INTERNATIONAL CONFERENCE ON ENGINEERING AND PRODUCT DESIGN EDUCATION
2 & 3 SEPTEMBER 2010, NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY, TRONDHEIM, NORWAY

LINKING DESIGN, ANALYSIS, MANUFACTURE AND TEST IN THE ENGINEERING STUDENT EXPERIENCE

Peter R N CHILDS, Niall R McGLASHAN, Graham GOSLING and Marco AURISICCHIO
Department of Mechanical Engineering, Imperial College London, SW7 2AZ, UK

ABSTRACT
The modern engineer needs to have diverse skills ranging from abilities in re-design, co-design, customisation, management of resources and intellectual property, combined with technical expertise. Design education needs to prepare individuals for these requirements and manage the expectations of the students concerned. A particular challenge is the disconnect between empowered design practice, where the practitioner already has the necessary skills to explore the task, and the novice who is still learning technical and design skills. In order to develop understanding of design processes commonly experienced in industry a combination of projects using fuzzy or constrained briefs are introduced in the first and second years on the MEng in Mechanical Engineering at Imperial College. Constrained briefs defining the limits for the design activity, are sometimes criticised as limiting the creative opportunities for the people involved. Some creative techniques however focus on identifying the constraints and conflicts involved with a view to resolving them. This paper explores a constrained brief project, used for the second year, where students are required to design, manufacture and then test their design for a pump. The project encourages use and exploration of analytical skills, engineering science and form development as well as basic manufacturing skills. Students can use CNC manufacture for their impeller and volute but are required to manually machine the majority of their bearing housing and shaft arrangement. The combination of concept development within constraints, use of analysis and engineering science, development of manufacturing and assembly skills and the student experience derived from testing their designs, are described within this paper.

Keywords: Design, make, test, manufacture, engineering, pump, project

1 INTRODUCTION

Modern undergraduate degrees in engineering include a combination of technical and transferable skills (as defined, in the case of the United Kingdom, for the recognition of professional engineers by UK-SPEC [1], and in the United States by ABET [2]). The National Academy of Engineering (2004) [3] define the requisite attributes of the engineer of 2020 to continue to include strengths in science and mathematics, practical ingenuity, creativity, good communication and mastery of the principles of business and management. In essence the modern engineer needs to have diverse skills ranging from abilities in re-design, co-design, customisation, management of resources and intellectual property, combined with technical expertise. This represents an advanced set of skills and a list that the entrepreneur and senior engineer would readily recognise, albeit with perhaps attention to particular areas where they perceive their own strengths. Nevertheless the need to operate successfully across a range of activities is well known in engineering practice [4]. Indeed expertise and skill development enables an engineer to operate at an advanced level where their understanding surpasses the basic mode of design, such as designing to the minimum requirements defined in a technical standard, but instead able to safely develop the detailed design for a product or process that both functions and meets the business requirements.

2 ENGINEERING DESIGN EDUCATION

Engineering design education represents a significant challenge. A number of strategies are available for developing ideation skills, detailed knowledge of engineering analysis and engineering science, business and project management. Design can be viewed as the integrating factor in engineering pulling together diverse discipline skills in the engineering sciences, such as thermodynamics and mechanics, along with marketing, manufacture and management considerations. A well recognised problem in design education is the frustration in both students and staff in the desire to produce functioning and meaningful artifacts in a course while also serving to advance important skills in engineering science and design. In the early years of a degree and industry-styled-experience-based-courses, rapid design and make projects using craft based skills can be exploited in order to provide students with experience of the entire design, make and test cycle (e.g. [5]). Rapid prototyping and manufacturing technology offers opportunities for student projects to include the production of an artifact (see for example [6]).

Of course, by comparison to many engineering science based courses, design and manufacture provision is resource intensive and therefore costly. Many Higher Education providers have striven to reduce costs incurred by space occupation and staff employment with consequent pressures on workshops and associated technician staffing levels. Some degree providers have justified the strategy of workshop reduction, or closure, by increased use of simulation and outsourcing manufacture of items. The pros and cons of such an approach are well rehearsed with issues such as advances in computational aids, skill shortages in manufacturing, limited workshop capacity, high student staff ratios and preferential appointment of engineering science research-based staff often cited. A particular concern for simulation based education without practical experience of the physical product and its formation, is the possibility that students will fail to gain knowledge of fabrication processes, the importance of tolerancing stack up in assemblies and practical design for manufacture and assembly skills as recognized in the definition of necessary stages in the Curriculum for Design developed by SEED ([4] and [7]). A common experience in novice design output is the realisation that an engineering drawing or solid model has inadvertently included a blind hole or other such impossible, or impractical to manufacture, feature. Such features can of course be realised by certain rapid manufacturing and rapid prototyping processes and courses that rely on such technologies, while providing a valuable step in design and manufacture education, unless supplemented by other activities, risk producing engineering designers without sufficient experience to operate effectively in product development.

3 FUZZY AND CONSTRAINED DESIGN BRIEFS

Design education needs to prepare individuals for diverse requirements and manage the expectations of the students concerned. A particular challenge faced by all educationalists is the disconnect between empowered design practice, where the practitioner concerned already has the necessary skills to explore the task, and the novice who is still learning both technical and design skills. In order to develop understanding of design processes commonly experienced in industry a combination of engineering design projects using either fuzzy or constrained briefs are introduced to students in the first and second years on the MEng in Mechanical Engineering at Imperial College London, where the student cohort comprises about 160 students in each year. Both fuzzy brief and constrained brief projects are necessary in order to provide experience of un-defined or open opportunities as well as specified requirements.

Constrained briefs defining the limits or scope for the design activity, are sometimes criticised as they reduce the creative opportunities for the people involved. Some creative tools however are focussed on identifying the constraints and conflicts involved in the design with a view to resolving them. This paper explores a particular constrained brief project, where students are required to design, manufacture and then test their design for a pump. The pump performance requirements are specified as part of the project along with the availability of CNC and manual manufacturing processes. The project, taking place in a technical university, encourages use and exploration of analytical skills and tools in engineering science and form development. Students can use CNC manufacture for their impeller and volute but are required to use manual machining for the majority of their bearing housing and shaft arrangement. The combination of concept development within constraints, use of analytical skills and engineering science, development of manufacturing and assembly skills as well as the student experience derived from testing their designs and reviewing their projected design performance, are described in Section 4.

4 HYDRODYNAMIC AND MECHANICAL DESIGN

Traditionally extensive use of empirical data and scaling has enabled satisfactory designs to be delivered for a wide range of pump applications. Modern pump design procedures are derived from this practical experience, combined with the use of finite element based software for detailed flow and stress analysis and use of appropriate optimisation procedures. In order to develop skills in the design of such turbomachinery it is important to experience each phase of the process. Such experience provides a detailed appreciation of the interrelated decision process and the impact this has on product performance, implicit in pump design and common to many other design tasks. This paper reports on the practical experience of specification, outline design, detailed design, manufacture and testing of rotary pumps by all second year MEng undergraduates at the Department of Mechanical Engineering concerned. Key elements of the project assignment undertaken include experience of the iterative nature of design, consideration and rationalisation of the compromises between conflicting requirements, addressing practical manufacture issues and testing practicalities. Evaluation of the significant variety in design implementations reveals the critical importance of machine design, technical specification of details, team work as well as that of hydraulic design in the practical realisation of a pump.

Specific learning objectives of the activity include the following:

- to experience a design make and test project in all the stages from design specification to manufacture and test and presentation of results;
- to understand and experience the application of Computer Aided Engineering in the design context;
- to develop an understanding of the application of machine components and their analysis;
- to understand the need to design for manufacture and assembly;
- to learn the basics of process planning and costing in a mechanical engineering context;
- to understand the interdisciplinary nature of design.

The primary requirements in the brief for the activity are listed below.

- To design, manufacture and test a centrifugal pump to deliver water at 10 m head.
- Subject to size constraints. A series of practical constraints on the pump are specified in order to reflect the limitations on facilities available and to provide experience of constraints found in practical design experience.
- Use a 200 W motor at 3000 rpm (this power can be altered year on year).
- All solid models and drawings must be generated on solid modelling CAD software. The drawings must be produced in Third Angle projection and presented on the Department drawing sheet template. They must be checked as to conform to BS 8888 (2002) as instructed in the first year design course and include full dimensional and geometric tolerances for shape and positional information.
- Designs must be restricted to the manufacturing techniques available in the Teaching Workshop and taught in year 1. Students need to be aware of the limitations of the manufacturing capabilities of the group members.
- The General Arrangement (GA) must also contain the Bill of Materials (BoM) which lists all the parts that appear on the GA.
- The General Arrangement drawing must contain sufficient views, with full or partial sections, of the assembled pump to show how and where all the parts fit together. It must contain all the required parts including all screws, nuts and washers. The GA may contain an exploded view, but this should be in addition to the customary orthogonal and sectional views. A single exploded view as a GA drawing is not defined as acceptable

The assignment accounts for about 45% of the total marks for the second year Design & Manufacture course marks with the remainder coming from an individual conceptual design assignment. The project commences in October and concludes in February. The work typically represents about a quarter of the student’s academic loading over the period concerned and is supplemented by lectures in machine elements such as bearings, seals, couplings and shafts, hydraulics, manufacturing, ideation and design process. A self, peer and tutor assessment scheme is used to apportion marks for the three assignment elements: report, manufacture quality and poster exhibition.

The output from the detail design phase is the final production documentation:

- a General Assembly drawing of the complete pump;

- a Bill of Materials containing all the manufactured & purchased part details and the quantities;
- detailed engineering drawings for all the manufactured parts;
- CAD solid models of the parts requiring CNC manufacture.

The procedure suggested for the hydraulic design follows that outlined in Jekat (1986) [8]. This involves definition of the following parameters.

- Performance specification, H, Q, N
- Derived performance parameters, Ω, N_s
- Outlet design η_h, β_2, n, μ, u_2, r_2, b_2, α_2, v_{t2}, v_{n2}
- Inlet design β_1, s, r_1
- Power requirements η_v, η, M_{loss}, DF_{loss}, P_s, T_q
- Volute design t, b_v, Δr_{max}

Where H is the head (m), Q is the volumetric flow rate, (m^3/s), N is the angular speed (rpm), Ω is the angular velocity (rad/s), N_s Is the Specific speed, η_h is the hydraulic efficiency, η_h is the volumetric efficiency, η is the overall efficiency, M_{loss} is the mechanical loss, DF_{loss} is the disc friction loss, P_s is the shaft power, β_2 is the impeller exit angle, n is the number of blades, μ is the slip factor, u_2 is the exducer tangential velocity, r_2 is the exducer radius, b_2 is the blade height at the exducer, α_2, β_1, v_{t2}, v_{n2} are angles and velocity components in the impeller velocity diagrams, s is the blade thickness, r_1 is the inducer radius and t, b_v and Δr_{max} are volute parameters. An example of the typical output from the hydraulic design is shown in Figure 1.

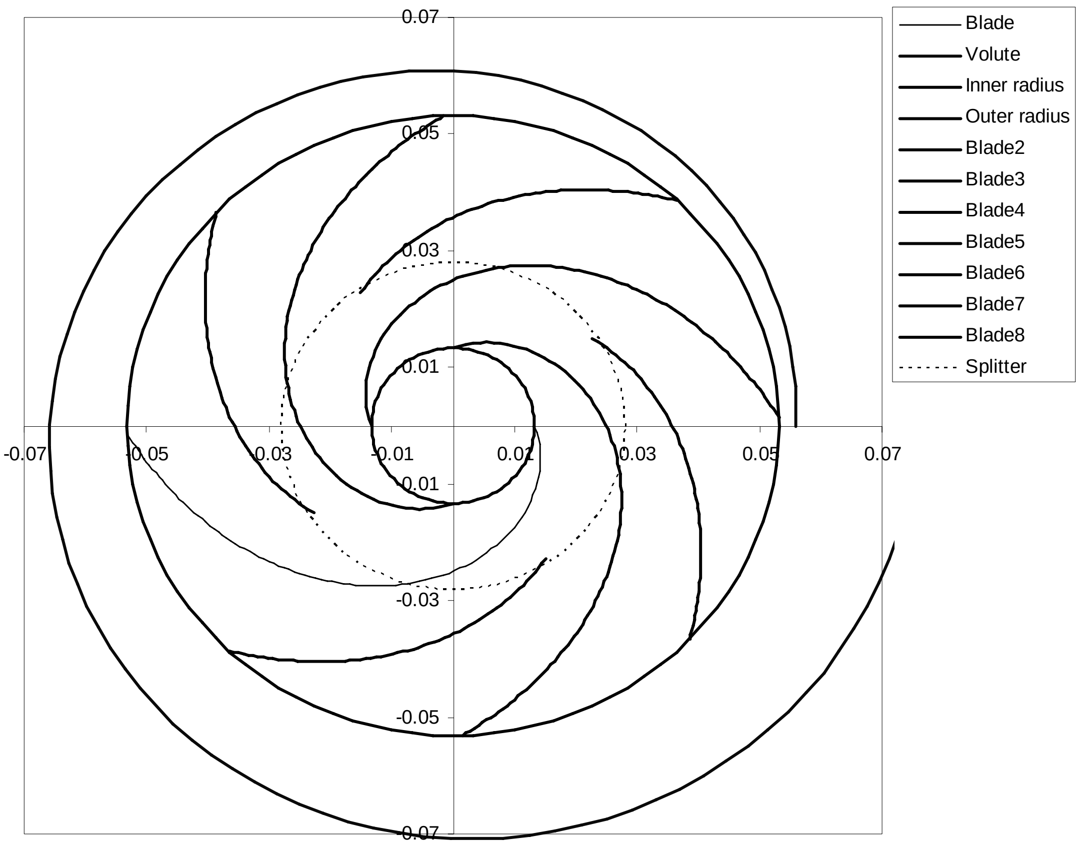

Figure 1. Typical hydraulic design output

An example of the components designed and then manufactured by students is shown in Figure 2 and examples of posters produced by the student groups used to present the pumps in an exhibition in the department are shown in Figure 3. Each group tests their pump in an event known as the 'Golden Bucket' competition. The event takes place in a stairwell in the Department and is subject to the appropriate risk assessment and health and safety strictures. A test rig used for mounting the pumps is set up on level one of the stairs. A suitable length of hosepipe is then run up the stairs to a 2 gallon bucket positioned on the fourth floor landing. The challenge is to see which pump can fill the bucket the quickest, while limited to a maximum shaft power of 200 W at 3000 rpm. If the power demanded by a pump is more than 200 W, the motor speed is reduced until the power demand is 200 W and the pump is deemed ineligible for the Golden Bucket Trophy. The winners have their names added to the trophy which is displayed in the Department.

Figure 2. A typical set of pump components manufactured by the student group

The project represents an activity that students look forward to in the curriculum. Students take great pleasure in seeing their design progress through from concept sketches, through design decisions to embodied realisations and physical components. The mixture of elements from design tutorials, problem based learning, manufacture, testing, competition and exhibition represent well-established mechanisms for deep learning. Although students do gain valuable skills in basic manufacturing technology including CNC manufacture, some of the techniques used are not suitable for batch or mass manufacture and subsequent education and experience is necessary in order for students to develop their knowledge to a basic level fit for industry. A particular issue relating to this long standing project is the level of acquired knowledge in the Department by all staff concerned. This can lead to recommendations by tutors and technicians for particular approaches that the students should follow being made. While beneficial, in terms of ensuring students develop a high performing pump, such behaviours can result in students not benefiting from the learning experience of exploring an issue by themselves and, for example, having to re-work components or realize the importance of tolerance stack-up. An example is the suggestion to use adhesive to take up excess clearance. While such an approach may be suitable for a one off prototype that only has to operate for at most a few hours, it can promote poor appreciation of manufacture processes. As a result the staff team has come to recognize the need for diversity of projects to keep all parties involved focused on the learning experience to the benefit of the students.

5 CONCLUSIONS

With a standard cohort of about 160 engineers in a given year, over 1500 engineers have now been trained in the valuable skill sets of problem solving within a set of defined constraints, the use of analysis to support design and basic design and manufacture. With such a long-running project many of its aspects have been optimised in terms of student experience, staff effort and resource. Workshop staff and tutors, for example, are well versed in resolving the type of issues faced by students in realising their designs and manufacturing an item for the first time. Design tutors and lecturing staff have prior knowledge of many viable and non-viable approaches to the task. Here-in lies one of the inadequacies of such a project as real design and manufacture tasks are beset by new challenges often outside the experience of those involved requiring ingenuity in their resolution. A repeated project denies all involved the valuable learning experience of facing such challenges. In order to mitigate against such set behaviours a series of projects are now being defined to provide alternative projects for the subject material of the constrained design project.

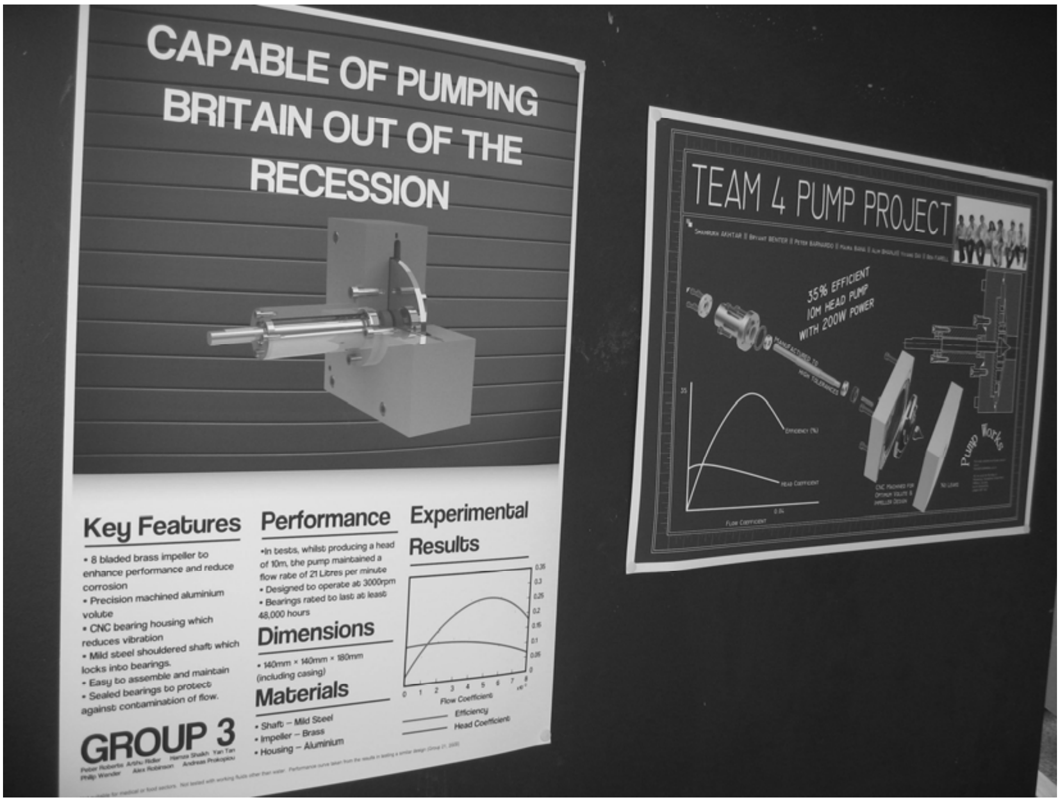

Figure 3. Student designed posters are used along with a display of the manufactured pumps

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