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DEMANDING IT ALL FROM THE NOVICE MECHANICAL ENGINEER THROUGH DESIGN AND MANUFACTURE

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ABSTRACT
A core design and manufacture group project has been run in the second year of the Mechanical Engineering undergraduate programme at Imperial College for over two decades where students are required to develop highly loaded rotating machinery, such as a pump or a winch, early in the second year of their undergraduate study. The aim has been to provide a practical opportunity to apply and develop skills learnt in the first year and to provide the experience of manufacturing, operating and testing what has been designed. While these projects have been a mainstay of the educational experience for many years, there has been a persistent concern that the projects are deterministic and highly constrained. The course team and student body have debated and now implemented a new project that is both less constrained and more appealing to the student cohort. In this project the students are tasked with developing a transmission for an electric scooter. The project has resulted in a significant diversity in designs and, importantly, the students embracing the curriculum content with fervour. The challenge still requires attention to the application of fundamental mechanical engineering principles such as transmissions, solid mechanics and materials, but also focuses on electronic control systems, battery and motor characteristics, high current and power, health and safety and a range of transferable skills. The multi-disciplinary nature of the project combined with an appealing application has resulted in a highly engaged year group. This paper reports on the project and includes an analysis of the diversity of designs and student effort.

Keywords: Design, make, test, manufacture, engineering, e-scooter, project

1 INTRODUCTION

The modern mechanical engineer is expected to possess a combination of technical expertise and a range of ‘soft skills’. These requirements for engineers have been extensively debated and defined by national bodies such as the Royal Academy of Engineering and the National Academy of Sciences, as well as professional institutions and national accrediting bodies. In 2004 the National Academy of Engineering [1] defined the attributes of the engineer of 2020 to include mathematical and science skills as well as creativity, practical ingenuity and communication, business and management skills. This required skill set is reflected in typical undergraduate Mechanical Engineering curricula, which contain technical foundation courses as well as applied and integrative components. The foundation courses, such as Thermodynamics, Solid and Fluid Mechanics and Materials, are often taught in a structured and 'linear' way, using a course plan that emphasizes the gradual build-up of complexity, whilst focussing on the understanding of the mathematical and physical backgrounds and solving a set of well-defined problems with clear boundary conditions. Next to creativity and technical drawing skills, important aspects of the design part of the curriculum are the integration and application of the knowledge acquired in the separately taught foundation courses and the ability to define and quantify the specifications and boundary conditions associated to a certain problem. In other words: in the design projects the students are given engineering freedom to demonstrate their capabilities in a combination of technical and non-technical subjects. An important part of a design engineering project is to work through a series of processes that are focussed on bringing structure to the entangled compound of the stakeholder’s demands and requirements and technical, physical and economical

possibilities and restrictions. Such a process is recursive, retrospective and involves a number of iterations. In educational design projects this inherent non-linearity is even more evident: ‘learning by doing’ plays an important part in a student's experience, which means that regularly an incorrect path may be followed. All these aspects make educational design engineering projects seem time consuming and inefficient by participating students and even by educational staff. Within an educational plan, the time that the students are expected to spend on each course is limited, and one way around the perceived inefficiency of design projects is to provide the students with a highly constrained brief in terms of design freedom, creativity, solutions, materials and complexity so that the students will be forced to gradually proceed through the design process. Furthermore, time expenditure on tasks that are not directly perceived as being academic (such as manufacturing and planning) is often limited or even omitted, whereas these subjects will provide students with valuable insights into the practicalities and feasibility of their designs.
The viewpoint outlined so far can result in design projects that are ‘educationally safe’: projects that are restricted in scope and have a large number of pre-set milestones driving the students towards a pre-determined outcome, focussed on mid-twentieth century engineering.

2 THE E-SCOOTER PROJECT

A core design and manufacture group project has been run in the second year of the Mechanical Engineering undergraduate programme at Imperial College for over two decades where students are required to design, build and test highly loaded rotating machinery. The aim has been to provide a practical opportunity to apply skills learnt in the first year and to provide the experience of manufacturing, running and testing what has been designed. Projects along these lines have included the design and manufacture of pumps and winches, see for instance [2], and there has been a persistent concern that the projects are deterministic and highly constrained. While this may represent a common experience in certain industries feedback, from students and some staff, indicated a preference for a more inspirational and aspirational problem that is more closely matched to the student’s areas of interest and way of life. This lead to the course team and student body to debate and implement a new project where the students are tasked with developing, i.e. designing, manufacturing and testing, a transmission for an electric scooter. Introducing a new project is always a concern in a successful and established curriculum, as there are pressures for any new project to be as good as, or better than its forerunner. Here, use was made of a master’s project prototype to gain confidence in the technology, followed by a detailed consideration of the student experience and the pedagogic journey.

2.1 The student experience - rationale behind a scooter

The electric scooter as a design project was suggested by an MSc student. The student's objective was to develop a portable means of transportation for a commuter to be used in an urban area such as London, to travel from a stop on the public transport network to the final destination. This means the topic of the design project is close to the day to day living experiences of the students, who typically travel to the college using the London Underground. The MSc student's prototype project was developed in a period of four weeks, during which the electric drive train was designed, manufactured, assembled and mounted onto a purchased push scooter. Following the successful development of the prototype, the project was introduced to the 2013 cohort of 146 second year undergraduate students in Mechanical Engineering. Project teams of 6 students were composed, with each student expected to spend a total of 90 hours on the project over a period of 14 weeks.

2.2 The project brief

The project brief handed to the students contained seven pages of text and imagery with background information on the project. This elaborate document provided only descriptive and non-quantified details, forcing the students to initially focus on the development of a product design specification; for example: the specified objective was to develop an electric scooter that would be able to provide transport from South Kensington Underground Station to the entrance of the Mechanical Engineering Department of Imperial College on Exhibition Road, a distance of about 500 m and a journey very familiar to the students, but further characteristics and the related requirements such as the distance and the time available for this journey were not specified. The students were provided with a push-scooter, an electromotor, a battery with casing and wires and an electronic speed control system including a thumb-throttle. Structural components had to be made out of steel or aluminium using the manually operated equipment and NC manufacturing techniques available in the department's student workshop whilst the transmission components (gears, chains, sprockets, belts, etc., depending on each group's design) were to be sourced from one dedicated supplier. The provided motor was a 1500 W, 60 A high speed, low torque motor that is normally used for radio controlled helicopters. The no-load speed of the motor is about 6200 rpm, which with a diameter of the driven wheel of 120 mm would result in a theoretical top speed of the scooter of 135 km/h. Irrespective of the required power, this implied that a direct drive solution is not possible and that a transmission with a reduction in the order of 1:6 to 1:10 was required to between the motor and the wheel. The only other restriction detailed in the brief was the compulsion to use a shaft that was fixed to the rear wheel. No other restrictions were made, enabling the students to freely develop their concepts during the first four weeks of term.

2.3 Pedagogic journey – project structure and phases

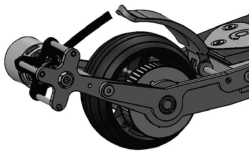
The project duration was 14 weeks, starting at the beginning of the student's second year in October. Three deadlines were set: a design gateway after four weeks, a design report in week 10 of the project and the hand-in date for the finished scooter transmissions at the end of week 14. During the initial stage of the project the students focussed on developing their design, as well as attending project related lectures on subjects including design, computer aided design and manufacturing, transmissions, various machine elements, stress analysis, fatigue, electric motors, batteries and reporting techniques. The expected time expenditure during this phase of the project was 10 hours per person per week. Experienced tutors were available for advice regarding practical design considerations and to provide support and guidance regarding the computer aided design software. These tutors took a passive role in the design process and were not actively providing design solutions. The intensive design phase was concluded with a 25 minute design review, during which each group presented their work to a panel of staff. The review panel asked questions regarding the design specification, the concept sketches and the followed selection procedure, the stress and fatigue calculations and the technical drawings. This gateway review provided a formal 'go or no-go' for the individual groups to proceed to the manufacturing phase. The discussions with the review panel were formative, meaning no marks or grades were awarded and the groups were free to use the provided feedback to alter their designs. The design stage of the project was concluded with a 25 page group design report, to be submitted 5 weeks after the design gateway review, discussing the product design specification, the generated concepts and the detailed design, including the stress and fatigue analysis, manufacturing considerations and the project planning. This report counted for 40% of the total mark for the project.

Following the design phase, the students spent a period of 10 weeks with a focus on manufacturing the designed transmission components [3]. The time the students were expected to spend on the project was significantly reduced, to an average of about 5 hours per week. A bench test set-up was available to test the performance of the manufactured product and the majority of the groups decided to make minor adjustments based on the outcomes of the bench testing, for instance because of a too small clearance between a moving component and the rest of the construction. At the end of the 10 week manufacturing period, the scooters were handed in and stored until a scooter test event at end of the year: the day after the final exams will be available for minor adjustments and preparing the scooter for testing and a day later the scooter test event will take place on a closed circuit in a square on Imperial College's South Kensington campus. This event is the unofficial end of year event for the second year students and is subject to the appropriate risk assessment and health and safety structures, with the departmental safety officer being part of the test event safety panel. Next to the safety aspects of the developed scooter, focus points will be the performance of the transmission in an endurance test and the manufacturing quality, forming the remaining 60% of the total mark awarded. The winners will have their names added to the golden scooter trophy which is displayed in the Department.

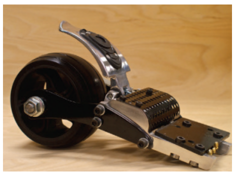
3 REFLECTION AND LESSONS LEARNED

3.1 The developed scooters

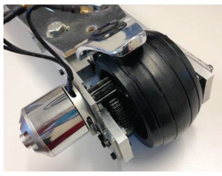
The complete project resulted in a wide variety of design solutions, and only a few of the scooters manufactured looked similar. The competitive element of the project resulted in the teams being engaged, but also operating quite secretively and not willing to share ideas with other groups. The required transmission ratio was achieved with either a one-step or a two-step reduction; some designs placed the motor behind the wheel, whereas others used the available space under the footboard. The photographs in Figure 1 provide an impression of the variety of designs. Designs can arguably be classified in groups, ranging from '*minimalist*' (Figure 1(a) and (d)) and '*simple and compact*' (b) and (c) to '*function before form*' (e) and '*large, bold and emphasizing'* (f). The majority of the groups (18 out of 24) decided to develop a transmission using a belt drive, whilst two groups decided to use a chain drive, two groups utilised a gear transmission and a further two groups opted to use a combination of a chain and a gear to reduce the motor velocity in two steps. The average mass added to the scooter was about 3300 g, ranging from a minimum of 1880 g to a maximum of 7000 g. The average expenditure, using standard university suppliers, on components such as bearings, sprockets, chains, gears and belts was £57.91 and also on this aspect the groups showed a rather large variation; some groups spent £32, whereas the top-spending group developed a two-stage reduction with a combined sprocket and chain transmission for more than £120.



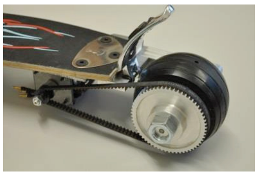
(a): belt drive with motor behind wheel.



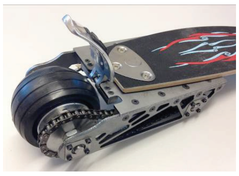
(b): belt drive with motor behind board.



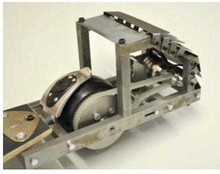
(c): gears with motor next to wheel.



(d): belt drive with overhung shaft.



(e): chain drive with motor under board.



(f): belt drive with motor behind wheel.

(g): a scooter in use.

Figure 1. Examples of developed scooters

3.2 Staff reception and perception

The e-scooter project replaced a long-running project that had been optimised over the years it ran. In the previous long running project, tutors knew what questions to expect from the students and the workshop staff knew of most design related manufacturing issues related to the project. Consequently, the introduction of the e-scooter project encountered some resistance and conservatism, mainly relating to expected issues that would be encountered during manufacturing and the expected time that the students would spend on the design and manufacture of their scooter; time that they consequently would not be able to spend on their other courses. The complete freedom given to the students regarding their component design could result in a large variety of parts with complex shapes to be manufactured, and when these parts need to be clamped on the machines using jigs that have to be custom manufactured, the required time for manufacturing could be extensive. Therefore, the need for proper jigging was repeatedly mentioned during the tutorials and the CAD/CAM lectures so that the students could take this into account. During the project, members of staff became very engaged in the project and the main point of attention for the involved design tutors was to maintain a good balance between providing feedback and actively participating in the design project and providing solutions.

A second consequence of replacing a long running and rather restricted project by a project that allows more freedom in design was that a number of unexpected minor technical, educational and organisational niggles occurred during the project. These ranged from the perceived health and safety concerns related to the use of a high current, high power drive train to the availability of components and differences in guidance provided by the different tutors. Students were actively encouraged to report any issues they encountered and developments within the project were continuously monitored. Feedback from students, tutors and teaching staff was used to continuously control and amend aspects of the project and these changes were communicated back, thus creating awareness of the actions that were taken. This flexibility of the organisation of the module and the direct actions taken contributed to the positive attitude of the students towards the project.

The use of high power, high current components with their apparent safety issues and risk of personal accidents resulted in a range of concerns. It is necessary to be up front and rigorous on health and safety protocols with both colleagues and students. Risk assessments were an integral part of the development process of the module and lectures on batteries and motors not only focused on theory, successful applications and best practice but also illustrated the potential risks. Such an approach enables projects such as this to be implemented.

3.3 Student's view

In a short survey at the end of the project, feedback from the students on the topic of the project, i.e. developing a transmission for a scooter, was very positive, with 97% of the second year students who participated in the survey stating a preference for developing a scooter transmission over previous design project topics, such as a pump or a winch. In the official student survey, the scooter project received a 68% positive overall approval rating from the students, with a further 23% of students being neutral. While these numbers are not overwhelming favourable, it needs to be recognised that the student group is large, 146 high-attaining and demanding students, operating within a culture where analysis is the dominant mode of operation.

Based on questions asked at tutorials and follow-up discussions with students the main aspects of the design process where the teams appeared to be encountering challenges during the project were:

- Dealing with multi-disciplinary subjects.
- Estimating the requirements for properties that were not quantified in the project brief.
- Design for manufacturing and assembly
- Cooperating in a team and division of tasks.
- Adhering to the project time planning.

3.3.1 Dealing with multi-disciplinary subjects.

The entry requirement for participation in the project was the successful completion of first year foundation courses, and even though all students passed these courses, the integration of the knowledge of the various subjects showed to be an issue. For example, the students had been taught about stress analysis (see Childs [4]) as well as transmission elements before commencing their work on the project but the students did not consider using beam theory as an estimate of the bending stresses that occur in gear teeth.

3.3.2 Estimating the requirements for properties that were not quantified in the project brief.

As stated above, the brief provided had a descriptive non-quantitative nature, and the project teams had to expand upon the details provided in the brief to define their product design specification, and make some assumptions and reasonable estimates to be able to start the design process. This turned to be a challenge for some groups, who got stuck in lengthy discussions without coming to a conclusion whereas other groups quickly managed to perform some simple experiments and a range of order of magnitude estimates, prior to launching into overall concept designs and general arrangements.

3.3.3 Design for manufacturing and assembly.

Even though the concepts of design for manufacturing and design for assembly were repeatedly mentioned in the supporting lectures, the manufacturing sessions in the workshop provided valuable lessons for the students. Every group reported delays because of ill-defined tolerances, poor manufacturing precision or the design being impossible to assemble after all parts had been manufactured. As this project represents the first highly stressed, rotating machinery item that any of the students have designed and then made, such issues and challenges are to be expected, and form a natural part of the learning experience, prior to the students engaging in further projects and professional engineering where right-first-time expectations apply. The bench testing sessions provided further opportunities for feedback on the developed transmissions, with a focus on the machine operation and dynamics, including sharp edges, non-alignment and too small clearances.

3.3.4 Cooperating in a team and division of tasks.

At the start of the project the 148 students who were signed up to participate were divided into twenty teams of 6 students and four teams of 7 students. Due to last minute non-attendance of students, two groups of initially 6 students were reduced to 5 students and because of scheduling restrictions these two groups could not be replenished using students from the larger groups. However, the groups composed of 5 students appeared rather successful, whilst the groups that were composed of 7 students were the ones that complained about difficulties in team management, division of tasks and noncommitment from individual team members. This observation ties in with published research on optimum group sizes, where the most common and preferred group size for projects of this size and duration is 5 or 6 students [5], [6].

3.3.5 Project management and adhering to the project time planning.

All groups made a detailed project plan at the start of the 4 month project. This plan included a Gantt chart with milestones and deliverables. However, the students treated their plan as a deliverable of the project and not as a tool for their project management. Consequently, many groups did not manage to adhere to the developed project plan and only flagged issues a few days before deadlines. Planning a long-term project remains an issue for teams inexperienced in design and group work, with many students being prone to only focus on the subject or course with the closest deliverables. As the project was set-up with only three deadlines (the design gateway, the design report and the final scooter submission) over a four month period with the students being responsible for their detailed planning, on-time delivery and continuity of work flow was an issue, with only 33% of groups managing to deliver the scooter on time and only two groups (8% of groups) flagging this up as an issue two weeks before the project due date. These planning issues may be solved by an increased formative (i.e. non-marked) focus on the detailed weekly planning during the manufacturing phase of the project and the introduction of weekly pulse updates, either using an online tool or in tutored sessions, where deliverables, milestones and dependencies are commented upon and status updates are given.

4 CONCLUSION

A new design and manufacturing project has been introduced for second year undergraduate students in Mechanical Engineering. The project aimed to move away from 'traditional' mechanical design education by defining a project with a multi-disciplinary nature and an application that aimed to appeal to the students. The objective was for the students to experience a full design, manufacture and test project without the restrictions that are usually associated to such projects in an educational setting. Main learning points were threefold: firstly, students will assume a positive attitude towards a project that is not fully optimised yet, when their feedback is taken seriously and reacted upon. Secondly, that apparent health and safety issues can be managed by adopting rigorous procedures. Thirdly, the project suffered from poor project planning by the students, resulting in poor on-time delivery of the developed transmission modules. This could be solved by additional attention to overall project management and detailed manufacturing planning. It can be concluded that the introduction of the scooter project resulted in a highly positive and engaged year group.

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