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Gas Turbine Course's Teaching Process at Instituto Tecnológico de Aeronáutica: Theory and Laboratory

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ABSTRACT: The Instituto Tecnológico de Aeronáutica (ITA) is an Engineering school maintained by the Air Force Command, Ministry of Defense. The aim of the Turbomachines Department at ITA is the human resources training for design and development of aeronautical and industrial gas turbines, necessary for the Gas Turbine Program of the Departamento de Ciência e Tecnologia Aeroespacial (DCTA). The human resources training is carried out in undergraduate and graduate courses at ITA, where topics in gas turbine and turbomachinery are taught. The gas turbine topic is taught in the undergraduate degree, in Mechanical-Aeronautical Engineering course, and focuses on gas turbines' performance for different configurations (turboshaft, turbojet and turbofan). Lecture notes containing the essential elements of the course are made available for the students, addressing the basic theory of the gas turbines required for the performance study at the design and off-design point. The technological aspects are presented and discussed during detailed studies of the actual cycle. Simple gas turbines and more sophisticated ones are studied, for both aeronautical and industrial application. Performance calculations at design and off-design point of the main engine's components and the cycle are done manually, encouraging students to develop spreadsheets. The theory is complemented with laboratory classes and technical visits, when the practicalities involving gas turbines operation and tests are presented to the students. As an activity laboratory class, the students perform disassembly-assembly of a small industrial gas turbine.

KEYWORDS: Teaching, Gas turbine, Performance, Preliminary design, Numerical simulation.

INTRODUCTION

Instituto Tecnológico de Aeronáutica (ITA) is a technological school focused on Engineering courses: aeronautical, mechanical-aeronautical, aerospace, electronics, computation and civil. Its mission and main aspects of original educational model is to provide research and Engineering education in support to the interests of the Brazilian defense and aerospace industry and related institutions. Academic excellence, self-discipline, citizenship development, full time students and professors, students living in campus and student-centered policy are some specific aspects of the ITA.

The Engineering courses last five years (two fundamental years and three professional years). The undergraduate gas turbines lectures are offered to the students of mechanical-aeronautical Engineering course in the second semester of the second professional year.

The students enter the gas turbine course with good knowledge of thermodynamics, fluid mechanics, heat transfer and flow machines. They had already been introduced to the operational aspects of the rotating machines from the flow machines course (compressors, turbines, pumps, velocity diagrams, losses, surge, choke etc.).

The gas turbines course (identified as MMT02) is taught during the 2nd semester of the 2nd professional year and comprises 48 lecture-hours of theory/exercises and 16 lecture-hours of laboratory. The theory classes are given in two weekdays (two hours of theory and one hour of exercise); the labs are given every other week, for two groups of students, therefore decreasing

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the number of students in the lab. Lab classes are for hands-on activities and visits to industries whose activities are linked to the gas turbines — Propulsion Division of Instituto de Aeronáutica e Espaço (IAE) at Departamento de Ciência e Tecnologia Aeroespacial (DCTA) and GE-Celma in Rio de Janeiro.

There is indication that the DCTA started activities on gas turbine area at the beginning of its existence. Plans were drawn to build a gas turbine laboratory comprising compressor, combustor, turbine and turboshaft test rigs at the PMO building (engines project), which belongs to ITA. The gas turbine activities at DCTA were discontinued and no records are now available to evaluate the extent of those activities. In 1975, DCTA restarted the gas turbine activities under a gas turbine project. Consultancy from Cranfield Institute of Technology (now Cranfield University) to establish a gas turbine group indicated that ITA should support the base of human resources training, while Cranfield would contribute essentially with specialized courses. In that period, ITA was involved with activities on gas turbines to support PMO's needs, with extra-curricular courses.

In the 1990's, ITA resumed its activities on gas turbines area, creating a new course called Gas Turbines, offered to the Mechanical Engineering undergraduate students, with focus on gas turbine performance calculations. It was decided to concentrate ITA's gas turbine activity in the graduate course due to the diversity and extent of the disciplines involved. Nevertheless, undergraduates are encouraged to take part in projects developed at the Turbomachines Department. Course projects and introduction to scientific research projects have been attracting undergraduate students, as indicated in this article.

The activities in the Turbomachines Department have been directed towards the design and development of a turbojet engine, named TAPP (aero gas turbine of small size), nowadays under development tests at APA (formerly PMO), the aero propulsion department of IAE. TAPP is financed by a consortium comprising Financiadora de Estudos e Projetos (FINEP), DCTA (ITA and IAE) and TGM Turbinas. TAPP was designed based on engine requirements of a local industry, but its gas generator was chosen for both turbojet and turboshaft versions of a 5 kN thrust and a 1.2 MW turboshaft. It is believed that such expertise can be used to improve the quality of the teaching, enrolling instructors who have practical skills acquired during the design and development of TAPP and other projects carried out at the Turbomachines Department (Bringhenti and Barbosa, 2008; Bringhenti *et al.*, 2006).

A study of the engine thermodynamics cycle is already being done (Bringhenti and Barbosa, 2004a; Silva, 2009). The engine will continue the development aiming at performance improvement by increasing pressure ratio and maximum cycle temperature.

At the time of submission of this paper, the Turbomachines Department had four staff with doctoral degrees, as well as seven PhD and ten MSc students. The Turbomachines Department is located in the building E-0028 of ITA and accommodates all the staff and full time students. Lecture rooms and offices are available for all.

Depending on the on-going projects, researchers from other institutions may work collaboratively. A few post-doctoral assignments may join the Department's workforce. It is the Department's policy to develop all computational tools needed for the design of the gas turbine's major components. Several computational codes have been specially developed for such purpose, covering design and performance calculations of both engine and components, flow calculation using Computational Fluid Dynamics (CFD) and lateral and torsional vibration (Barbosa, 1987; Bringhenti, 2003; Alves, 2003; Tomita, 2003, 2009; Tomita *et al.*, 2012). Such in-house developed codes are also used for teaching support, as presented by Tomita and Barbosa (2012) and by Barbosa and Bringhenti (2000). Current software development effort concentrates on the CFD code for turbomachines, with incorporation of chemical reactions, compressor design optimization, multi-fuel combustor design, gas turbine performance deterioration and noise prediction. Major international congresses are attended by the Department's staff and students as a means to exchange ideas and provide update. Several papers have been written as part of the project developed in the Department.

GAS TURBINE COURSE

THEORY

The course's contents and supporting literature are listed in Table 1.

In addition to the three references, the handout lists other books as well as special reports and the students are encouraged to be familiar with them. All the references are made available to the students at the ITA's library. The classes are given in Portuguese, but English may be used by invited specialists.

The course starts with an overview of gas turbine applications (industrial, aeronautical, marine, army) and configurations (single and multi-spool, low and high turbofan bypass ratios, military and civil engines) and it is stressed that physics is associated to the production of power and thrust. Cycles for production of shaft power are studied in details, followed by the cycles for aeronautical propulsion.

Table 1. Course's contents and supporting literature.

MMT-02 Gas Turbines	
Course's contents	Description, classification and applications: turboshafts, turboprops, turbojets, turbofans and ramjets. Main components and their performance characteristics: compressors, combustors, turbines, ducts, intakes and exhausts, propelling nozzles and heat exchangers. Ideal and real cycles. Enthalpy-entropy diagrams. Shaft power cycles. Cycles for aeronautical propulsion. Design and off-design performance. Performance curves. Engine decks.
Required	Flow Machines
Weekly hours	3 hours for theory and exercises, 1 hour for lab and 4 hours for home study.
References	Barbosa, J.R., 2001, "Desempenho de Turbinas a Gás", ITA coursepack; Saravanamuttoo, H.I.H, Cohen, H., Rogers, G.F.C. and Straznick, P., 2009, "Gas Turbine Theory", Sixth Edition, Prentice Hall, USA; Walsh, P.P. and Fletcher, P., 1998, "Gas Turbine Performance", Pennwell Books, Tulsa, USA, 656p.

Design and off-design performance calculations are explained in details, followed by calculations of more complex engines using in-house developed computer programs. The Gas Turbine Performance Program (named GTAnalysis), developed to assist the student in complex cycle calculation, is based on modular engine blocks build-up (Bringhenti, 2003; Barbosa and Bringhenti, 2000; Bringhenti and Barbosa, 2004a, 2004b, 2004c, 2008; Bringhenti *et al.*, 2006; Silva, 2009). The interacting blocks describe the actual component performance to produce high-fidelity gas turbine model and actual engines are quite well modeled. Combining the blocks adequately, it is possible to numerically simulate almost all types of gas turbines (turboshafts, turbojets and turbofans). The program is equipped with libraries of compressors, combustion chambers and turbine maps, which are selected to better represent the studied engine. The program's capabilities have been disclosed by means of publications (Barbosa and Bringhenti, 1999; Bringhenti, 1999; Bringhenti and Barbosa, 2002, 2004a, 2004b, 2004c, 2004d; Barbosa *et al.*, 2011; Tomita *et al.*, 2005; Bringhenti *et al.*, 2010; Silva, 2007; Silva *et al.*, 2005). In addition to the steady state design point performance calculation, the program is able to simulate gas turbines' performance at off-design points, transient operation, using nozzle, compressor and turbine variable geometry, as well as to predict the engine's noise and performance deterioration. If it is necessary to evaluate a specific engine to be designed, the major component maps (compressor, combustor and turbine) can be generated using in-house developed software (Barbosa, 1987; Bringhenti, 2003; Tomita, 2003, 2009). The students have access to the program to evaluate: gas turbine's performance configurations; the importance of variation in main parameters; the best cycle parameters and configurations for a given application; engine degradation. The students are also encouraged to develop their own programs during the course.

Engine decks, like the ones used by the aeronautical industry, are discussed and the in- house developed high-fidelity gas turbine performance calculation is presented. Gas turbine modeling and performance calculations are carried out by the students. Phenomena like choke, stall and surge are presented. The program developed can also be used as a supporting tool in undergraduate and graduate courses. It will allow the discussion of more complex exercise and examples during class. The "student version" is an executable file through which the student has access only to the information he/she needs for his/her particular study. Due to the complexities of the calculations involved, only simplified problems are approached in classroom. More complex calculations are just introduced to the students in a quantitative way. Due to this simplification, important passages in the resolution of exercises are omitted.

The commercially available computer programs were developed for specific tasks and settings and, therefore, cannot be used for general purpose, as well as for any configuration and application. As the programs are developed in this manner, in most cases, not flexibly, they cannot be used for a particular case of study, if it was not previously foreseen. These programs, for example, do not allow users — even advanced ones — to have access to the source code, allowing them to modify the code for a specific case study, which prevents certain types of studies/application.

Several universities, industries and researchers are devoting time to develop gas turbine performance simulation programs around the world, among them, McKinney (1967), that developed SIMulation Of Turbofan Engine (SMOTE); NASA, which developed the GENeralized ENGine (GENENG); Koenig and Fishback (1972), Fishback and Koenig (1972), that developed an advanced version of the GENENG, named GENENG II. Besides, Szuk (1974) developed a computer program named HYDES, a hybrid, analogical and digital program. Sellers and Daniele (1975) developed the DYNGEN, a program for calculating steady-state and transient performance of turbojet and turbofan engines. Wittenberg (1976), OTAN, developed a computer program for off-design performance calculation of turbojet and turbofan. At Cranfield University, Palmer (1967, 1983, 1990) and Palmer and Yang (1982) started to develop gas turbine performance simulations programs, TURBOMATCH and TURBOTRANS. Flack (1990), Stamatis *et al.* (1990), Ismail and Bhinder (1991) also contributed to the developments in this area. TESS (University of Toledo, Reed and Afjeh, 1994); ON-X/OFF-X (Mattingly, 1996). The industry contributed to the development of SOAPP (P&W), CWS/ICS (GE), GECAT/NEPP (SRS Technologies, 2007), TERMAP (2000) (Allison/USAF), RRAP (Rolls Royce), JANUS (Snecma), FAST (Honeywell Allied Signal), ATEST (AEDC, Chappell and McLaughlin, 1993), GASTURB (2015) and GSP (2015).

Invited lecturers may contribute to the course, giving their lectures in other languages, mainly in English. The classes follow the traditional teaching methods, with support of computational resources. The students must attend the lectures and, if they fail to do so, they must justify to their counselor and submit written justification to ITA. Depending on the justification, it is made available to the student a special psychological support.

The course's targets are set in the first lecture, specifying the minimum knowledge expected from the student after each chapter is concluded. For example, at the end of the fundamentals of gas turbine performance, the students must master:

- Description of a gas turbine working at off-design condition.
- Calculation of steady-state operating lines for the different types of gas turbines.
- Utilization of computer programs for performance calculations.
- Correct utilization of engine decks.

Assessment is made based on these targets through two bi-monthly tests, which include theoretical and practical exercises, as well as a final exam. The minimum final score is 65%. If the student gets a score below 50%, his/her enrollment with ITA is finished.

Use is made of a PT6 Pratt & Whitney turboshaft engine to show the students the major engine components and internal flow path. Figure 1 shows details of the engine.

Figure 1. PT6 sectional view.

ENGINEERING EDUCATION METHODS SOUGHT AT THE TURBOMACHINE DEPARTMENT

New Engineering education methodologies have been changing and implemented based on several experiences using different teaching manners to deliver good lectures, facilitating the transfer of information (Mazur, 2012). Generally, the proposals for the culture change in Engineering education modify the course's syllabus and, sometimes, a huge course reconstruction is necessary (Karltun, 2013; Kamp and Klaassen, 2013).

Some of the habits to improve the Engineering education have to be updated and this is not a trivial process because it depends on a common action and culture change. Goldberg (2013) related some important aspects and described some key-points about three habits that must be rethought:

- Noticing, Listening and Questioning: this is applied for both instructors and students.
- Dot Connecting: the need for changing the Engineering education at so many levels as departments, systems, society and schools.
- Collaborative Disruption: the competition between different institutes should be analyzed. Generally, the competition for innovation brings advantages for one institute or another. The open innovation movement sounds a good way to be applied among different schools.

Actually, one of the most common methodologies is presented in Darmofal (2012), in which the Concept, Design, Implement and Operate (CDIO) was applied in Aero Astro at MIT. The change in course's syllabus and research cycle are presented and explained based on lessons learned. There are several CDIO implementations and results in the literature; it is interesting to understand them and to find out what are the experiences and format to adopt for each particular case or course (Karltun, 2013; Al-Atabi, 2013; Koster *et al.*, 2013; Malmqvist *et al.*, 2010; Friesel, 2013; Hoffman, 2013; Lassudrie and Kontio, 2013; The Royal Academy of Engineering and Massachusetts Institute of Technology, 2012). The need for accomplishing a good matching between practice and science can be achieved using CDIO education process as presented in Fig. 2.

The new engineer's generation should be flexible and adapted to the modern world. Personal values, different skills, social and mutual interaction are important items to reach success in a globalization era (Friesel, 2013; Mäkimurto-Koivumaa *et al.*, 2013). Figure 3 shows the coupling requirements to be an entrepreneurial professional (Mäkimurto- Koivumaa *et al.*, 2013).

To achieve these goals, it is highly necessary to have a solid communication between instructor and student. A collaborative class makes big and profound differences to educational process. An interesting structure was studied and presented in Connor (2013), including many students' testimonials, how to manage tasks, team work, preconceptions and so on.

The methodology called ICED (Connor, 2013) brings an idea to infuse creativity and innovative education process based on a team-oriented and problem-based learning program. This involves since science, technology, Engineering and Mathematics (STEM) until science and technology (S&T) focuses. The purpose is to integrate basic Engineering concepts with problem-solving techniques involving real world problems. A schematic diagram of ICED is shown in Fig. 4.

The general ideas of each Engineering education methods can be found in Chubik and Zamyatina (2013). The authors mention the implementation of Elite Engineering Education Program

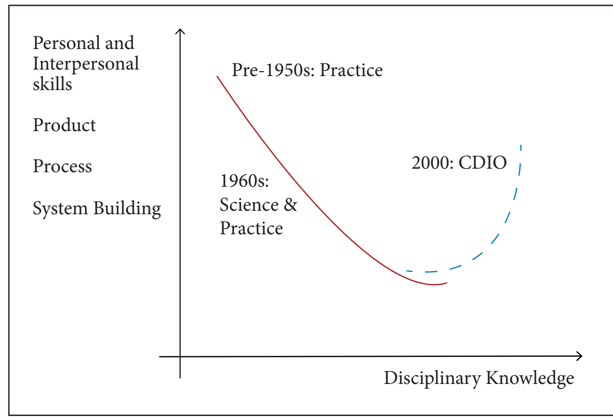


Figure 2. Improvements desired in education applying CDIO.

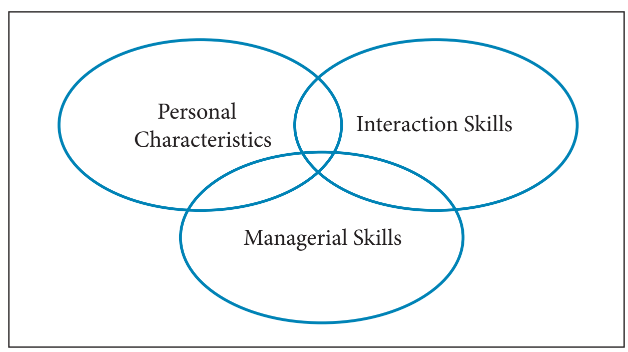


Figure 3. Entrepreneurial behavior and mindset.

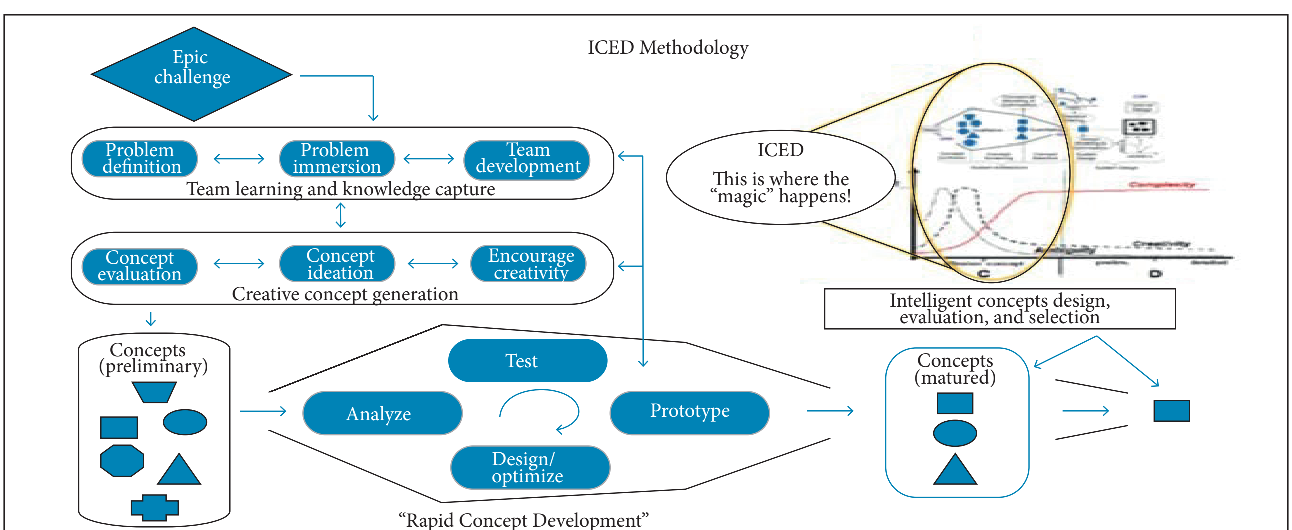


Figure 4. The concept of ICED methodology (Camarda et al., 2013 - courtesy of the authors).

(EEEP) and its capabilities to create competencies with profound fundamental knowledge in Physics, Mathematics and Economics, leadership and team-building qualities, including participation in project-oriented activities. The need for innovation and competition strategies of the industry and society are described and discussed.

What is in common between these methodologies and techniques? All of them mention the importance of Engineering education for interdisciplinary future (Yang, 2009). The characteristics of new professionals should be highly inter and multidisciplinary. The student's skills must be vastly explored. These abilities start in the classroom with adequate and effective education process.

LABORATORY

A gas turbine laboratory requires special and expensive infrastructure. ITA's Gas Turbine Laboratory uses ITA's and IAE's facilities. ITA has two Rover turboshaft engines, model IS60 (45 kW). This engine runs using kerosene and its power is measured through a dynamometer. The former is used only for hands-on training activity (disassembling-assembling). IAE has a 320 N turbojet engine of its own design and development, which runs on liquid (kerosene, diesel, ethyl alcohol and biofuels) and natural gas fuels, and a gas turbine test stand kit, whose details are described below.

The Gas Turbine Laboratory course is based on the following activities:

- Engines at lab: the students are presented to the Rolls-Royce Viper engine, located at the lab. The engine had parts of its body removed, so that the major components can be seen, as shown in Fig. 5. The students, who have already learnt the component associated theory, are induced to answer simple questions about the engine operational characteristics.

The Wright Cyclone engine is used to teach at the lab. Although this engine is very old and is a piston engine, it is used to show the engine's evolution, quoting the major modifications along the time. This engine is coupled to an electrical motor that makes it to work.

In Fig. 6, it is shown one of the first gas turbine engines produced by Rolls-Royce the Derwent. This engine is used as a tool to help to explain the gas turbine's evolution, major modifications and applications of each engine type.

- Visit to GE, Rio de Janeiro, Brazil: it is an engine overhaul company. In this visit, the students have contact with medium and large aero gas turbine engines. All areas are visited by students and detailed information of the activities are explained by GE's staff, associating lecture information with hardware: high-performance fan blades, compressor blade airfoils, Low-Pressure Compressor (LPC), High-Pressure Compressor (HPC), Low-Pressure Turbine (LPT), High-Pressure Turbine (HPT), rotating groups, cooled blades, wall treatments, bypass duct, cold and hot parts, filters, pumps, lubrication systems, secondary flow path, Full Authority Digital Engine Control (FADEC), bearings and its installation positions, blade overhauling, blade material analysis, corrosion, balancing and engine's assembly area.
- Visit to Propulsion Division of the IAE: The DCTA gas turbine project is housed in this institute. Some publications made by the Gas Turbine Group at

Figure 5. Viper engine with its main parts exposed.

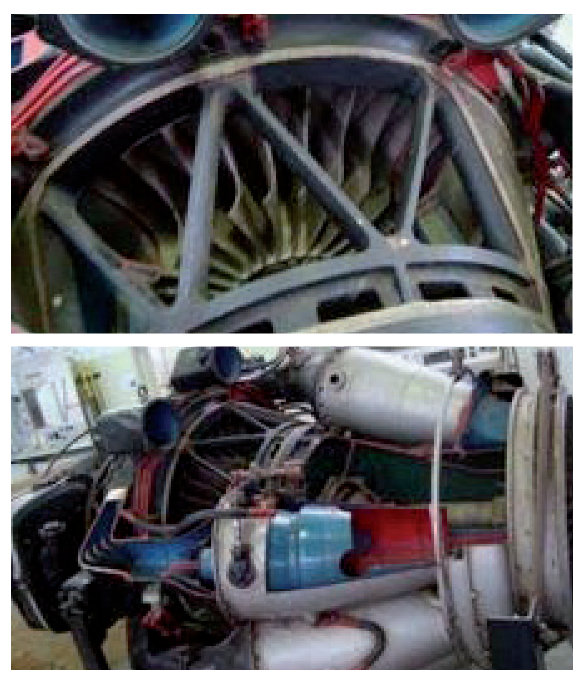


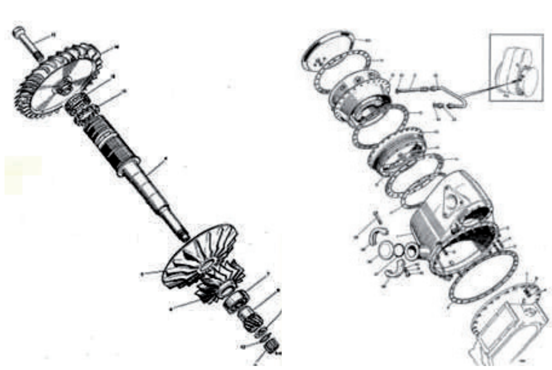
Figure 6. Rolls-Royce Derwent.

ITA/IAE (DCTA) (Bringhenti and Barbosa, 2003, 2004c, 2004d; Barbosa *et al.*, 2011, 2012; Tomita *et al.*, 2005; Bringhenti *et al.*, 2010; Silva, 2007; Silva *et al.*, 2005; Creci Filho *et al.*, 2009, 2011) indicate the capability of gas turbines' design and development. In this visit, the students are presented to test facilities, including one of the piston engines. The 15 kN turbojet test facility, which is used to test the 5 kN turbojet under development, is presented in details to the students.

- Small gas turbine engine's disassembly and assembly: usually performed with a small gas turbine, namely the 45 kW Rover IS/60 engine. Firstly, the students are briefed about the engine configuration (compressor type, combustion chamber type, dynamometer, operational envelope, gearbox, among others) with focus on the engine's components. Then, the 60 kW Rover IS/90 engine, which is installed in a dynamometer, is presented to the students, together with significant engine's drawings to support the disassembly. Figure 7 shows some of such drawings that help the students to find the adequate order in which each component should be removed.

This is particularly interesting for understanding the way the engine's components are linked to each other, besides details of couplings and bearings and their locations in the engine. Although this is a simple engine, it is possible to deduce what are the parts and their role in more sophisticated gas turbines.

Figure 8 shows the Rover gas turbine disassembled at lab. The engine is used by the students to assemble and disassemble, which approaches them to the real engine's components and



(a) (b)

Figura 7. (a) Rotating group (centrifugal compressor and axial turbine), (b) Engine's external parts (casing, seals, ducts, connections etc.).

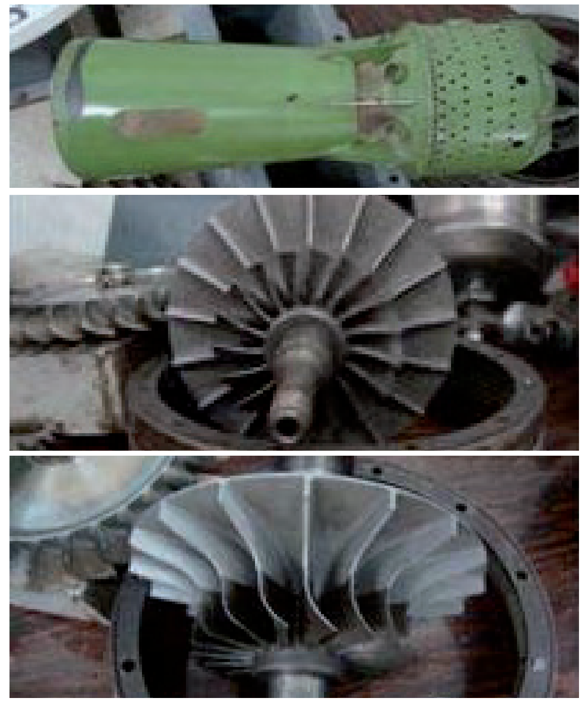


Figure 8. Rover gas turbine's components disassembled.

stimulates them to make questions. The procedure is accompanied by the professor, while the students make questions about engine and components.

- Engine's run and data acquisition: the students follow an engine's run, from the test preparation to the data acquisition. They are briefed about the test rig and its hydraulic dyno. The engine is the Rover IS/60 turboshaft engine, running with kerosene (Jet-A). A technical report must be submitted by the students, containing the engine's performance calculation obtained from data reduction acquired during the lab class.

Figure 9 shows view of the gas turbine's installation. Recorded data are inlet temperature, fuel pump pressure, fuel consumption, engine's rotational speed, applied load, temperatures and pressures at compressor and turbine's inlet and outlet. Required results are the engine's performance showing fuel consumption, efficiency, pressure ratio and shaft power.

Figure 10 shows the new gas turbine demonstrator purchased for educational purpose and housed at IAE. The Mini Gas Turbine Power System (http://www.turbinetechnologies.com) is a self-contained jet engine laboratory, the SR-30 Turbojet engine. All aspects of the gas turbine's theory, flowpath and thermodynamics are easily demonstrated and readily explored.

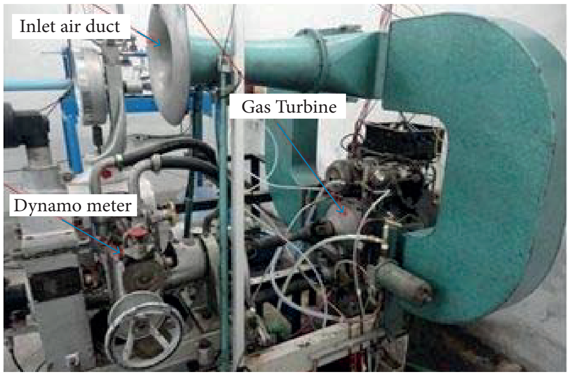


Figure 9. Lateral view of the Rover IS/60 gas turbine.

Figure 10. Mini gas turbine's power system.

RESEARCH CARRIED OUT BY UNDERGRADUATE STUDENTS (FINAL PROJECT AND INTRODUCTION TO SCIENTIFIC RESEARCH)

The Turbomachines Department encourages undergraduate students to start their end-of-course projects (monograph of Engineering undergraduate course) at their fourth year, to give them time to go deeper in their researches. The studies made by Sabóia Filho (2011), Ando (2010), Martins (2011), Müller (2011), Ibler (2011) and Carvalho (2012) show some of the research carried out by undergraduate students, in support to the gas turbine activities of the Department.

INTEGRATED ENGINEERING-MASTER PROGRAM

High-end undergraduate students may follow the Integrated Engineering-Master's Program (PIGM), enrolling to post-graduate courses concomitantly with their undergraduate courses, during the fifth year. This would enable them to complete the Master program in one additional year, that is, the student may leave ITA with the Engineering and the Master's degrees in six years. It is strongly recommended that the Master's dissertation be associated to the end-of-course project. As a result, the student that intends to continue with a doctoral program would spend one less year if he/she joins the PIGM program.

LESSONS LEARNED, COMMENTS AND CONCLUSIONS

The Engineering education process has been changing during the last years. Several new techniques and methodologies were created and evaluated to measure the teaching quality and effectiveness. Methodologies as CDIO, used at Chalmers University, MIT and Linköping University (Malmqvist *et al.*, 2010), present the importance of updating the education's development process.

At ITA, the Gas Turbines course is currently focused on the traditional methodology, associating theory and lab classes, but the introduction of hands-on on more complex Engineering problems is being progressively implemented, mainly in the graduate courses. For example, the students are requested to follow the whole design process of a gas turbine's part/component and its manufacturing process (machining) to get acquainted with real life procedures.

The coupling of theory and lab has proved to be very important so far. The students confirm that they understand more easily the subjects taught during the lectures when they see and feel the hardware. Moreover, lab exercises complete the theory, since, generally, the book's exercises have little of practical content.

The lecturers of Turbomachines Department have plans to implement the use of lab classes, despite the high costs. For example, the IAE's Gas Turbine Laboratory is being improved with engine test stand, compressor and overspeed test rigs, so that the students will have new test facilities to exercise their abilities. The test stand is being finalized, where the 5-kN gas turbine is being tested this year.

Taking advantage of the development of computational tools and manufacturing processes for gas turbine's components, a small gas turbine project is being developed at DCTA. A 5-kN/1.2-MW turbojet engine is already in the turbojet's test bed (not shown here) for the performance assessment, after a series of cold runs to check lubrication and vibration. ITA, IAE (DCTA) and TGM Turbinas, a Brazilian steam-turbine industry, are working in this project. The developed gas turbine is a 5:1 pressure ratio, 5-stage transonic axial compressor, single-stage axial turbine and multifuel annular combustion chamber.

Students have been involved in current developments and it is expected that the lessons learned can provide the basis for a new Engineering education methodology and improvement. Effort is being made to work with other universities in order to learn their experiences and incorporate them to our courses (Konstantinos *et al.*, 2012).

The result of the work being done by the Turbomachines Department in undergraduate, graduate (Professional Master, MSc and PhD) as well as in training courses has been helping the industry to hire professionals qualified in turbomachines.

Recently, the DCTA/IAE/TGM absorbed students that finished the Professional Master program at ITA to work in their gas turbine development programs, test bench development and tests. The gas turbine under development (Fig. 11) at DCTA by IAE/TGM is also supported by ITA's staff.

The Turbomachines Department contributes to training professionals who are already working at the industry, as DCTA/IAE, EMBRAER, PETROBRAS, TGM Turbinas and Thermal Power Plants. The training process is done through short courses or through integration of these professionals in Master's and PhD programs at ITA.

Figure 11. Gas turbine designed by IAE, TGM and ITA.

ITA has agreements with universities abroad, thus students who complete the Master's degree in Brazil can do PhD or sandwich PhD abroad. The goal is: when they return to Brazil, they initiate other gas turbine research groups.

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REFERENCES

Al-Atabi, M., 2013, "Grand Challenges for Engineering and Development of CDIO Skills", Proceedings of the 9th CDIO Conference, MIT and Harvard University School of Engineering and Applied Sciences, Cambridge, USA.

Alves, M.A.C., 2003, "Non-Adiabatic Transient of Gas Turbines" (in Portuguese), Ph.D. Thesis, Technological Institute of Aeronautics, São José dos Campos, Brazil, 2003.

Ando, V.F., 2010, "Project Optimisation of High-Performance Axial Flow Compressor" (in Portuguese), Final Project, Technological Institute of Aeronautics, São José dos Campos, 2010.

Barbosa, J.R., 1987, "A Streamline Curvature Computer Programme for Performance Prediction of Axial Compressors", Ph.D. Thesis, Cranfield Institute of Technology, Cranfield, UK.

Barbosa, J.R. and Bringhenti, C., 1999, "Gas Turbine Performance Numerical Simulation", Proceedings of Congresso Brasileiro de Engenharia Mecânica (COBEM), Águas de Lindóia, Brazil.

Barbosa, J.R. and Bringhenti, C., 2000, "Numerical Simulation in Classroom", Proceedings of Congresso Nacional de Engenharia Mecânica (CONEM), Natal, Brazil.

Barbosa, J.R., Bringhenti, C. and Tomita, J.T., 2012, "Gas Turbine Transients with Controlled Variable Geometry", ASME Turbo Expo 2012, Copenhagen, Denmark.

Barbosa, J.R., Jefferds, F.S.S., Tomita, J.T. and Bringhenti, C., 2011, "Influence of Variable Geometry Transients on Gas Turbine Performance", Proceedings of ASME TURBO EXPO 2011, Vancouver, Canada.

Bringhenti, C., 1999, "Steady State Gas Turbine Performance Analysis" (in Portuguese), Master Thesis, Technological Institute of Aeronautics, São José dos Campos, Brazil.

Bringhenti, C., 2003, "Variable Geometry Gas Turbine Performance Analysis", Ph.D. Thesis, Technological Institute of Aeronautics, São José dos Campos, Brazil.

Bringhenti, C. and Barbosa, J.R., 2002, "Study of an Industrial Gas Turbine with Turbine Stators Variable Geometry", 9th Brazilian Congress of Thermal Engineering and Sciences, Caxambú, Brazil.

Bringhenti, C. and Barbosa, J.R., 2003, "Analysis of Gas Turbine Off-Design Safe Operation Using Variable Geometry Compressor", Proceedings of International Congress of Mechanical Engineering, São Paulo, Brazil.

Bringhenti, C. and Barbosa, J.R., 2004a, "Gas Generator Study for Use in Turboshaft and Turbojet", Proceedings of Congresso Nacional de Engenharia Mecânica (CONEM), Belém, Brazil.

Bringhenti, C. and Barbosa, J.R., 2004b, "Part-Load Versus Downrated Industrial Gas Turbine Performance", Proceedings of ASME Turbo Expo 2004: Power for Land, Sea, and Air, Vienna, Austria.

Bringhenti, C. and Barbosa, J.R., 2004c, "Performance Study of a 1 MW Gas Turbine", Proceedings of the 10th Brazilian Congress of Thermal Sciences and Engineering, Rio de Janeiro, Brazil.

Bringhenti, C. and Barbosa, J.R., 2004d, "A Methodology for Gas Turbine Performance Improvement Using Variable Geometry Compressors and Turbines", Journal of Power and Energy (Part A), Vol. 218, pp. 541-549.

Bringhenti, C., and Barbosa, J.R., 2008, "Effects of Turbine Tip Clearance on Gas Turbine Performance", Proceedings of ASME Turbo Expo 2008: Power for Land, Sea and Air, Berlin, Germany.

Bringhenti, C., Tomita, J.T. and Barbosa, J.R., 2010, "Performance Study of a 1 MW Gas Turbine Using Variable Geometry Compressor and Turbine Blade Cooling", Proceedings of ASME Turbo Expo 2010: Power for Land, Sea, and Air, Glasgow, UK.

Bringhenti, C., Tomita, J.T., Souza Júnior, F. and Barbosa, J.R., 2006, "Gas Turbine Performance Simulation Using an Optimized Axial Flow Compressor", Proceedings of ASME Turbo Expo 2006: Power for Land, Sea, and Air, Barcelona, Spain.

Camarda, C.J., Weck, O. and Do, S., 2013, "Innovative Conceptual Engineering Design (ICED): Creativity and Innovation in a CDIO-Like Curriculum", Proceedings of the 9th CDIO Conference, MIT and Harvard University School of Engineering and Applied Sciences, Cambridge, USA.

Carvalho, D.S., 2012, "Determinação das Características de Operação de Uma Turbina de Fluxo Radial Utilizando a Técnica da Dinâmica dos Fluidos Computacional" (in Portuguese), Final Project, Technological Institute of Aeronautics, São José dos Campos, Brazil.

Chappell, M.A. and McLaughlin, P.W., 1993, "Approach to Modeling Continuous Turbine Engine Operation from Startup to Shutdown", Journal of Propulsion and Power, Vol. 9, No. 3, pp. 466-471.

Chubik, P.S. and Zamyatina, O.M., 2013, "Training Elite Specialists in Engineering and Technologies", Proceedings of the 9th CDIO Conference, MIT and Harvard University School of Engineering and Applied Sciences, Cambridge, USA.

Connor, J., 2013, "Listening by Design: Teaching Students to Be More Collaborative", Proceedings of the 9th CDIO Conference, MIT and Harvard University School of Engineering and Applied Sciences, Cambridge, USA.

Creci Filho, G., Menezes, J.C. and Barbosa, J.R., 2009, "Numerical Modal Analyses of Blades and Rotors in a Single Spool Gas Turbine", Proceedings of the International Symposium on Dynamic Problems of Mechanics, Angra dos Reis, Brazil.

Creci Filho, G., Menezes, J.C. and Barbosa, J.R., 2011, "Rotordynamic Analysis of a 5- Kilonewton Thrust Gas Turbine by Considering Bearing Dynamics", Journal of Propulsion and Power, Vol. 27, No. 2, pp. 330-336.

Darmofal, D., 2012, "Rethinking Engineering Education: An Overview of the CDIO Approach", LASPAU/Brazil Program, Harvard University, Cambridge, USA.

Fishback, L.H. and Koenig, R.W., 1972, "GENENG II: A Program for Calculating Design and Off-design Performance of Two-and Three-Spool Turbofans with as Many as Three Nozzles", NASA, Washington, DC, USA.

Flack, R.D., 1990, "Analysis and Matching of Gas Turbine Components", International Journal of Turbo and Jet Engines, Vol. 7, pp. 217-226.

Friesel, A., 2013, "Engineering Education Resulting in Skilled, Inventive and Innovative Professionals, How?", Proceedings of the 9th CDIO Conference, MIT and Harvard University School of Engineering and Applied Sciences, Cambridge, USA.

GASTURB, 2015, "Gas turbine performance… has to be understood by all concerned with gas turbine technology", Retrieved in January 23, 2015, from http://www.gasturb.de/

Goldberg, D., 2013, "Three Habits at Three Levels for Improved Engineering Education, Huff Post, Education", Retrieved in January 23, 2015, from http://www.huffingtonpost.com/david-goldberg/3-habits-at-3-levels-for-_b_1751699.html.

GSP, 2015, "Gas Turbine Simulation Program", Retrieved in February 01, 2015, from http://www.gspteam.com/home

Hoffman, J.A., 2013, "Evolution of MIT's 'Introduction to Aerospace Engineering and Design' Course", Proceedings of the 9th CDIO Conference, MIT and Harvard University School of Engineering and Applied Sciences, Cambridge, USA.

Ibler, F., 2011, "Flow Calculations Within Axial Compressor Based on CFD Techniques and Its Comparison with Streamline Curvature Results" (in Portuguese), Final Project, Technological Institute of Aeronautics, São José dos Campos, Brazil.

Ismail, I.H. and Bhinder, F.S., 1991, "Simulation of Aircraft Gas Turbine Engines", Journal of Engineering for Gas Turbines and Power, Vol. 113, No. 1, pp. 95-99. doi: 10.1115/1.2906536

Kamp, A. and Klaassen, R., 2013, "Making Curricular Change: Case Report of a Radical Reconstruction Process", Proceedings of the 9th CDIO Conference, MIT and Harvard University School of Engineering and Applied Sciences, Cambridge, USA.

Karltun, J., 2013, "Renewal of a Local Concept for Engineering Education Including CDIO", Proceedings of the 9th CDIO Conference, MIT and Harvard University School of Engineering and Applied Sciences, Cambridge, USA.

Koenig, R.W. and Fishback, L.H., 1972, "GENENG: a Program for Calculating Design and Off-design Performance for Turbojet and Turbofan Engines", NASA,Washington, DC, USA.

Konstantinos, K., Gronstedt, T. and Barbosa, J.R., 2012, "Gas Turbine Lessons Learned from the Development of Courses on Gas Turbine Multi-Disciplinary Conceptual Design", ASME Turbo Expo 2012, Copenhagen, Denmark.

Koster, J.N., Uhmeyer, K.L. and Soin, G.S., 2013, "Designing a Blended Wing Body Aircraft Globally", Proceedings of the 9th CDIO

Conference, MIT and Harvard University School of Engineering and Applied Sciences, Cambridge, USA.

Lassudrie, C. and Kontio, J., 2013, "Managing the Continuous Improvement Loop of Educational Systems: Students as Key Actors in Program Evaluation", Proceedings of the 9th CDIO Conference, MIT and Harvard University School of Engineering and Applied Sciences, Cambridge, USA.

Mäkimurto-Koivumaa, S., Väänänen, M. and Belt, P., 2013, "Developing Engineering Education to Support Entrepreneurial Behavior", Proceedings of the 9th CDIO Conference, MIT and Harvard University School of Engineering and Applied Sciences, Cambridge, USA.

Malmqvist, J., Bankel, J., Enelund, M., Gustafsson, G. and Wedel, M.K., 2010, "Ten Years of CDIO - Experiences from a Long-Term Education Development Process", Proceedings of the 6th International CDIO Conference, École Polytechnique, Montréal, Canada.

Martins, V.A.C., 2011, "Projeto Preliminar de uma Turbina Axial para Uso em Turbinas a Gás de Pequena Potência" (in Portuguese), Final Project, Technological Institute of Aeronautics, São José dos Campos, Brazil.

Mattingly, J.D., 1996, "Elements of Gas Turbine Propulsion", McGraw-Hill, New York, USA.

Mazur, E., 2012, "Educating the Innovators of the 21st Century", LASPAU/Brazil Program, Harvard University, Cambridge, USA.

McKinney, J.S., 1967, "Simulation of Turbofan Engine - SMOTE: Description of Method and Balancing Technique", pt. 1-2, Air Force Aero Propulsion Lab., s.l..

Müller, L., 2011, "Cálculo de Escoamento Turbulento em Uma Turbina Axial de Simples Estágio Aplicando a Técnica da Dinâmica dos Fluidos Computacional" (in Portuguese), Final Project, Technological Institute of Aeronautics, São José dos Campos, Brazil.

Palmer, J.R., 1967, "The 'TURBOCODE' Scheme for the Programming of Thermodynamic Cycle Calculations on an Electronic Digital-Computer", CoA Report Aero 198, Cranfield Institute of Technology, Cranfield, UK.

Palmer, J.R., 1990, "The TURBOMATCH Scheme for Aero/Industrial Gas Turbine Engine Design Point/Off Design Performance Calculation", Thermal Power Group, Cranfield University, Cranfield, UK.

Palmer, J.R., 1983, "The 'TURBOMATCH' Scheme for Gas Turbine Performance Calculations, User's Guide", Cranfield Institute of Technology, Cranfield, UK.

Palmer, J.R. and Yan, C.Z., 1982, "TURBOTRANS: a Programming Language for the Performance Simulation of Arbitrary Gas Turbine Engines with Arbitrary Control Systems", s.n., s.l.

Reed, J.A. and Afjeh, A.A., 1994, "Development of an Interactive Graphical Propulsion System Simulator", June 1994.

Sabóia Filho, F.A.T., 2011, "Turbojet: an Overview on Design, Off-design and Transient Performance", Monograph, Technological Institute of Aeronautics, São José dos Campos, Brazil.

Sellers, J. and Daniele, C., 1975, "Dyngen: a Program for Calculating Steady-State and Transient Performance of Turbojet and Turbofan Engines", NASA, Washington, DC, USA.

Silva, F.A., 2009, "Preliminary Design and Analysis of a One Stage Axial Flow Turbine for Conversion of a Turbojet into a Turboshaft" (in Portuguese), Master Thesis, Technological Institute of Aeronautics, São José dos Campos, Brazil.

Silva, F.J.S., 2007, "Gas Turbines Transient Performance Study for Axial Compressor Operation Characteristics", Proceedings of the 19th International Congress of Mechanical Engineering, Brasília, Brazil.

Silva, F.J.S., Bringhenti, C. and Barbosa, J.R., 2005, "Transient Performance of Gas Turbine, Proceedings of the 18th International Congress Mechanical Engineering, Ouro Preto, Brazil.

SRS Technologies, 2007, "Graphical Engine Cycle Analysis Tool, GECAT", www.stg.srs.com.

Stamatis, A., Mathioudakis, K. and Papailiou, K.D., 1990, "Adaptive Simulation of Gas Turbine Performance", Journal of Engineering for Gas Turbines and Power, Vol. 112, No. 2, pp. 168-175.

Szuk, J.R., 1974, "Hydes: a Generalized Hybrid Computer Program for Studying Turbojet or Turbofan Engine Dynamics", NASA, Washington, DC, USA.

TERMAP, 2000, "Innovative Visual Modeling Environment for Turbine Engine Reverse Modeling Aid Program (TERMAP)", SRS Technologies, www. stg.srs.com

The Royal Academy of Engineering and Massachusetts Institute of Technology, 2012, "Achieving Excellence in Engineering Education: The Ingredients of Successful Change", Retrieved in January 23, 2015, from http://www.raeng.org.uk/publications/reports/achieving-excellence-in-engineering-education

Tomita, J.T., 2003, "Numerical Simulation of Axial Flow Compressors", Master Thesis, Technological Institute of Aeronautics, São José dos Campos, Brazil.

Tomita, J.T., 2009, "Three-Dimensional Flow Calculations of Axial Compressors and Turbines Using CFD Techniques", Ph.D. Thesis, Technological Institute of Aeronautics, São José dos Campos, Brazil.

Tomita, J.T. and Barbosa, J.R., 2012, "Numerical Tools for High Performance Axial Compressor Design for Teaching Purpose", Proceedings of the ASME Turbo Expo 2012, Copenhagen, Denmark.

Tomita, J.T., Bringhenti, C. and Barbosa, J.R., 2005, "Study of the Air Bleed Influence in the Industrial Gas Turbine Performance", Proceedings of the 18th International Congress of Mechanical Engineering, Ouro Preto, Brazil.

Tomita, J.T., Bringhenti, C., Barbosa, J.R. and Carlesse, V.M., 2012, "Performance Evaluation of a 5kN Gas Turbine Based on Specially Designed Components", ASME Turbo Expo 2012, Copenhagen, Denmark.

Wittenberg, H., 1976, "Prediction of Off-Design Performance of Turbojet and Turbofan Engines", s.n., s.l..

Yang, H.T., 2009, "Engineering Education and Research for an Interdisciplinary Future", University of California, Santa Barbara, USA.