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Model Engineering of Ancient and Historical Machines as a Training Tool for Mechanical Engineering Students*

FERNANDO G. TORRES
Department of Mechanical Engineering, Catholic University of Peru, Lima 32, Peru. E-mail: fgtorres@pucp.edu.pe

Model engineering has played an important role in the development of several technological breakthroughs. Some examples include James Watt's work on the broken Newcomen engine model at Glasgow University, which introduced him into steam engines. Richard Trevithick developed several scale models in order to demonstrate the way of functioning of his early road steam locomotives. Recent advances in computer aided design (CAD) and computer modelling have provided resources for a more virtual oriented education to mechanical engineering students, which may have resulted in a reduction in the actual time dedicated to the construction of real pieces of machinery or equipment. The choice of the type of machines to be modelled also represents a challenge for a curious student, especially if we try to recreate devices engineered by the ancient Greeks, Romans, by Leonardo da Vinci, or the more recent steam and hot air engines. The list of potential devices to be modelled is almost endless. In this paper, we report on a contest for the construction of functional models from the ancient Greeks. We also report on the development of steam and hot air (Stirling) models. The difficulties found by the students during the projects are discussed in terms of the course level of the students and their specific backgrounds and interests.

The construction of operating scale models also represents a good option for university departments with limited budgets, since the amount of materials and production time required is considerably less than what is required for full scale machines. Some suggestions for the implementation of this kind of workshops and contests are also given.

Keywords: model engineering; engineering education; steam engine; historical machine

1. Introduction

Model engineering cannot be considered only as a hobby for home shop machinists. In fact, it is also used by professionals in industry and among researchers in different kinds of projects. In these cases, scale models are useful to study items in development. They are used to test structural responses, aerodynamic properties, and dimensional details, among other properties. Nowadays, the use of model in engineering education is still common practice for the study of fluid mechanics, to test the aerodynamic response of different shapes. However, due to the advance of computer aided design and computer modelling there are fewer opportunities for the students to construct real pieces of machinery. Some engineering teaching institutions have used Rapid Prototyping technologies to allow students to construct solid models. These experiences have proved to enhance students active learning in the teaching of multiple subjects connected with product development [1–2].

Building scale models is an activity that requires specific skills to be developed. Previous workshop experience is particularly useful. Skills in drafting and drawing are also needed. Furthermore, during the construction of models the students have to deal with similar problems as those found in the construction of full scale machines by professional engineers. Decisions need to be taken regarding the materials to be used, the choice of adequate manufacturing techniques, debugging, commissioning, among other issues.

In a previous paper, the author has suggested some methodologies for the teaching of polymer processing to mechanical engineering students [3]. These methodologies were based on the use of practical examples during lab courses, case studies and other analytical tools. In this paper, we propose the use of model engineering as a training tool for mechanical engineering students in a more or less systematic way, using modelling contests or workshops as the suggested methodology. The role of models in the study and the development of new technology by professional engineers is briefly reviewed. Two main activities from our department designed to encourage mechanical engineering students to get them started into model engineering are described and analysed. The first activity was a contest aimed at the construction of working models from the ancient Greek world and the second activity was a steam and Stirling engine workshop. The usefulness of these activities and the difficulties found during the projects are discussed in terms of the course level of the students and their specific backgrounds and interests.

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2. Model engineering and 'professional' engineering

Models have been used in engineering for many years. Before the era of computer aided design, engineers used models in experiments on the stability of retaining walls, the performance of columns, bridge design, flow problems, and many other practical problems. With such models engineers were able to analyze a variety of problems even when theoretical frameworks were not completely elucidated. Smith [4] even claims that in the nineteenth-century, British engineers mistrusted results from mathematical analysis.

The construction of models can be an effective medium to study and improve existent technology. It was the work with a model that brought Watt into the world of steam engines, for which he is now world famous. Watt was asked by Professor Anderson to repair a model of a Newcomen engine belonging to the Natural Philosophy class of Glasgow University [5]. The Newcomen engine was the first practicable atmospheric steam pumping engine that allowed miners to reach greater depths and, thus had a great impact on the industrial revolution. When Watt worked with this model engine, he carried out several experiments that showed him many problems that were inherent to the Newcomen engine design itself, such as steam condensation by colder bodies, different rates of heat transfer by various materials, hot water boiling at low pressures, and some other problems [6]. According to Hills [6], there is evidence showing that while Watt was working with the Newcomen's engine model, he came up with several new ideas to improve such an engine in order to prevent the waste of steam. Not only made Watt the model work but at the same time he used it to understand the basic principles of steam engines.

The Newcomen's engine model was useful for Watt in the same way that models are useful nowadays. Engineering students can use models to study physical phenomena and technological solutions. When students are asked to build a model, they have to develop necessary skills that they will need as professionals. For those students who are comfortable with experimentation and handwork, the construction itself can be quite stimulating, whereas those who prefer more theoretical approaches can use models to show and also understand themselves how physical principles work in real situations.

Further developments in steam engine technology were carried out to improve Watt's engine. One of the inventors that experimented with the use of 'strong steam' (i.e. high pressure steam) was Richard Trevithick. He has been called the 'Father of the locomotive' because he had constructed several models of such a machine before the end of the eighteen century. Model engineering was a key issue for Trevithick's developments. Finally, in 1801, he constructed a large scale carriage which he patented in 1802 [7].

3. The *Mechane* Contest at PUCP

The aim of the *Mechane* Contest was to encourage engineering students to develop fully functional models of ancient Greek machines. The idea was to allow the student to freely choose an ancient Greek machine to be modelled. The models had to be presented for the contest accompanied by a theoretical description of its physical working principle, as well as with the design and construction details. The six categories considered were thermal machines, war machines, hydraulic and pneumatic machines, medical instrumentation, ancient ships and ancient navigational instruments. A jury would pick the best three models, and the students who built them would receive a monetary prize.

Ancient Greek science has received much attention; however, ancient Greek technology has been the subject of fewer studies [8]. The ancient Greeks applied scientific principles to the develop machines just in the same way Watt and Trevithick did, or just as modern engineers do. The machines and artefacts developed and used by the ancient Greeks present several case studies of engineering solutions that are worth reviewing in modern engineering courses. Some of these solutions include mechanisms that used old versions of cogs and screws, machines that use fluids and steam, war machines, among others [9–10]. Models of such machines can be built using materials that are easy to shape such as wood, rope, copper, and other similar ones, and represent an excellent choice for beginners in model engineering.

In the *Mechane* contest, the first prize was awarded to a model of the OXYBELES (*bolt gunner*), an ancient Greek catapult that shot arrow-shape missiles [11]. It was formed by an inverted compound arc with a winch mounted on a tripod. The model of this machine was constructed in wood (Fig. 1). Even if the finishing of the model was rather crude, the student produced a fully working model machine and made use of some clever engineering solutions. In order to produce enough tension in a small version of the actual machine, the student decided to use a metal spring instead of the probable flexible material that might have been used in the original version. This was well documented and the jury considered it an adequate engineering solution. It is worth mentioning that for the jury, the engineering aspect of the solution had a more relevant weight than the actual historical representation.

The first runner up model was Hero's magic

Fig. 1. Oxybeles presented at the *Mechane* contest.

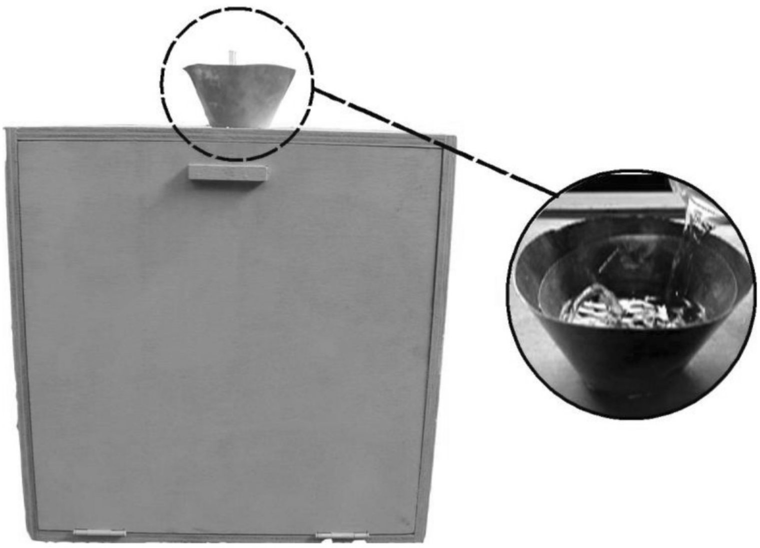

Fig. 2. Hero's Fountain presented at the *Mechane* Contest.

fountain (Fig. 2) where a vertical jet of water is produced and sustained above the height of its source by air pressure. This model was built using wood and plastic parts, and its counterintuitive working principle caught the attention of the jury as well as that of the visitors who viewed the models on display. The third prize was awarded to a model of the AEOLIPILE (*wind ball*) which is considered to be the first steam engine of history as it uses the power of steam to produce rotational movement. Its construction was described in one of the known Hero's books called PNEUMATICA. It was formed by a hollow sphere with two oppositely oriented outlet tubes mounted over a cauldron by means of two supporting tubes that allow the steam to enter into the sphere. The steam that left the machine produced an angular momentum that forced the sphere to rotate. This was a beautiful metal model (Fig. 3) based on a quite clever idea. The actual model had some friction problems at the bearings at the time it was presented to the contest.

Some of the skills developed by the students are summarised in Table 1. Some of the academic modules that are part of the current engineering course and that are related to such skills are also listed on the table. It is worth noting that two of the awarded student had not taken at the time of the contest all the academic modules that would provide them with the skills necessary to fully understand the model. However, they managed to understand these principles on their own without any problem. As an example, the student that

Fig. 3. Aeopile presented at the *Mechane* contest.

constructed the model of Hero's fountain had not taken the Fluid Mechanics course; however, he had no problem using Bernoulli's equation to explain the working principle of such model.

4. The Model steam and Stirling (Hot air) Engine Workshop at PUCP (Catholic University of Peru)

The steam engine uses steam to produce mechanical work. The most used steam engine is the reciprocating steam engine which is formed essentially by a cylinder and a valve or steam chest. The valve opens and closes the ports to admit and release steam. The steam that enters into the cylinder moves the piston in a reciprocating linear motion that is converted into a circular one [12].

Stirling engines use air or another gas to produce mechanical work. In these engines the air or gas is moved into the hot and the cold part of a cylinder. In the hot part the working fluid expands and performs mechanical work, whereas in the cold part it reduces its pressure and it is reduced back to its original volume. The working fluid performs more work during its expansion than it is required during its compression. Stirling engines were used in the nineteenth century to operate low power water pumps due to their ease of operation and maintenance, and their efficiency [13].

The Steam and Stirling Engine Workshop at PUCP was opened to all engineering students as an extracurricular activity. No grades or credits were granted for participating in such a workshop. In this way, only enthusiastic students signed in. The workshop was opened to all students at every level (from the first year to the last (fifth) year of the Engineering Course at PUCP). The aim of this workshop was for every participant to build a functional model of a simple Stirling or steam engine.

The students were provided with plans, drawings and schemes of simple steam and Stirling engines, already built and tested by model engineers. Most of such plans were available in the internet. They were allowed to pick a project by themselves if they wanted to do so. If they did not show any preference, they were given a suitable project. In most cases, for first year students the plans were clear enough to start the construction of the machines, whereas for advanced students there were constructive details that had to be inferred by them. A general meeting was held once a week. During these meetings the students presented their project advance and would ask for advice from the instructors. The project was to be developed in stages. In the first stage the students had to draw 'their own' schemes of the machine by using the plans provided (Fig. 4). This was a really important part of the project. They also had to understand how the model worked. Some students had the plans in printed and digital versions; however, it was not quite clear for them

Table 1. Description of the models presented at the *Mechane* contest

Model	Student level	Needed skills	Relevant academic courses
Oxybeles	3rd year	Structural engineering, materials, design of machine elements, workshop skills	Studied: statics, dynamics, strength of materials Not taken yet: machine elements design, mechanical design
Hero's magic fountain	3th year	Fluid mechanics, materials, workshop skills	Studied: themodynamics Not taken yet: fluid mechanics
Aeolipile	5th year	Fluid mechanics, materials, thermodynamics, workshop skills	Studied: fluid mechanics, thermodynamics, turbomachinery

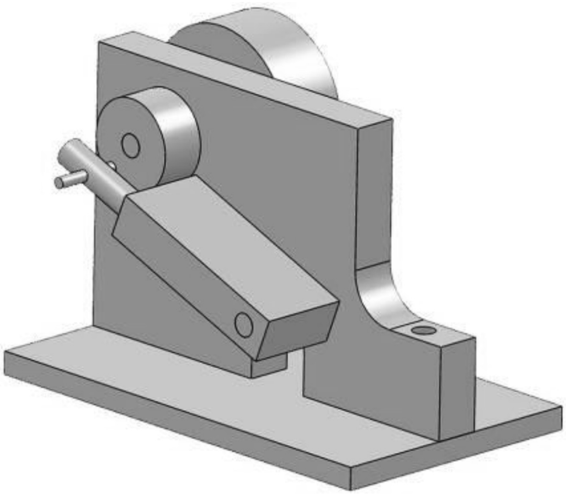

Fig. 4. Isometrical drawing of the 30° oscillating steam engine produced using Solid works®.

what the pieces actually looked like in reality, or how the machine actually worked. In the second stage the students had to prepare a list of all the materials needed. Finally, in the last stages the students had to start the construction of the individual parts of the machine and then assemble them into a working model.

Table 2 shows a list of the projects presented in the workshop, indicating the general skills necessary to build the model, as well as the specific skills developed during the project. The academic level of the students that took part in the workshop is also indicated in table 2, and we can observe that students from different levels were attracted to the projects. First and second year students received finished plans with detailed instructions. They did not need to take many important decisions regarding the materials to be used or the manufacturing process but they had developed other basic skills such as understanding plans, drawing sketches, using machine tools among others. In contrast, students of higher levels were asked to select the materials to be used and to calculate and dimension some of the machine parts. They also needed to understand the thermodynamics involved in the functioning of the models.

The construction of these engine models has immersed the students into fields not yet studied in the classroom. In all cases, the students managed to find solutions and overcome difficulties originated due to lack of training. This type of practical activities has shown to be useful to introduce students into new topics and to integrate the knowledge acquired in different courses, relating them to an actual product.

Most students had had previous experience on basic engineering topics such as drawing. However, some drawing courses do not relate theory to practice as the students are asked to draw pieces whose function they do not know or understand. Some of the participants not only drew the machine parts of their models but also selected the materials needed. During the testing of their models, students can actually find out whether the materials they selected were the right choice or not.

During the workshop, the students were given the opportunity to express their opinions by answering informal questionnaires. Most students thought that the workshop was a challenging experience, given that they are not used to the building process of real pieces of machinery. It was not possible for the students to determine whether the skills and knowledge acquired in the workshop had an overall influence on other coursework. However, they considered that such skills and knowledge would be more useful for the real practice of their profession than for their academic progress.

Table 2. Description and analysis of the projects from the Steam and Stirling Engine workshop

Model	Student level	General skills	Specific skills addressed	Relevant academic courses
Horizontal steam engine	2rd year	Drawing, design, machining, thermodynamics	Drawing sketches, isometrical drawing, study of the Rankine cycle	Thermodynamics, mechanical design
Wobbler French steam engine	2rd year	Drawing, design, machining, thermodynamics	Drawing sketches, isometrical drawing, study of the Rankine cycle	Thermodynamics, mechanical design
Stirling engine	4th year	Drawing, design, machining, thermodynamics	Choice of materials to be used, bearings choice, heat resistance of materials, study of the Stirling cycle	Thermodynamics, mechanical design
Vertical steam engine	1th year	Drawing, design, machining, thermodynamics	Drawing sketches, isometrical drawing, machining: turning, drilling and welding	Thermodynamics, mechanical design
30 degree oscillating steam engine	4th year	Drawing, design, machining, thermodynamics	3D Drawing, choice of materials to be used, bearings choice, study of the Rankine cycle	Thermodynamics, mechanical design

The human and material resources used were not too many. One mechanical engineering professor and 2 graduate students were the instructors of the workshop. The material resources provided included materials in semi finished shapes, such as brass, aluminium, steel, stainless steel, plastics, and wood. Other resources included tools, a modelling lathe, bench drill, welding equipment, adhesives and some other modelling workshop equipment. Although it was possible for the students to use these materials and tools, we believe that an 'immersion-style' quick training module on workshop practice for the model engineer should be given as part of the modelling workshop, so that the students can use the equipment properly and safely.

5. Conclusions and recommendations

The model engineering experiences of ancient and historical machines reported in this paper have proved to be a useful methodology to provide engineering students with practical approaches to machine design and construction and to introduce them into new academic subjects. This type of workshops can be useful to complement the average engineering curriculum, which tends to focus on engineering science and technical calculations, without relating academic knowledge to industrial practice.

The interest among students and media for these types of activities and workshops can be triggered by interesting subjects. In the cases reported here, historical subjects were used, but some other subjects can be useful too. Media diffusion is critical to the success of these initiatives, and therefore, workshops and contests have to be carefully planned. All planned resources, human and material need to be confirmed and allocated timely.

Human and material resources need to be guaranteed throughout the entire project for the experience to be successful. Otherwise, the students can get discouraged and abandon their projects unfinished. Instructions on the safe operations of machine tools as well as on the use of steam and other hot and potentially dangerous fluids need to be provided.

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Fernando G. Torres has a mechanical engineering degree from the Catholic University of Peru and holds a Ph.D. and an M.Phil. in polymer engineering from the University of Manchester (UK). Dr. Torres is an associated professor of Mechanical Engineering at the Catholic University of Peru. He is the leader of the 'Polymers and Composites group' and of the 'Biomechanics, Biomaterials and Biomimetics research team'. His research interests include the study and characterization of polymer composites, nanocomposites, biopolymers and bionanocomposites.