

# Updating Turbomachinery Aerodynamics Teaching on an Undergraduate Course Using 3d Design Tools

**Grant Ingram**

Department of Engineering,  
Durham University,  
Lower Mountjoy,  
Durham, DH1 3LE, UK  
email: g.i.ingram@durham.ac.uk

*This paper outlines the update of a turbomachinery course to cover 3D aerodynamics using a Reynolds Averaged-Navier Stokes solver. Prior to the activities outlined in this paper the course was taught in a conventional way with a series of lectures and a timed, written, open book examination in a formal exam setting. Students were equipped with a calculator and set of notes including correlations from Howell and Soderberg. The students had around one hour to answer the turbomachinery question which was revealed to them only when they opened the paper at the start of the exam. This limited the depth of any aerodynamic problem they could get through and so they were restricted to simple design or analysis exercises.*

*The genesis of the course update was the release in 2017 of “MULTALL OPEN” [1] a freely available turbomachinery design system and this was adopted as the course software – although other software choices were considered.*

*Students now produce two turbomachinery designs during the course. These are both based on the J85 turbojet – largely to keep cycle calculations to a minimum but it was also important to ensure that students recognise that they were completing a real engineering task. The first task was a 3D aerodynamic design of multi-stage turbine which includes compressible flow, tip clearance and stacking techniques such as lean or sweep. The second task was a midspan (2D) compressor design. The exact cycle conditions were varied each year to explore design scenarios such as an increase in firing temperature. Assessment was by means of a short report where the best students report on their design choices, provide critical analysis of the design using appropriate post-processing techniques and compare their designs to the state of the art in the wider literature.*

*As well as describing the successes and challenges of the update to 3D design methods the paper provides some guidance for educators thinking about adopting a similar approach.*

*Keywords: Turbomachinery, Education, Gas Turbine, Undergraduate, CFD*

## 1 Introduction

This paper outlines the update of a final year turbomachinery course to cover 3D aerodynamics using a Reynolds Averaged-Navier Stokes solver. The aim was to bring the course up to date to use the latest technology and ensure graduates are equipped with the skills they need to rapidly contribute in a modern environment.

Prior to the update outlined in this paper the course was taught in a very conventional way with a series of one hour lectures and a timed, written, open book examination in a formal exam setting. Students were equipped with a calculator and set of notes including correlations taken from [2]. The turbomachinery question was allocated one hour of the exam which obviously limited the depth of any aerodynamic problem they could attempt. The questions were focused either on very simple design/analysis exercises or theoretical derivations.

There is enormous power in using simple paper based calculations and models to understand and solve design problems but doing a very simplistic aerodynamic design using correlations from the 1930s did not seem representative of modern industrial practise or the best preparation for an engineering career in a digital age.

The impressive advances in modern computing power and the development of turbomachinery design software means that the average undergraduate now has more computing power and better tools than design teams had for many in-service engines. The wide

availability of these tools at low computational cost is the key enabler for this course update rather than any recent innovation in solution methodology.

The release in 2017 of “MULTALL OPEN” [1] a freely available turbomachinery design system was opportune and was adopted as the course software. Although as outlined later in the paper other choices were considered. The course was run using this software in academic year 2018-2019 and has run every year since. This means that this paper is based on four complete years of running the course plus observations made in the academic year 2022-2023 that the paper was written in. The course has about 60 students on it per year so the author has taught and examined around 300 students in total. This means the insights and observations in this paper are based on substantial experience of delivery and the author hopes they will be of interest to educators considering a similar approach.

## 2 Literature Review

Turbomachinery is a vital technology: all aircraft propulsion and every form of electrical production excepting solar power rely on it. A steady supply of graduates well versed in the technology is an obvious contribution that Universities can make to society. It is not surprising that the challenges of educating turbomachinery engineers has attracted interest in the literature.

These studies include discussions about the method of teaching

and assessment. For example Backman et. al. [3] describe using blended learning for fluid mechanics and turbomachinery. Later Grönman et. al. [4] describe adapting the same course to use problem based learning. The authors record positive impacts on student learning in both iterations of the course but noted that such approaches could be time consuming for staff and that students might pass the course with less effort than a traditional examination. The syllabus and integration with design exercises of a turbopump design course at Instituto Tecnológico de Aeronáutica - ITA are described by [5] who highlight the importance of having a project activity for the students to reinforce learning. The use of oral assessments at the United States Air Force Academy (USFA) and Oklahoma State University (OSU), is discussed in [6] these assessments provided benefits by students being able to self-assess their own level of understanding.

The development of a course on gas and steam turbines at Muenster University of Applied Sciences supported by cost-efficient experiments is described by [7]. Of note is that the course development was supported by industry surveys which highlighted the importance of rotordynamics and vibrations as well as the more traditional thermodynamics and fluid mechanics knowledge. This was reflected in the course content and the range of experiments used. The syllabus required for turbomachinery education at the United States Air Force Academy is discussed by [8] who describe the introduction of life cycle cost analysis into a gas turbine engine design course. A learning platform at Aeronautics Institute of Technology São José dos Campos, Brazil is described by [9] and the syllabus used with the tool is described in [10]. Both the interactive tool and the syllabus draw on a variety of correlations when estimating performance and follow the pattern of instruction commonly found in textbooks.

The introduction of a block taught project based course in Graz University of Technology is described by [11]. Here the goal was to provide a holistic view of the whole design process rather than a particular specialism. As well as design, work students conduct aerodynamic and mechanical experiments on example test objects.

A number of authors have focused on Brayton (or Joule) cycle calculations. A team process to teach such cycle design at Baylor University is described in [12]. A particular feature of this syllabus is that the design task is actually impossible requiring students to negotiate with the (simulated) customer to come up with a tractable solution. An outline of the syllabus and course structure at Malardalen University in Sweden is provided by [13] a key point being the need to keep the valuable assignment based activity to a manageable level for the students.

Using software to enhance the understanding of the engine cycle has been a popular topic for authors. For example [14] describes the development of an aircraft engine simulation and compressor map application for smartphones (and other devices). This software enabled students to quickly evaluate thermodynamic cycles to examine which cycle meets the required specifications. The use of this application in the syllabus is explored in [15] where the benefits were that students were able to explore design concepts more broadly whilst increasing their interest in the course.

A similar problem is solved by [16] at Ohio State University who describe the production and evaluation of cycle solution software. The software was used during a part of a course rather than covering the whole course and was rigorously evaluated using surveys. Alternative simulation software for engine cycles is discussed in [17] at the USAF Academy who examine use of an updated cycle calculation program in place of their existing solution which provided better outputs and allowed them to explore off-design conditions.

Most of the software described in the educational literature covers cycle design rather than component or blading design. By way of contrast [18] describe the development and deployment of software that covers the design of a blade row and accompanying disc. There is a strong emphasis on both the mechanical and aerodynamic considerations in producing a viable design. An updated version of the software is available on the web [19] and the author's

webpage describes a similar motivation to the present paper.

Recently Tsinoglou et. al. [20] describe the use of a smartphone app based to complete 1D blading design. The "VTA" App assists students in velocity triangle calculations at hub, midspan and tip having first specified loading coefficients ( $\psi$ ), flow coefficients ( $\phi$ ) and reaction ( $R$ ) or some other combination of input parameters. The authors reported the innovation improved students understanding of velocity triangles and that they readily adapted to the use of this technology. The VTA application replicates much of what is found in the MEANGEN program used in this paper.

The description of Whitacker et. al. [21] provides the closest example in the literature to the present paper. In contrast to the present work this is an application of problem based learning where students work in small groups and study what they need to know in order to solve the problem. Each student on this course has 160 hours allocated for their work. The authors reported that students had more interest and attention where a real engineering problem is present. In common with the present work a real world test case is used to design blading. The example was a turbopump for the space shuttle main engine and was designed by students starting from 1D design to 3D Navier-Stokes calculations of a blade row. Commercial, off-the-shelf software was used for the design work. The approach reportedly improved the student experience in drawing and interpreting velocity triangles, boundary layer visualisation, understanding design procedures and generating ideas for further improvements of the design. The use of a real world example with measurement data allows validation of the results.

Some key points can be extracted from this survey of the literature:

- Many authors (particularly those with industrial inputs) have highlighted the need to consider mechanical integrity as well as aerodynamics.
- Most work describing the educational benefit of introducing software on teaching focuses on cycle and not component design
- Authors report improved student engagement and outcomes at the expense of both staff and student effort when more realistic engineering challenges are used.

### 3 Details of the Design System

The publication of MULTALL-OPEN in 2017 provided a good incentive for the course update but there are other turbomachinery design tools and systems available for a fee or at no cost. A number of other design systems were considered during the development of the course: using the Turbomachinery features of a general purpose solver such as ANSYS Fluent, an integrated design system such as SoftInWay's AxSTREAM or other no-cost systems. Systems available at no-cost usually come from the academic community, examples are MULTALL-OPEN or the Bladed Disk Education Suite from the University of Cincinnati [18].

Of the freely available systems MULTALL-OPEN best matched the feature set needed. It incorporates a much wider range of design features than there is time for in the course, runs rapidly (typical run times are under 20 minutes) and is very robust (always produces a solution given a coherent set of inputs). In addition, mesh generation is automatic, it is capable of compressor and turbine design with multiple stages and, solves the flow field in 3D with viscous losses and compressible flow. The drawbacks are an old fashioned user interface, a slightly convoluted setup, lack of multi-platform support and a limited set of graphics outputs.

Commercial systems can match the technical features of MULTALL-OPEN and have a modern user interface but avoiding a purchase order or license acceptance process and allowing an unlimited number of users outweighed any technical advantages other systems might enjoy.

The MULTALL-OPEN system can convert files to a "tecplot" format that can be read into a number of different data readers.

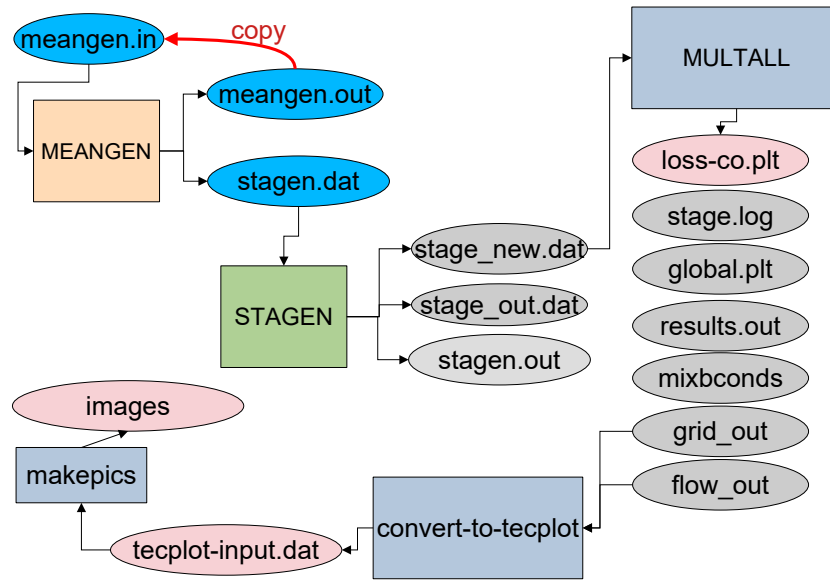


Fig. 1 Structure of the Design System used in the Course

The program "Visit" [22] was chosen to process the data, this is an open-source program so like MULTALL has no user limits and robustly imported the MULTALL-OPEN outputs in the author's preliminary testing.

The operation of MULTALL-OPEN is described in detail in [1] but a brief description of each element is provided here. The system consists of three main programs:

**MEANGEN:** which takes inputs from either the screen or a text file and performs one dimensional velocity triangle calculations at three blade heights to define a machine. Inputs here are typically in the form of non-dimensional parameters such as flow coefficient, stage loading coefficient and reaction as well as things like machine diameter and rotational speed.

**STAGEN:** this is a geometry generation program which takes the output of MEANGEN and prepares an input file for the next program in the chain. This is the step at which users can add a tip clearance, adjust the blade count and add three dimensional features such as compound lean.

**MULTALL:** this is a 3D Navier-Stokes solver for multistage turbomachines. This takes the STAGEN output file and solves the flow field without further user input.

In addition two utilities are used in the course: **convert-to-tecplot:** is simply a format conversion file that produces a tecplot format file for processing and a post-processing script written by the present author called "makepics". This produces a series of plots for students to examine and is simply a Python script for the Visit visualisation software. Each program produces a number of input and output files and the full chain of programs and output files is shown in Fig. 1 and a typical output of "makepics" is shown in Fig. 2.

The software was deployed to students on the Linux service provided by the author's University. This system features two modes of access: i) remote access to a time-sharing system (via an application called "X2go") and ii) the option of booting classroom machines up directly into the Linux operating machine and running programs directly. Whilst remote access can get the job done the direct booting option is preferred. The calculation runs faster (how much faster depends on the usage of the time sharing system but a 2x speed up is typical) and provides much lower latency for the users (in remote access graphical screen redraws can take 0.25s). Each user has a small (10 GB) file system which is accessible to

students no matter which operating system they use as well as much larger (1 TB) cloud based storage. The Linux system at Durham features a wide variety of programs such as a FORTRAN compiler installed by default.

The software is deployed by students obtaining a zip file of the programs from the University virtual learning environment (VLE). MULTALL-OPEN is delivered as source code which needs to be compiled and then run from the command line. Advanced features are accessed by editing configuration files. The zip file contains a minimally edited version of the sources from the default MULTALL-OPEN distribution to remove some graphics capability. The first task the students are presented with in the course is "software setup", which involves downloading the file, compiling the programs, running an example and carrying out some simple post processing. Detailed step-by-step written instructions were provided initially. From the second year of the course a screen-cast (a recording of the computer screen with audio narration) of the author working through the step-by-step instructions was added. This helped the students by clearing up implicit steps in the instruction, particularly around file management and where to find things in the user interface.

This process went very smoothly over the five years this course has run. There have been surprisingly few questions about compilation, running the programs or the mechanisms of editing the configuration files. The most difficult problem that arose was when one student edited the configuration file in Microsoft Word and the character encoding caused a series of strange errors. The most common operating system or software issue was students using up the modest (10 GB) shared space that they have. In this case files are simply truncated when disc space is used up and this causes chaos when read into the next program in the chain.

Overall any concerns about asking students to compile software and editing configuration files proved to be unfounded and MULTALL-OPEN provided a robust platform for students to learn about turbomachinery aerodynamics.

#### 4 Course Syllabus

The course forms part of the final year programme for Mechanical and Aeronautical students on a UK integrated masters programme (MEng General Engineering (Mechanical) or MEng General Engineering (Aeronautical)), which maps to a second cycle

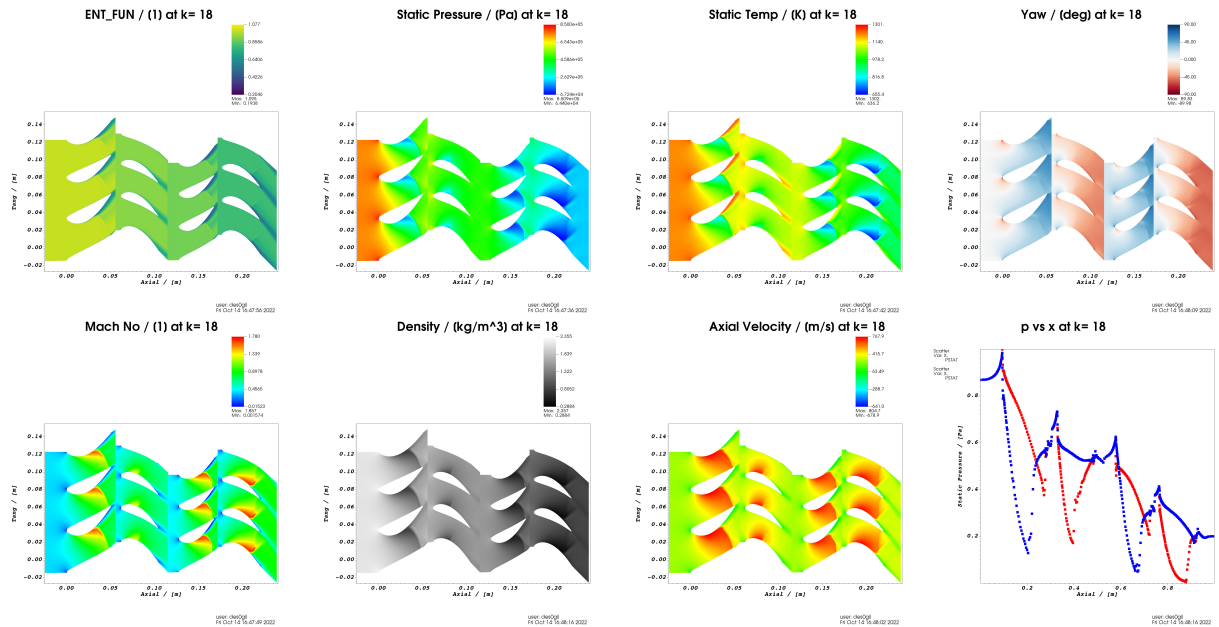


Fig. 2 Typical Blade to Blade Plots of the First Iteration

qualification in the European Higher Education Area. Graduates from this programme typically enter the Engineering Profession without further study. Graduate Outcome survey data for 2018-2020 graduates shows 94% of graduates in "highly skilled work" with the top three destinations being: Engineering professionals (39%), Information Technology Professionals (24%) and Finance Professionals (8%) [23]. The same content is also available to students on a one year masters programme (MSc in Advanced Mechanical Engineering) but there is less data on graduate destinations.

The course fits into a two part 10 credit module entitled "Turbomachinery and Propulsion" this paper refers to the 5 credit "Turbomachinery" part where the focus is on the aerodynamic design of turbomachinery components. The complimentary "Propulsion" side of the module covers topics such as engine cycles (turbofan vs turbojet) etc. The turbomachinery course is worth 5 credits and students are expected to expend 50 hours effort to achieve these credits.

All the teaching and assessment is carried out by a single member of the departmental "faculty" (Assistant Professor, Associate Professor or Professor). For the work described in this paper all the duties were executed by the author. Marks and feedback are moderated by another faculty member before being presented to the Departmental Board of Examiners for approval.

The prerequisites for the course are modules in basic fluid mechanics and thermodynamics so students are expected to understand continuity, the steady flow energy equation and the Euler work equation, the concept of entropy, Bernoulli's Equation, Ideal Gas Laws, Static and Stagnation Conditions, Compressible Flow Relations (Mach number) and the idea of choked flow. Students are also expected to have some understanding of velocity triangles and the basics of cascade geometry. For students not familiar with these concepts background material is provided in the form of online videos or references to an introductory textbook [24]. The main reference for the course is Dixon and Hall [25] which is made available to students electronically in the University library.

The course consists of ten contact hours which are traditional lectures given at a rate of one hour per week. This leaves the students with forty hours or around four hours per week for their own activity on the course. Students are provided with a "weekly task" to complete which is designed to take the average student less than four hours. Bookable time-slots with the academic in charge

of the course, called "Office Hours" are also available for one hour per week during term time. These slots are not well used by the students and around half the time no appointments are made with an uptick in activity near the deadline.

**4.1 Lecture Content.** The ten lectures are divided up as follows:

- (1) Introduction and Background Work
- (2) Dimensionless Parameters and Blade Heights
- (3) Blade Profiles and How to Improve Them
- (4) Entropy Creation in Turbomachinery
- (5) 3D Aerodynamic Design Techniques
- (6) Axial Flow Compressors and Ducted Fans
- (7) Details of the Calculation Method
- (8) Off Design Performance, Verification and Performance Maps
- (9) Aerodynamic Design in Context
- (10) Summary. Advice for Analysis and Write Up

The content is designed so that the material needed to complete the "weekly tasks" is provided at the appropriate time. All the information required to complete the assignment is provided by lecture six, the remaining lectures provide more detail and background but they can achieve a passing grade with only the first six.

The lectures are recorded and made available to review by students using the virtual learning environment. The recording captures the lecturer's voice and anything that is displayed on the projection screen in the lecture theatre which can include visualiser outputs so real blades, etc. can be shown to students. This lecture capture system automatically produces captions from the audio file and recognises text on slides or handwriting. This means both the audio and visual aids can be searched by students after the lecture. The system is not perfect but students particularly appreciate being able to go back and review difficult sections as well as being able to catch up in case of illness or other unavoidable commitment.

**4.2 Assessment.** Assessment is by means of a short report which is unremarkable except for one feature the author highly recommends. The format is specified as "IEEE Journal Format" and students are referred to the Journal website for any questions as to font size, figure placement and referencing style. Mandates for

**Table 1 Typical Specifications**

Parameter	Value
Compressor axial space	0.5 m
Turbine axial space	0.3 m
Outer diameter	0.50 m
Pressure ratio	8.3
Turbine inlet temperature	977 °C
Air mass flow	20 kg/s
Nominal thrust	13 kN
Max RPM	16500
Tip clearance	1.0% of blade height
Minimum blade thickness	5% of axial chord

feedback that can be easily quantified (e.g. provide six comments on this report) seem to lead to a focus on trivial matters: students are told a great deal about formatting of reports and they get the mistaken impression that this is key to good academic content and obsess about things like title spacing. Specifying a highly detailed document specification allows the students and the academic to focus on the content.

The content of the assessment is in three parts:

- A Turbine Design with 3D features [50%]
- Midspan Compressor Stage Design [25%]
- Report and Discussion [25%]

Assessment is conducted by the academic reading the report and matching up the work to a set of descriptors in a "marking matrix", an example of which is shown in Fig. 3

The turbine and compressor design are based on the GE J85 Turbojet cycle using publicly available specifications. The aim is to have students complete simple cycle calculations before going into the aerodynamic design so to keep the problem tractable a turbojet cycle is preferred. The GE J85 is still in service on a small number of platforms so we are able to point to existing airframes as an example of "real world" engineering.

A typical set of parameters given to students is found in Table 1. These are varied from year to year to modify the assignment. For example students have been asked to examine higher and lower turbine inlet temperatures and design first or last stage compressor blades. The exercise is for a single design point stationary at sea level, off-design is discussed in the lectures but the students don't have to do any off-design calculations.

A key feature of the course is that the students calculate fully 3D geometry with compressible flows, boundary layers, tip clearances etc. and then apply some 3D design techniques such as compound lean.

## 5 The Student Experience

The plan was for students to complete the weekly tasks in parallel with the lectures, but in practise there is a burst of enthusiasm at the start of the course and then students often fall behind. This is not unique to this course but as educators we should encourage good habits rather than embracing a last minute culture. The weekly tasks emphasise a small number of design iterations to achieve the final design - a maximum of ten runs is suggested - this is guidance and is not enforced.

*Week 1: Setup of Design System.* This is where students set-up the software and run a turbine design. At this point they don't really understand how the software works so they are very much following a script. However this allows any software issues to be identified early on and fixed rapidly.

*Week 2: Determine Initial Dimensionless Parameters.* Here students complete basic cycle calculations to determine the non-dimensional parameters for the turbine. This task doesn't actually

require extensive use of any software so allows any problems found in Week 1 to be addressed. The students start with simple Joule or Brayton cycle calculations and these paper sums allow students to determine the power output required from the turbine component. This provides a link between the aerodynamic design and basic studies students will have completed elsewhere in their academic career.

Students are given a Smith Chart [26] and encouraged to use repeating stages. A key learning point here is that the turbomachinery designer does not have a lot of freedom. Once all the parameters in Table 1 are taken into account the student can pick the number of stages (which sets the stage loading coefficient  $\psi$ ) and the blade height or axial velocity (which sets the flow coefficient  $\phi$ ). If they have chosen to use a repeating stage with an axial inlet, the reaction ( $R$ ) is then obtained directly from:

$$\psi = 2(1 - R - \phi \tan \alpha) \quad (1)$$

The MULTALL system generates an initial geometry for the user once the non-dimensional parameters are set.

*Week 3: Adjust 2D Profiles.* For the engine conditions in the assignment the MULTALL design system produces a set of default blades which usually feature an extensive shock structure and have a considerably lower massflow than requested in the setup. Although the MULTALL software has a variety of methods of specifying the blade shape in the course students are encouraged to use the simplest method which involves setting a maximum thickness and the position of that thickness both as a fraction of the chord shown in Fig. 4.

The lecture material borrows from [27] to explain how surface pressure changes in terms of streamline curvature. The task for the students is to inspect the pressure vs axial chord diagram and adjust the shape of the blade to achieve a smoother pressure distribution. This is completed largely by means of reference to blade to blade plots at hub, midspan and tip produced by the post processing script, an example of which is found in Fig. 2. The entropy is plotted as entropy function which is defined as:

$$\text{ENT FUN} = e^{-\Delta S/R} \quad (2)$$

This means that minimising entropy gain means keeping ENT FUN high - i.e. larger numbers are better.

*Week 4: Adding a Tip Clearance.* Having achieved a good 2D aerodynamic design and usually improved the default efficiency by several percentage points, students are asked to add a tip clearance to the design. The fraction asked for varies from year to year but is of the order of 1%. The tip clearance vortex that results usually negates all the improvements in 2D profile improvement that they have made but it is a good introduction to three dimensional flows and losses in the machine. The lecture content this week is essentially a summary of Denton's IGTI Scholar Paper from 1993, [28], where the basic physical mechanisms of loss (viscous friction, non-equilibrium processes and heat transfer across finite temperature differences) are introduced so the students gain an understanding of what causes entropy gain.

*Week 5: Apply 3D Design Features.* Students are encouraged to experiment with various 3D design techniques to see if they can obtain an improvement in performance. Compound lean is suggested at the "default" technique but sweep has been used by a number of students to obtain good performance. The lecture content in this week covers various 3D design techniques (lean, sweep and twist) that students might like to try. The idea of blade displacements in a static pressure field from [29] is used in this lecture.

*Week 6: Compressor Design.* The course includes a short compressor design exercise, to keep the problem tractable this exercise is a 2D midspan design only. Students need to determine the appropriate non-dimensional coefficients, come up with an initial design and adjust the 2D profile.

	Mark: 80-100%	Mark: 70-79%	Mark: 60-69%	Mark: 50-59%	Mark: 40-49%	Mark: 0-39%
<b>Turbine Design Section</b>	State of the art design solution that stretches the limits of the design tool. No reasonable way to improve the design.	Design solution illustrates best practise in current design techniques. Including sophisticated use of 3D features. Would be suitable for detailed design work.	Design solution that represents good practise and produces sound results. Good use of 3D features.	A design solution that follows conventional practise closely. Little evidence of 3D design. Design can be can be trusted.	A design solution that works but with question marks over the results. Poor organisation and presentation of material.	Not a credible solution. OR Difficult to read and lacks a logical train of thought or argument. OR Fails to follow all submission guidelines.
<b>Compressor Design Section</b>	State of the art design solution that stretches the limits of the design tool. No reasonable way to improve the design.	Design solution illustrates best practise in current design techniques. Would be suitable for detailed design work.	Design solution that represents good practise and produces sound results.	A design solution that follows conventional practise closely. Design can be can be trusted.	A design solution that works but with question marks over the results. Poor organisation and presentation of material.	Not a credible solution. OR Difficult to read and lacks a logical train of thought or argument. OR Fails to follow all submission guidelines.
<b>Discussion Section</b>	Flawless discussion of the design that realistically assesses the design and incorporates the latest research findings.	Design is critically analysed with a very good discussion of the engineering utility of the solution.	Design is analysed with good discussion of the engineering utility of the solution.	The designs are explained with useful discussion of the engineering utility of the solution.	Limited discussion of the engineering utility of the solution. Poor organisation and presentation of material.	Not a credible solution. OR Difficult to read and lacks a logical train of thought or argument. OR Fails to follow all submission guidelines.

Fig. 3 Marking Matrix Used in the Course

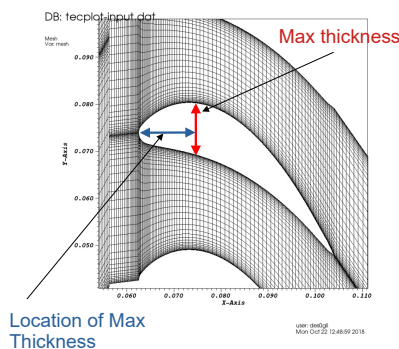


Fig. 4 Control of the 2D Profile

Week 7-10: *Checking and Write Up*. The remaining four weeks of the course are devoted to final checking and write up and this allows students who have fallen behind to catch up. The lecture content is now no longer directly related to assessment and covers background topics such as mechanical integrity, as a result lecture attendance falls somewhat.

The makepics script and a variety of files related to the course have been made available at <https://grantingram.org/> for download by interested readers.

## 6 Marks and Student Evaluations

Student evaluations were obtained through the module evaluation questionnaire process run by the University for the undergraduate (MEng) cohorts. However there are many confounding factors affecting these evaluations: i) questions are asked at the module level which is made up of a number of courses, ii) none were conducted in Academic Year 2019-2020, iii) the mode of teaching had to be adjusted due to the pandemic, iv) the questions asked have changed over time and v) the course was moved to a smaller module for Academic Year 2019-2020. Table 2 attempts to summarise the most comparable data from these questionnaires with data from Academic Year 2017-2018 where the conventional syllabus was followed included as a benchmark. The questionnaires use a five point likert scale (Definitely Agree = 5, Mostly

Agree = 4, Neither Agree nor Disagree = 3, Mostly Disagree = 1, Definitely Disagree = 1) and the mean value is used in Table 2. Participation in the evaluations has fallen markedly during the pandemic but there is an obvious explanation for this.

In order to ensure parity across different assessments a Departmental standard for both coursework and examinations required that an average mark of 65% within a band of  $\pm 5\%$  should be returned for cohorts of more than ten students. The logic being that large deviations in marks are likely to be down to changes in assessment difficulty rather than a sudden change in ability of the student body. Staff are required to use their academic judgement when marking to bring assessments "into the band", if this is impossible they can make a report to the Board of Examiners to ask for an exception. This means that no dramatic change in marks is expected when a syllabus changes and this is reflected in the data shown in Table 2.

The most useful information from student evaluations are the free text comments where students are asked to identify highlights and areas for improvement in the course these comments refer to the module as whole and key data is extracted in Table 3

The overall picture is confounded by a number of factors but it is possible to argue that there was a reduction in key metrics when the new syllabus was introduced and then the situation has recovered to be the same as the more conventional examination. In the free text comments workload complaints reduced somewhat over time but the complaints about the fairness of marking are not correlated with the average grade.

## 7 Discussion

**7.1 Student and Staff Workload.** A consistent theme in student feedback has been that the course is very high workload for the students. This has also been reported by other authors making syllabus changes such as [13]. There are a number of causes for this: Firstly, the course is a highly technical and open ended problem and students struggled to stop work as there are always more design iterations that they could attempt. Secondly, not all students demonstrate exemplary time management, the submission is after the Christmas break, and a significant portion of the students in the early years of the course attempted to complete the majority of the assignment during the vacation. Finally, the course is a challenging assignment and it is true that the students had a high workload.

**Table 2 Quantitative Evaluation and Marks Data from the Undergraduate Cohort**

Academic Year	17/18	18/19	19/20	20/21	21/22	22/23
Mode of teaching	In-Person	In-Person	In-Person	Online	Hybrid	In-Person
Cohort size	53	45	-	52	48	48
Responses	26	25	-	18	13	15
Response Rate	49.1%	55.6%	-	34.6%	27.1%	31.3%
Question Text (5 point likert scale used for grading)	Mean	Mean	Mean	Mean	Mean	Mean
"challenged me to achieve my best work"	4.08	3.68	-	3.72	4.00	4.20
"explore ideas in depth"/ "intellectually stimulating"	4.27	4.04	-	4.17	4.20	4.20
"satisfied with the quality of this module."	-	3.68	-	3.50	3.69	3.73
Coursework Marks						
Mean mark returned	-	61.7 %	70.3 %	65.9%	64.0 %	65.2 %
Standard deviation	-	7.8 %	8.1 %	10.7%	15.4 %	12.6 %

**Table 3 Analysis of Free Text Comments**

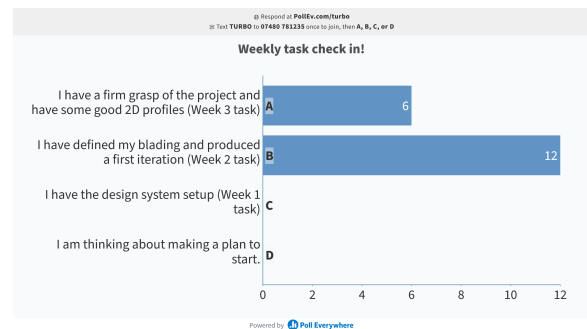
	18/19	20/21	21/22	22/23
Total comments	38	30	18	24
Workload complaints	5	3	0	6
Complaints about marking	8	9	7	1
Positive comments about relevance or enjoyment	7	2	3	7

These issues have largely been addressed in the version of the course described in this paper, the key changes since the start of the course have been:

- To emphasise that the course should be tackled "one afternoon a week" and provide a detailed set of tasks of what to do in that time. Students are encouraged to use the office hours system if they have done their "afternoon" and are still stuck. The tasks included the report write up and so provided the students follow the guidance they have a clear path to complete the coursework.
- Students are encouraged to complete each iteration with a clear design intent and limit themselves to ten design iterations. The fact that there is no correct answer and they have to stop at some point is made clear and compared to product development.
- In-class electronic polling of the form "Which Weekly Tasks have you completed?" was used regularly to find out where students were with each task and crucially the progress of the cohort is visible to all as the results of the poll are displayed in real time in the lecture. An example is shown in Fig. 5.
- There is also a clear cutoff date before the Christmas vacation after which the teaching is complete and no further student queries will be addressed. After this date students need to rely on the course materials to overcome any issues they might encounter.

These actions have largely been successful in reducing the volume of workload complaints. However if the aim of higher education is to generate positive student evaluations then this course update has had limited success. As described earlier the evaluation data is difficult to interpret and the only clear point that can be drawn is that delivering a cutting edge course to students is not a guaranteed route to improved student evaluations.

In terms of staff workload this course has certainly been much more work than a conventional pattern of giving ten lectures and then asking a highly simplified exam question about a small aspect of turbine design. Additional workload arises from i) providing

**Fig. 5 Screen Grab of In-Class Polling used to Reveal Progress during Week 4**

guidance on the operation of the software, ii) the burden of providing coursework feedback and iii) queries about how to improve designs. The creation of screen-cast videos showing how the software is run reduced the number of queries about software operation substantially. There is an internal Departmental standard to provide six comments for feedback on any coursework, and this takes considerably more time to produce than simply marking an exam. The first two points can seem more of a burden than a value adding activity especially in an academic environment where time is very precious. Dealing with queries about how to improve designs is a highly worthwhile use of academic time as you can coach the students to examine the various charts they have produced to discover where entropy generation takes place and what they can do about it.

**7.2 General Observations.** A key decision in the syllabus design has been to remove content. Correlations are not used and there is no throughflow calculation stage between the meanline velocity triangle calculations in MEANGEN and the 3D Navier-Stokes calculations in MULTALL. Given the short calculation time on a modern system (<20 minutes) the computational time saved by a simplified calculation will be exceeded by the time taken to explain it to the students. The concept of a throughflow calculation is explained in the course lectures as background information. In addition although correlations are mentioned in the course lectures no detailed instructions on how to use them are given. This creates space to focus on the physical causes of loss which simplifies the syllabus considerably. The design aim becomes to maintaining a given level of performance (e.g. thrust output) whilst minimising entropy gain.

One consequence of changing the course is that the teaching staff had to learn a lot of new concepts and material. The mechanics of the previous course were on how to apply a particular correlation and you can get quite comfortable answering detailed questions about that. Simpler and bigger questions such as "how is the

axial spacing determined?" can prove more challenging especially if your background has mainly been in research as your expertise might be narrowly focused. Learning at any stage of your career is a good thing but it can be an uncomfortable experience to realise that you don't know the answer to some basic questions without further study.

A small minority of students (one or two per cohort) attempted to find an optimum design by carrying out a large number of calculations. The guidance is that they should carry out a number of targeted design decisions based on their understanding of the underlying flow physics. Carrying out a large number (50 to 100) of MULTALL-OPEN calculations and picking the best means that they are unable to demonstrate understanding of the link between geometry changes and flow physics. As a result these students often have considerable frustration as despite carrying out a lot of work they have missed one of key learning points in the course.

Optimisation is of course a huge enabler in many engineering design activities but attempting to use an optimiser with MULTALL-OPEN is unlikely to lead to success as i) the design space is huge and ii) you are far more likely to discover errors in the model at the edges of applicability than a good design. Having seen this happen a few times students are now strongly guided to try only ten iterations of the design, each with a clear link to a physical improvement. It is interesting that [21] also noted that students seemed enthusiastic to try out optimisation and this might represent an opportunity to encourage learning that is missed with the present course structure.

The simple turbojet cycle calculations that the students start with can dominate the reporting they produce. The idea was that they should rapidly move from basic engineering thermodynamic cycles, which they already know, to carrying out detailed aerodynamic design, which is new to them. Clearly, for this course the aerodynamic design is the more important but a number of students devote pages to the initial calculations and neglect the aerodynamic design.

It is possible to achieve a passing grade by simply following prompts and not demonstrating much understanding of the underlying processes. This is a similar drawback to that noted by [4] when introducing problem based learning. On the other hand there is no guarantee that in more traditional courses students would not just input numbers into formulae from data sheets without showing any real insight to achieve a passing grade.

The most perplexing ideas that students encounter are the modelling assumptions and simplifications involved in the various programs. The fact that MEANGEN uses a 1D model of the flow and MULTALL solves the Reynolds Averaged Navier Stokes equations in 3D is missed by a number of students. For example you can ask for a mass-flow in MEANGEN of 20 kg/s but MULTALL predicts a shock structure that means you only get 16 kg/s. Students appear to regard the programs as a single entity and have struggled to determine the reasons for the differing mass-flows despite it being explained in the lecture series.

**7.3 Impact on Student Learning.** On the positive side, the course has met the aim of bringing the material up to date. Most students show a good understanding of the causes of loss in turbomachines and apply 3D features to mitigate this loss. The very best of them reach into the wider literature around turbomachinery and compare and contrast their design work with what has been reported elsewhere. A number of students demonstrate clear post processing of their solutions, explaining how and why their designs improve performance. This is illustrated with two examples from student reports.

Figure 6 shows that the student has presented entropy function contours of their first design iteration and their final 2D profile design for the turbine. Note that for ENT FUN higher numbers are better. The student has adjusted the blade profile to remove the shock structure in the second stator and reduce the losses from the second rotor boundary layer.

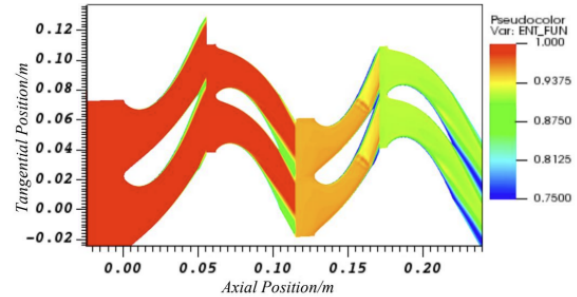


Figure 2: Mach number (top) and entropy function (bottom) contour at midspan of first iteration

Figure 3 shows there is a smaller drop in entropy function following the trailing edge and the flow is now subsonic.

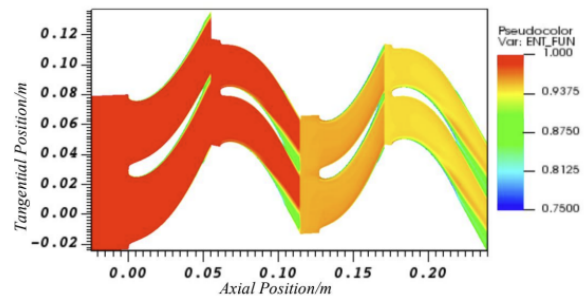


Fig. 6 Extract from a Student Report showing the Impact of 2D Design

	Change	Justification	Eff (%)	$\dot{m}$ (kg)
6	ADDED TIP CLEARANCE		91.20	16.17
7	Added 5° twist to centre of 1 <sup>st</sup> stage stator.	Open up throat to take more flow through centre of machine [3][4].	91.29	17.43
8	Added - 2° twist to tip of rows 2 & 4.	Discourage flow through tips of rotors [4].	91.36	17.57
9	10% forward sweep from midspan on both rotors.	Discourage flow through tips of rotors [5].	91.42	17.57
10	Added 10% compound lean to 1 <sup>st</sup> stage stator.	Develop a pressure gradient to push flow away from tips [3].	91.48	17.53

Table 2: 3D Design Iterations

Fig. 7 Extract from a Student Report showing 3D Design Rationales

Figure 7 shows a good illustration of how to describe a complex series of design choices. This table extracted from a student report shows the iteration number, what change has been made and provides a clear rationale for why each design change has been made. Each change is linked to a reference describing the design technique used. The gains with 3D design are relatively modest but the student has managed to produce some incremental gain in machine efficiency. Figure 8 shows the final design with tip clearance losses clearly shown.

The point of including both examples is not that they represent the ultimate in turbine design, but they illustrate student learning that is simply impossible to deliver using the previous iteration of the course with only a calculator and a set of notes.

**7.4 Future Improvements.** Post processing has been challenging: although students are able to easily access the full 3D data set, the 3D post-processor used (VisIt) is a generic one that does not have any built-in understanding of turbomachine geometry. Visualising vortex structures is difficult and producing streamlines has so far been impossible. In addition, getting averages of flow quantities



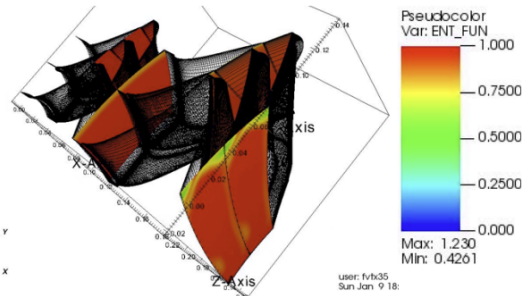


Figure 5: Turbine Entropy Function

Fig. 8 Extract from a Student Report showing 3D Flows

is something that students have struggled with. Attentive readers will have noted that some of the variables in Fig. 2 should be dimensionless. Although students are usually encouraged to plot results in non-dimensional form this requires either an averaged value from VisIt or a read in from MULTALL-OPEN outputs to normalise with and the "makepics" script is not yet sophisticated enough to do this. The post processing has been improved over time but there is room for improvement. Students will only reap the full benefits of the course once it is easy to visualise the flow fields they are studying.

The link between basic turbomachinery design (velocity triangles) and the numerical work is not as strong as it could be. Velocity triangles are asked for in the report but students start asking how to obtain data for them very late on in the course - indicating that they are not used in the early design work.

The method of specifying the blade 2D profile is simple and can lead to excessive acceleration around the leading edge if the blade is made quite thin. It has been phased out as the recommended method of specifying the blade geometry in MULTALL-OPEN so an obvious upgrade already exists.

In the first year of running the course there was little consideration of mechanical integrity. The maximum RPM was always specified in the brief but a constraint of a minimum thickness has been added. Students still tend to make thin blades, and a more nuanced consideration of mechanical integrity would enhance the course especially given the recommendations found in the wider literature such as [18] and [7].

A potential enhancement is the inclusion of cooled blades into the assignment, at present they are discussed and described in the lecture series only. This would enable students to examine the complete set of loss mechanisms by adding heat transfer over a finite temperature difference, but would make the cycle calculations more complex and add to the student workload.

## 8 Conclusion and Recommendations

This paper has described the update of a turbomachinery course to cover 3D aerodynamics using a Reynolds Averaged Navier Stokes solver. This update has transformed the technical content to one where the students routinely apply sophisticated 3D design techniques with a clear design intent based on an understanding of the flow physics.

The course has been taught over five years with up to sixty students per year. Recommendations arising from this experience are as follows:

The course involves more workload for both students and staff but the effects of this can be mitigated somewhat. For students a clearly laid down series of tasks each week provided a way of directing their efforts so they did not get stuck on unnecessary activity. A suitably designed series of tasks still allows students considerable freedom in how to approach the open ended problem. For staff the production of screen-cast type videos about software usage removes ambiguity and reduced the volume of questions

about software operation. However there is no avoiding the fact that this approach will be harder than a conventional course.

Academic staff who haven't carried out turbomachinery design need to be prepared for a learning curve even if they have familiarity with a related research area. A lot of the material on how to apply correlations and simplified design techniques simply becomes redundant and new material needs to replace it.

Include some realistic mechanical integrity constraints into your design brief from the start. It is easy for students to produce an aerodynamic design which is completely unfeasible to make.

Emphasise design intent from the start. The advice to students is that each design iteration should have a *physically plausible reason for working*. It may not turn out as planned but students must be encouraged to have a plan. Otherwise they will just attempt to explore the design space by running a large number of simulations without clear thought.

Finally set high expectations for your students - they will deliver impressive work if you give them the tools to do so.

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## Nomenclature

### Roman letters

$R$  = Reaction [-] or Radius [m] or Gas Constant [ $Jkg^{-1}K^{-1}$ ]  
 $V$  = Absolute Velocity [m/s]  
 $W$  = Relative Velocity [m/s]  
 $U$  = Blade speed [m/s]  
 $w_x$  = Specific Work Input/Output [J/kg]

### Greek letters

$\alpha$  = Absolute Flow Angle  
 $\beta$  = Relative Flow Angle

### Dimensionless groups

$\phi$  = Flow coefficient,  $V_x/U$   
 $\psi$  = Stage Loading coefficient,  $w_x/U^2$

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