 homeworks and a written exam. The home work (weight 9/20) intends to verify if the students are able to apply the knowledge presented in the course. The written exam (weight 11/20) has 2 parts: a closed book one (6/20) to verify the knowledge related aspects, the open book one (5/20) is a further evaluation of the student’s competence to apply that knowledge.

BOUNDARY LAYERS AND FLOW SEPARATION IN THREE DIMENSIONS

(3DBL - 1.25 ECTS)
G. DEGREZ

The aim of this optional course is to provide a deep insight into the specificities of threedimensional boundary layers, i.e. the impact of cross flows, how they occur on flat plates with parabolic free stream and in flows over sheared wings (infinite swept wings). It is complementary to the course on 2D boundary layers.

Learning objectives

At the end of this course the student should have a good understanding of the boundary layer equations in surface-oriented coordinate systems, the nature of integral equations and singular points. He should also have clear insight into flow separation, the corresponding streamlines and skin friction lines, the critical points, the topological rules and their evolution with parameters, the dynamical constraints of flow patterns and vortical structures. He should be able to interpret results of 3D transonic flow calculations and surface flow visualizations.

Course notes

- Three Dimensional Boundary Layers and Separation, G. Degrez, VKI-CN 154

Literature

Bibliography listed in VKI-CN 154

Evaluation

Evaluation is based on a written exam. A closed book part (weight 10/20) verifies the knowledge related topics; the open book part verifies the student's capacity to apply that knowledge to practical cases (weight 10/20).

LOW SPEED WIND TUNNELS ANALYSIS AND DESIGN (WTAD - 1 ECTS)

B. BOTTIN

This course focuses on the different aspects of subsonic wind tunnel design i.e. industrial requirements, configuration types, sizing and geometrical and performance requirements.

Learning objectives

The objective is to make the student aware of the different non-dimensional parameters that are important in wind tunnel testing. He/she should know the different aspects of open and closed tunnels of conventional, pressurized and cryogenic operation, their power requirements and the parameters that affect the Reynolds and Mach numbers. He/she should be able to specify/select individual wind tunnel components, such as test section, diffusers, fan, corner vanes, wide angle diffusers, settling chamber, screens and honeycombs, contraction and heat exchangers. He/she should be capable of estimating the impact of design options on power and turbulence reduction requirements.

Course notes

- From Subsonic to Supersonic Wind Tunnels: Similarity Laws, Tunnel Types and Components,
Design Considerations, B. Bottin, VKI CN 151

Literature

Bibliography in VKI-CN 151

Evaluation

The evaluation consists of an individual design of a new wind tunnel (open book), followed by an oral interview. Justification of the selected design options is the major evaluation criterion.

LOW SPEED WIND TUNNEL TEST TECHNIQUES (WTTT - 1 ECTS)

B. BOTTIN
M. CARBONARO

This course offers additional information on specific wind tunnel measurement techniques for aeronautics. The first part covers wall corrections. The second one concerns force and moment measurements.

Learning objectives

After following this course the student should understand the following topics not already covered in other courses:

Part 1

At the end of this part the student should understand and master the concepts behind wall interference assessment and corrections required for testing models in open or closed sections including mechanical adaptation (flexible walls) and pneumatic adaptation (slotted walls) of wind tunnels.

The student should also be able to make rough estimations of interferences for design purposes and be familiar with the specialized literature in order to find the appropriate corrections for the tests data.

Part 2

At the end of part 2 the students should have a good knowledge of the techniques for force measurements, be able to design a multi-component strain gauge balance, know how to calculate the measuring range of an existing strain gauge balance and have the competences to apply them in a wind tunnel

Course notes

- Assessment and Correction of Wind Tunnel Wall Interferences and Wall Adaptation techniques, B. Bottin, VKI CN 161.
- Force and Moments Measurements, M. Carbonaro, (PowerPoint slides)

Literature

- Bibliography in VKI-CN 161
- Low-speed wind tunnel testing, By Rae, W.H. & Pope, A., New York : Wiley, 2nd edition, 1984.
- MicroMeasurements Datasheets

Evaluation

The evaluation consists of an individual problem for each part of the course, to be solved by the student. For part 1, this problem may be coupled with the WTAD evaluation problem in case the student follows both courses. For part 2, the evaluation is based on the understanding of a given balance architecture and the calculation of the measuring range of a given strain gauge balance.

The need for reference material justifies an open book exam for both parts. Weighting is 8/20 for part one and 12/20 for part two.

PHYSICAL GAS DYNAMICS (PHYSGD - 4 ECTS)

T. MAGIN

D. GIORDANO

Learning objectives

Addressed primarily to engineers, this course is an introduction to the basic tools of quantum mechanics, statistical physics, irreversible thermodynamics, kinetic theory, plasma physics, and collisional and radiative elementary processes, used to model and understand chemically reacting and plasma flows encountered in hypersonic and combustion applications. A series of practical problems encountered in aerospace missions will be discussed in class, focusing on the simulation of atmospheric entry flows and ground testing.

Course notes

Physical Gas Dynamics, T. Magin, VKI-CN 213 (Partial notes)

Literature

J. D. Anderson, Hypersonic and high-temperature gas dynamics, American Institute of Aeronautics and Astronautics, 2006
M. Mitchner, C. H. Kruger, Partially Ionized Gases, Wiley, 1973
G. Vincenti, C. H. Kruger, Introduction to physical gas dynamics, Wiley, 1965
L. C. Woods,The Thermodynamics of Fluid Systems, Oxford University Press, 1975
G. A. Bird , Molecular Gas Dynamics and the Direct Simulation of Gas Flows, Oxford University Press, 1994

Evaluation

Evaluation is based on 2 homeworks and 1 oral exam including the explanation of an original paper from the literature (given a few days before the exam)

LECTURE SERIES 2012-2013

1. Introduction to Measurement Techniques
   08-12 October 2012

2. Introduction to CFD
   21-25 January 2013

3. Small aeroplane Design
   25 February-01 March 2013

4. CFD for atmospheric flow and wind engineering
   11-13 March 2013

5. Accurate and efficient aeroacoustic prediction approaches for airframe noise
   25-28 March 2013

6. Aeroengine Design: from state of the art turbofans towards innovative architectures
   08-12 April 2013

7. Fluid Dynamics associated to Launcher Developers (AVT-STO)
   15-19 April 2013

8. Radiation and Gas-Surface Interaction Phenomena on High Speed Re-Entry (STO/AVT)
   06-08 May 2013

9. Turbulent combustion
   13-17 May 2013

10. 37th Computational Fluid Dynamics: Advanced algorithms
    21-24 May 2013

11. Source terms characterization of the consequences of storage tank aggression
    03-05 June 2013

12. Transition and turbulence in High-speed flow
    10-14 June 2013

13. Flow Characteristics and performance of safety valves
    09-11 September 2013

14. Accurate Temperature Measurements
    16-20 September 2013

VKI FACILITIES, INSTRUMENTATION AND COMPUTATIONAL AIDS

The information contained in the brochure entitled “Von Karman Institute, Test Facilities and Technical Support”, 50TH anniversary edition 2006 is updated and summarized here below:

MAIN FACILITIES

Low Speed Wind Tunnel L-1A : An open-jet test facility for aeronautical and industrial research and development. Test section diameter 3 m, length 4.5 m; velocity up to 60 m/s (Mach number 0.2).

Low Speed Wind Engineering Facility L-1B : A closed test section wind tunnel of 3 m x 2 m section. The length of the test section of 15m allows simulation of atmospheric boundary layers, for studies of urban microclimates and pollutant dispersal, and wind effects on buildings and structures. A special test section is available for model studies of vehicle aerodynamics. Velocity from 1 to 50 m/sec.

Low Speed Wind Tunnel L-2A : A small size, open circuit, multipurpose facility for the study of aircraft and capsule wakes, aerofoils, junction flows, jet interactions and vortical flows; section 0.28 m x 0.28 m, velocity up to 45 m/s, turbulence level 0.2%.

Low Speed Wind Tunnel L-2B : A moderate size, open circuit, multipurpose facility for the study of low speed flows: aeroelasticity, turbulence, unsteady flows, wind effects on buildings and structures, urban microclimate and pollutant dispersal, car aerodynamics. Velocity up to 30 m/s, section 0.38 m x 0.38 m equipped with moving ground belt.

Low Speed Wind Tunnels L-7 and L7+ : Two small, low cost, portable, low speed facilities, specially designed for student training in lab. Section 0.16 m x 0.16 m, velocity up to 20 m/s, turbulence level 0.2%; and 0.27 m x 0.36 m, 16 m/s, 0,5%.

Low Speed Wind Tunnels L-10 and L-12: Two small, low cost, portable, low speed facilities, using L-7 design, especially devoted to student training. Section 0.2 m x 0.2 m, velocity up to 15 m/s, turbulence level 0.3%.

Low Speed Wind Tunnels L-11 : A small, low cost, portable, low speed facility, similar to L-10, recently rebuilt to allow injection of water droplets to study particles-turbulence interactions, as well as slag entrapment in a 2D-cold flow model of a solid propellant rocket engine with submerged nozzle. Section 0.2 m x 0.2 m, velocity up to 15 m/s.

Low Speed Wind Tunnel for study of impinging jets : A duplication of the L-10 wind tunnel, adapted to accommodate an array of nozzles (perforated plate) to create air jets impinging on a heated plate. Infrared Thermography measurements, flow rate between 0.1 and 0.25 m^3/s.

Cold Wind Tunnel CWT-1 : A small thermally insulated low speed facility designed for the study and aerodynamic certification of aircraft de/anti-icing fluids. Possible cooling down to -40°C by liquid nitrogen sprays. Presently used at ambient temperature for general studies. Section 0.1 m x 0.3 m with 1.6 m length, optical access, maximum speed 70 m/s.

Adaptive Wall Wind Tunnel T'3 : A small, cryogenic, pressurizable, adaptive wall wind tunnel, on loan from ONERA to VKI. Presently run in non-cryogenic mode, for wall interference-free aerofoil testing, at Reynolds numbers from 2 x 10^5 to 1 x 10^6. Test section 0.1 m x 0.12 m, speed up to 80 m/s.

Supersonic Wind Tunnel S-1 : Continuous flow facility with low stagnation pressure for fundamental and applied research on aircraft/missile/shell shapes in transonic and supersonic regimes. Recently improved for transonic airfoil testing. Mach numbers from 0.4 to 1.0 and 2.25 in a 0.36 m x 0.4 m test section. Reynolds number 1 x 10^6/m. Equipped with a schlieren/shadowgraph imaging system, and a high accuracy Laser Doppler Velocimetry traversing table. Incorporates as an option a turbine blade cascade test section, located in the first corner, for low Reynolds number and high subsonic Mach number testing.

Supersonic Wind Tunnel S-4 : High stagnation pressure intermittent facility for basic and applied research. Mach number 3.5 in an 80 mm x 100 mm test section, with a schlieren/shadowgraph imaging system, and PIV capability. Reynolds number to 1 x 10^8/m.

Hypersonic Tunnel H-3 : High stagnation pressure blow-down facility for studies of boundary layer heat transfer, separation and transition, shock wave boundary layer interaction, simulation of ablation, aerodynamic loads. Mach number 6 in a 120mm diameter free jet, with a schlieren/shadowgraph imaging system, and infrared measurements capability. Reynolds number from 3 x 10^6/m to 30 x 10^6/m.

Hypersonic "Longshot" Tunnel : Very high stagnation pressure, short duration high Mach number facility for studies of laminar and turbulent heat transfer, transition, static and dynamic stability, flow fields around bodies and forces/moments measurements. Mach number 14 to 20 in a 250 mm diameter free jet, with a schlieren/shadowgraph imaging system. Reynolds number 3 x 10^7/m at Mach 15. Operation with nitrogen (γ = 1.41) or CO_2 (γ = 1.33), for Earth and Mars entry simulation.

The "Minitorch" : A small, 15 KW, inductively heated plasma jet facility for instrumentation studies and training. Frequency of induction heating 27 MHz, jet diameter 30 mm, discharging in a 300 mm diameter, 1.2 m long test section, where pressure can be varied from 30 mbar to atmospheric. By addition of a Laval nozzle, a supersonic plasma jet (Ma = 2.2) can be obtained. Argon, air or other gases (CO_2) can be used. Particles addition for simulation of dusty Mars atmosphere, and model pre-cooling to simulate Mars entry initial conditions. Recently added capability of simulation of Titan atmosphere radiation for the Huygens entry

The "Plasmatron" : A high enthalpy facility generating an argon, air or CO_2 plasma jet in a vacuum test section. The plasma is generated by electrical induction heating at 400 kHz, 2 kV, 8 kA to yield better purity than arcjets. Electrical supply power 1.2 MW (most powerful ICP in the world). Jet diameter is 80 or 160 mm, plasma temperatures up to 8.000°K, test chamber pressure from 1 to 200 mbar. Application to space re-entry materials testing, as well as to fundamental studies on plasma flow dynamics.

Water Tunnel WT-1 : Continuous closed loop facility using water for flow visualisation over small models. PIV and LDV measurements are also possible. Section 0.12 m x 0.24 m, length 0.9 m, full optical access, velocity up to 0,15 m/s.

Water Tables : Two free surface water tables (1.4 m x 0.9 m, and 3 m x 0.8 m) using the hydraulic analogy for the visualisation of 2-D internal and external sub-critical (Froude number less than 1) and super-critical flows (Froude number from 1 to 4).

Water Spray Test Facility WS-1: A facility for tests of water nozzles and study of interactions between single and multiple sprays and surrounding gas for pollutant abatement. Equipped with a 1 l/s, 8 bar pump and a 3 m x 4 m water collecting pool. Also used to study the infra-red radiation shielding properties of a water spray curtain.

Wind Gallery WG-1 : A specially designed very low speed wind tunnel for the investigation of dispersion of gases and absorption by water curtains: ejector driven, equipped with liquid drainage, 1 m x 1,3 m test section, 11 m long, speed $V < 4$m/s. Optional addition of rough floor for simulation of atmospheric flows.

Plate Galvanization Simulation Facility "Essor" : Consists of a water bath through which a 0.9m wide rubber belt is drawn, to simulate a steel strip coated with liquid zinc. Equipped with an air knife to study control of residual film thickness. Belt velocity up to 4 m/s. (presently disassembled)

Jet-Wiping Facility “Ondule”: Facility for the study of plane jet wiping of surfaces covered with viscous liquids, using a rotating transparent cylinder dipping in liquid bath, and wiped by a turbulent plane jet generated by a 2-D slot nozzle. Equipped to allow optical non-intrusive measurements of liquid film characteristics.

Multi-Jet Cooling Facility “Drever” :Facility for the study of fast metal strips cooling in galvanizing plants, using planar jets (more than 50 different nozzles), at velocities up to 100 m/s. Also used for metal strip vibrations studies.

Continuous Casting Simulation Facilities "Vulcain & Pluton" : Water-based facilities for the study of continuous casting of steel. Simulation of flow in the mould (1/2 scale) and in the ladle and tundish above it (1/4 scale). Full optical access for flow visualisation and non-intrusive measurements.

High-Speed Train Simulation Facility : A crossbow launcher facility used to propel train models at high speed on steel wires, to study pressure fluctuations at entrance of tunnels and underground stations. Train tunnel at 1/87 scale, tunnel length 6m, train velocity up to 150 km/h.

Aeroacoustics Facility “Acous” : For the study of coherent structures in shear layers, and of noise generation, with application to aircraft turbojet engines. Consists of 40mm and 20mm diameter steel nozzles, supplied by air ejectors through acoustically damped 0.5m x 0.5m x 2m settling chambers, and mounted inside a 4m x 3m x 3m acoustically insulated room. Fitted with loudspeakers for acoustic jets excitation. Jets velocity up to 75 m/s.

Solid Propulsion Facility "Booster": A cold flow model of a solid propellant rocket motor combustion chamber, used to study the aeroacoustics instabilities, which lead to pressure and thrust fluctuations. Axisymmetric 76 mm-diameter test section with porous walls for radial injection of cold air, in turn feeding interchangeable nozzles fitted with moveable needle to vary the throat area. Air flow rates up to 0.3 kg/s.

Biological Flows Facility "Bio" : Transparent scaled-up model of human lung bifurcations, using water-glycerol mixtures to simulate respiratory flows, specially designed for non-intrusive optical diagnostics.

Low Speed Cascade Tunnel C-1 : Continuous facility for the study of flows in low speed turbomachinery blading. Section 120 mm x 500 mm, velocity up to 100 m/s, blade Reynolds number from $5x10^4$ to $8x10^5$.

High Speed Cascade Tunnel C-3 : Intermittent facility for the study of flows in subsonic, transonic and supersonic blade cascades up to Mach 2.2. Test sections of 100 mm x 250 mm, or 200 mm x 400 mm for large subsonic model testing, inlet angle continuously adjustable. Test durations up to 10 min.

Jet Calibration facility C-4 : Vertical jet axis used to calibrate directional probes in the transonic domain, benefiting from the same 40 bar air supply system as the C3 facility. Calibration nozzle outlet diameter is 50 mm. The accuracy in the angle calibration is better than +/- 0.5 deg. Test duration up to 10 minutes

Shock Tube ST-2: small shock tube from Snecma (groupe Safran) installed at the VKI for frequency response characterization of pressure transducers and lines. Length 8000 mm, diameter 100 mm, operating pressure 2 bar.

Compression Tube CT-2 : Short duration hot compressible flow facility for studying heat transfer and film cooling effectiveness on turbine blades. Stagnation pressure and temperature ranging respectively between 0.1 to 5 bar and 300 to 600°K; flow duration 0.1 to 1.0 sec; test section 100mm x 200mm.

Compression Tube Turbine Facility CT-3 : Short duration facility for testing full scale advanced high-pressure cooled nozzle guide vanes, blade rows and complete1 and ½ stages of transonic turbines. Full simulation of Mach and Re numbers and temperature ratios; maximum outer diameter: 800 mm, maximum power: 2-3 MW. .Equipped with opto-electronic data transmission system to allow unsteady measurements on the rotating frame.

Internal Cooling Channels LC1, LC2, LC3 : Steady state or short duration test sections simulating a turbine cooling passage. Test section 50 mm x 50 mm and 100 mm x 100 mm; velocities up to 15 m/s; provision for wall surface (20 … 60°C) or flow heating (20 … 60°C).

Rotating Channel Facility RC-1: Facility to perform aero-thermal studies of low Reynolds number flows in ducts in presence of strong Coriolis forces, wall roughness and heat transfer. For application to micro gas turbines and HP turbines cooling channels. Consists of a 2.5 m diameter rotating disk, up to 160 RPM, fitted with a transparent channel and optical measurement technique (time-resolved PIV).

Low Speed Compressor Facility R-1: Open-loop continuous facility for the study of rotating stall and flow distortions in axial compressors. 50 KW motor, rotor tip diameter 700mm, blade height 75mm.

High Speed Compressor Facility R-2 : Open loop continuous facility for testing axial flow compressor stages. 185 KW motor, 10000 rpm, rotor diameter up to 50mm.

High Speed Compressor Facility R-4 : Closed loop continuous facility for testing axial and radial compressor stages. 500 KW motor, 25000 max rpm, axial rotor diameter up to 400mm. Has been refurbished and is now being equipped with a booster test section.

High Speed Radial Compressor Facility R-7 : Open loop, variable speed facility for studies of radial compressor stages. 50 KW motor, maximum shaft speed 30000 rpm.

Low Speed Turbine Facility T-1 : Open loop continuous facility for low speed flow studies in turbine stators, single stage rotors, and 1½ stages. Maximum air supply of 7 m3/s at 16 kPa.

Turbocharger Facility T-2 : Test bench for the study of turbocharger components. Microcomputer-controlled data acquisition and active surge control.

INSTRUMENTATION

Pulsed and CW Lasers : A number of He-Ne continuous lasers are available (power range from 1 to 35 mW). Four continuous Argon lasers, with power up to 5 W, are also available for visualisations, Laser Doppler Velocimetry, Rainbow Interferometry, Particle Image Velocimetry and Doppler Global Velocimetry. Three mini-YAG , for Particle Image Velocimetry, producing double pulses of 10 ns duration with spacing as low as 200 ns, at repetition frequency of 10 Hz and output energy ranging between 150 and 180 mJoule. One of these lasers can emit in the UV range as well as in the visible range. Two old Nd-YAG lasers with energy of 150 to 400 mJ are also available.. A fourth mini-YAG is part of a micro-PIV system.

Laser Doppler Velocimetry : Five complete optical systems for LDV measurements are available: three modular multipurpose systems, a TSI two-component dual color backscatter system, and two phase Doppler analysers (PDA) measuring particle size (from 1µm to 10mm) and velocity. Various accessories such as Bragg cells or beam expanders may be added to the modular optics. Five period counters are available for the Doppler signal processing. One of these accepts Doppler frequencies up to 200 MHz, and the four others operate in a range of 10 kHz to 20 MHz. The PDA have a range of 1 kHz to 30 MHz. The TSI LDV is equipped with an IFA processor working in the frequency domain.
Several traversing tables are available for use with these LDV systems. Four of them are motorised and allow displacements along three axes. Among these, a traversing table is fully computer-controlled. Airflow seeding systems include four oil-smoke

generators together with a pressurized Laskin's nozzle system and several atomizers for aerosol generation.

Particle Image Velocimetry : Over the past twenty years a large number of developments in this domain have been made at the VKI. Several home-made systems are available. The three Nd-Yag pulsed lasers described above are available for PIV. Three PCO cameras are used for PIV. They have a resolution of 1280X1024, a 12-bit output and are capable of a time interval of 200 ns between the grabbing of the two images. Each camera is associated with a frame grabber installed on a PC computer. The PCO cameras can be combined for stereoscopic measurements. PIV processing is mostly performed using the VKI-developed software WIDIM, but another processing technique also developed at VKI, the Particle Tracking Velocimetry or PTV is also available for multiphase flows. A micro-PIV system that includes a mini-YAG laser connected to a microscope through a fiber optics and a PIV camera is also available. It is used to measure single or two-phase flows in channels ranging from 25 micrometer to 2 mm.

Hot Wire Anemometers : More than 20 VKI-designed and constructed systems are available, some including a linearizer, and some without, but with a signal conditioning filter/amplifier for data acquisition. A commercial state-of-the-art 4-channel hot wire anemometry system was very recently purchased.

Microcomputers/Acquisition : More than 20 PC's equipped with multi channel analog and digital interface boards, with 12 bit resolution and acquisition frequencies ranging from 4 KHz to 1 MHz. A 96 channel, multiplexed, 100 KHz A/D 12 bit converter, PC based data acquisition system is available for the Plasmatron. Four 8-channel, 1 MHz systems are available in the TU department.

Transient Recorders : Two 32-channel non-multiplexed systems are available for the Longshot facility which may be used individually or in tandem; controlled by a PC; 50 kHz sampling rate per channel. Three additional systems for the CT2/CT3 lab, also PC-controlled, have respectively a channel capacity, max sampling frequency and memory depth per channel of: 32 channels at 1 MHz/ch 16 bits, 64 channels at 300 kHz/ch and 64 k; 8 channels at 1 MHz/ch and 256 k; 48 channels at 50 kHz/ch and 128 k.

Infrared radiometer system : 2 infrared cameras, operating in the 8 to 12 µm and in the 8 to 9 µm wavelength range, for remote, non-intrusive surface temperature mapping.

Optical pressure measurements : A UV light source, optical bench and calibration set-up for pressure sensitive paints. Compact UV light sources are now available for installation in facilities. Improved paints and a 12-bit video camera are also available

Image Acquisition and Processing: A number of video cameras, recorders and PC video acquistion/processing boards are available for use in optical/visualization experiments. A high speed camera with variable framing rate up to 100 kHz is also available for recording of transient phenomena.

Emission Spectrometer System : A spectrograph with a focal length of 1m equipped with 2 gratings (1200 gr/mm with spectral range 400-1200 nm and 3600 gr/mm with spectral range 150-450 nm) and with a LN2-cooled array of CCD detectors (800 x 2000 pixels) is available for the Plasma Facilities. Commercial software allows performing data acquisition and part of the processing on line. A new compact, fast-sample spectrometer that covers the spectral range from 200 to 900 nm provides complementary capability for temporally resolved measurements at lower spectral resolution. Two new compact, fast-sample spectrometers that cover the spectral range from 200 to 900 nm provide complementary capability for temporally resolved measurements at lower spectral resolution.

Laser Spectroscopy Optical Laboratory : : A third Nd:YAG laser is used to pump a high spectral resolution, tunable dye laser for spectroscopic experiments. This laser is also equipped with frequency tripling to obtain UV radiation for single-photon excitation of molecular species and multi-photon excitation of atomic species. Dedicated instrumentation includes fast digital oscilloscopes and a multi-channel, gated integrator detection system and a small flow reactor for calibration of fluorescence signals to allow absolute species concentration measurements.

VKI COMPUTER CENTER

The IT infrastructure in VKI consists in a wired gigabit and in a fast wireless network connecting three high performance clusters, desktop workstations, and network resources like dedicated file servers, web servers, CAD hardware, printers, scanners, etc.

The VKI local area network is connected via optical fiber to its internet service provider, Belnet, the high bandwidth Belgian national research network managed by the Federal Office for Science Policy.

IT Infrastructure

The wired network has a backbone made of fully gigabit Ethernet compliant HP Procurve switches and CAT6 cabling between buildings and main network resources. Logical trunking and physical cabling insure bandwidth up to 1 Gbit/s between all the important nodes, with a reduced speed of 100 Mbit/s for non essential clients.

A wireless network consisting of two VLANS, one for the visitors, one for the authenticated users offers a complete coverage in essential areas, thanks to seven access points directly connected to the network backbone.

Important data is stored in central servers that are object of incremental backups every night, for a capacity of over 3.6 TBs. This data is protected in addition by physical protections against hardware failure including RAID5 configurations with hot spares. CAD resources consist in several Windows and GNU/Linux workstations with 19" or 21” monitors, digitizing tablets and two HP plotters (a B/W and a photo quality color) for A0 paper format.

Workstations and User PC's

Many workstations are publicly available for designated purposes: 24 GNU/Linux workstations offers ample development capacity for students and researchers to prepare their simulations for the HPC clusters or to process their experimental data. The hardware ranges from baseline P4s, to Dual Opterons and Intel Quadcores, all running a 64bit OS and with an average of 2GB RAM for core.

Dedicated workstations assigned to users (researchers and Phds) are around forty, and range from P4s to Dual Intel Xeon Quads with 24GB of RAM for heavy meshing and simulations.

The total number of workstations located in offices, labs and public rooms is around 180. Normal productivity stations offer the Microsoft branded OS and office productivity suite, and will be more and more based on a thinclient-server architecture to reduce costs and reduce environmental footprint reducing electrical comsumption.

Parallel Computer Platforms

The main High Performance Computing (HPC) platform for students and researches, often the first contact with the HPC world, is a BEOWULF, Ethernet based parallel computer. Commodity workstations, connected via gigabit Ethernet, run under a 64bit GNU/Linux OS using the ROCKS software stack for node provisioning and the SGE Sun Grid Engine queuing system for jobs management. Currently, it counts around 300 cores and 0.6 TB of RAM. The hardware is heterogeneous, it counts P4s for serial jobs, and Intel dual and quad cores for main parallel jobs, with some Dual Opterons that will be arranged with infiniband connections in the future.

A second, denser HPC rack mounted cluster from SGI with 48 processors (including three rack-mounted units with four Intel Xeon quads each) connected via infiniband has been bought, using a financing from LMSintl, to run aeroacoustic simulations.

The current state-of-the-art HPC solution is provided by a 512-cores, 1TB RAM and 12TBs storage infiniband blade cluster used for massively parallel jobs of great scientific interest and scale. This cluster is reserved to advanced research and studies.

Software

VKI researchers and students have access to dedicated commercial scientific computing packages (e.g. Matlab, Mathcad, Tecplot, Flowmaster, SolidWorks, CosmosWorks, C/C++ and Fortan compilers) and to a series of commercial and open source CFD solvers (such as Fluent, CFX, Fine, CFD-ACE+, STAR-CD, OpenFOAM, CFD++). A number of in-house developed CFD codes are used for dedicated applications in optimization, plasma flows, aeronautics, turbomachinery, multiphase flow, turbulence modeling, large eddy simulation and aeroacoustics, exploiting the parallel computing capacity without licenses restrictions. Access to Computer Aided Design (CAD) is available in various services and in public rooms, by means of Autodesk INVENTOR running under a network license for 30 concurrent users and via VariCAD under GNU/Linux.

Internet

The VKI maintains a highly visible internet site (http://www.vki.ac.be), which contains full information about the VKI's educational programs (including Lecture Series), laboratories, ongoing research and noteworthy events. A SSL/VPN service is installed to provide secure access to VKI network for VKI personnel needing to remotely connect through Internet.

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