AC 2009-1062: THE USE OF RAPID PROTOTYPE MODELS IN MECHANICAL DESIGN COURSES

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Use of Rapid Prototype Models in Mechanical Design Courses (or "How Much Should We Spend for a RP Machine?")

Abstract

In recent years, rapid prototyping (RP) equipment has become widely available. The decreasing costs as well as the ease of operation of these machines make them well suited to the university environment. The most commonly used machines in academia include fused deposition modelers and powder-based 3D printers. In spite of the fairly modest cost of these RP machines, the decision to utilize RP technology in the classroom should be based on a thorough assessment of both cost and benefits. Students will be using these tools in industry and should become familiar with their capabilities. Moreover, the ability to create and manipulate physical models and/or functional prototypes can enhance student learning in many aspects of mechanical design. This paper explores the use of rapid prototypes in a variety of courses as presented in the literature, in addition to the author's experience with a junior-level advanced CAD course for mechanical engineering students and senior design projects. The discussion will focus on the learning objectives that can be achieved using design projects facilitated by the manufacture of rapid prototypes, advantages and disadvantages of RP, and unique features of RP that can be used to enhance the students' understanding of engineering concepts.

Introduction

Rapid Prototyping is a manufacturing method that is based on additive, freeform fabrication methods. The prototypes are constructed by the addition of successive thin layers of material to the model. The cross-sections of the object are obtained from 3D CAD solid models. RP models are typically used in industry for form, fit and functional analysis as well as concept visualization[2]. In addition, RP models can be used as patterns for conventional manufacturing methods such as casting.

Development of the Rapid Prototyping (RP) process began in the 1960s; the first commercially available RP machines were sold in the late 1980s at a cost of several hundred thousand dollars. By the mid to late 1990s, low cost desktop 3D printers were available for as little as $20-35,000[1]; these machines are now available for less than half that cost. Thus, the cost of purchasing a RP machine is not beyond the reach of the university, or even some secondary schools. The question now is which technology to use, and how to incorporate it into the curriculum.

Low Cost RP Technologies

There is a variety of RP technologies, including stereolithography (SLA), selective laser sintering (SLS), layered object manufacturing (LOM), fused deposition modeling (FDM), and powder binder printing(PDP)[2]. While the original laser-based technologies are expensive and require high maintenance of the equipment, the newer FDM and powder-based printers are considered to be essentially plug-in desktop peripheral devices. This alleviates previous problems with "care and feeding" of early machines, making these newer machines easier to use and more suitable for the academic environment.

Fused Deposition Modeling

Fused Deposition Modeling (FDM) is a technique whereby a nozzle extrudes a thin stream of molten material, usually a thermoplastic (ABS or PC) or wax. The position of the nozzle is controlled to trace out the cross section of the part as it deposits material on a build platform. The platform is then lowered and the next cross section is deposited. For overhanging features, the model requires support material to be built in the layers beneath the protruding feature. This support material can be dissolved or broken away after the part is built. The maximum build volume is approximately one cubic foot, extrusion diameter ranges from about 0.007-0.013" with tolerances of +/- .002-.005 in the cross sectional plane and +/- 0.010 in the vertical (build) direction[3]. FDM machines can be purchased for as little as $18,000; material cost is about $5-8 per cubic inch.

Powder Binder Printing

Powder Binder Printing (PDP) uses various methods to deposit layers of powder particles (starch, polymers) which are then fused together with adhesives or heat. Powder particles may be spread over the entire build volume or distributed using a roller. Overhanging features are supported by loose powder particles within the build volume. The starch adhesive is applied using a method similar to ink-jet printing. Parts are limited in size to a build volume of about one cubic foot, similar to FDM machines. Layer thicknesses are typically 0.003-0.008", with a resolution of about 300-600dpi in each layer[5]. PDP printers are now available for as little as $5000 with a material cost of $1 per cubic inch[4].

Use of RP in Academia

Several schools have reported the use of RP in courses ranging from introductory CAD to aeronautics [6-8, 10-12]. Frequently cited objectives address ABET outcomes such as 3(k) "an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice."[9] In lower level introductory engineering courses, these objectives include familiarizing students with new technologies and using the prototype as a motivator or reward to encourage student engagement[6-8]. In introductory CAD courses, the objective may also include enhancing visualization skills[12]. In upper level courses, the prototypes may be used to facilitate other learning objectives such as understanding and experiencing the design process and full design cycle, evaluation of experimental data, or fulfilling realization requirements in the engineering curriculum[8-11].

Advantages and Disadvantages

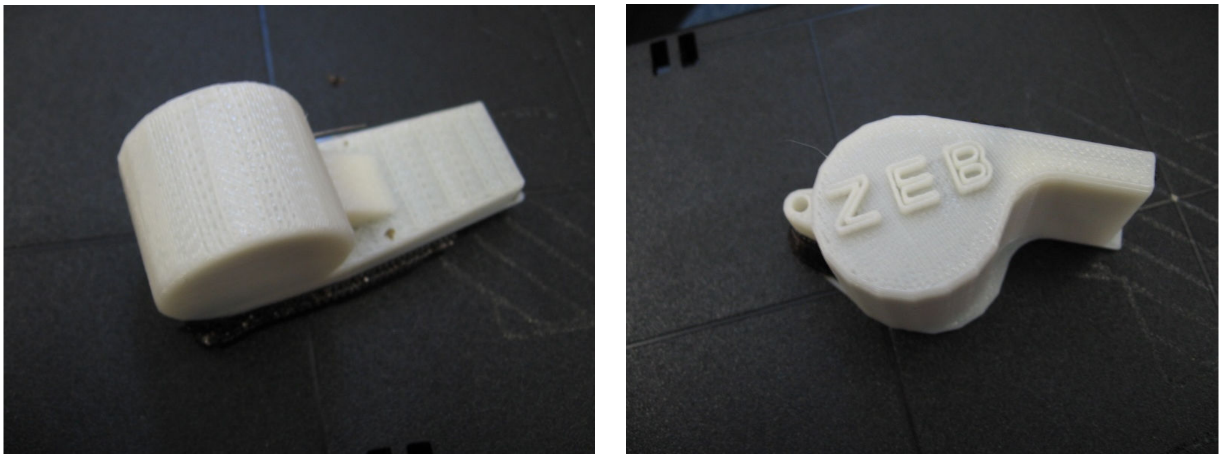
Use of RP technologies has similar benefits in academia to those benefits realized by practicing design engineers. RP manufacturers tout the benefits of their products as rapid turnaround for low volumes, low capital expenditure, ease of use, and unlimited part complexity[3]. Rapid turnaround is achieved because the method does not require skilled technicians, tooling and finishing operations. Some factors to be considered are restrictions in the available materials, low volumes, and limitations on accuracy of the fabricated parts. Surface finish of FDM models can be somewhat rough in the build direction. Parts made using powder adhesive methods may be brittle and exhibit low strength.

Experience in Advanced CAD Course

In a recent offering of our advanced CAD course (junior/senior level) the students completed a design project that involved the use of rapid prototyping. The entire project needed to be completed within two weeks. The intent of the project was not only to expose the students to this new technology, but more importantly, for them to design a device that was geometrically complex, thus demonstrating their CAD modeling skills, and for which the performance of the device was dependent upon the geometry. Thus, the device would need to be manufactured and tested in order to demonstrate that the design was geometrically valid.

The object to be designed in this project was a whistle. The specific goals from the project handout were “to design, fabricate and test a small wind instrument … [and to] include some additional objective such as intensity, frequency, size or shape for a particular purpose or function”. Students were expected to research the physics of sound and instrument design, and perform benchmarking or reverse engineering to develop their personal design specifications. Limits on overall size, weight, and wall thickness were specified to ensure that the designs would be manufacturable. In addition, the students were given a lecture on the RP process and limitations of the specific machine used. A microphone connected to a digital signal analyzer capable of measuring frequencies up to 50kHz was used to measure of the amplitude and frequencies of the sound generated from the whistles.

Results of this project were mixed. All of the students (16) were able to design manufacturable parts. Students were very enthusiastic about expressing their artistic creativity and creating complex shapes, interlocking or internal parts, and personalized designs. One student even designed his whistle in the shape of a cow. Figure 1 shows several of the student designs. While some students chose to imitate conventional pea whistle designs, others chose to experiment with flutes, ocarinas and trumpets, as well as their own original shapes.



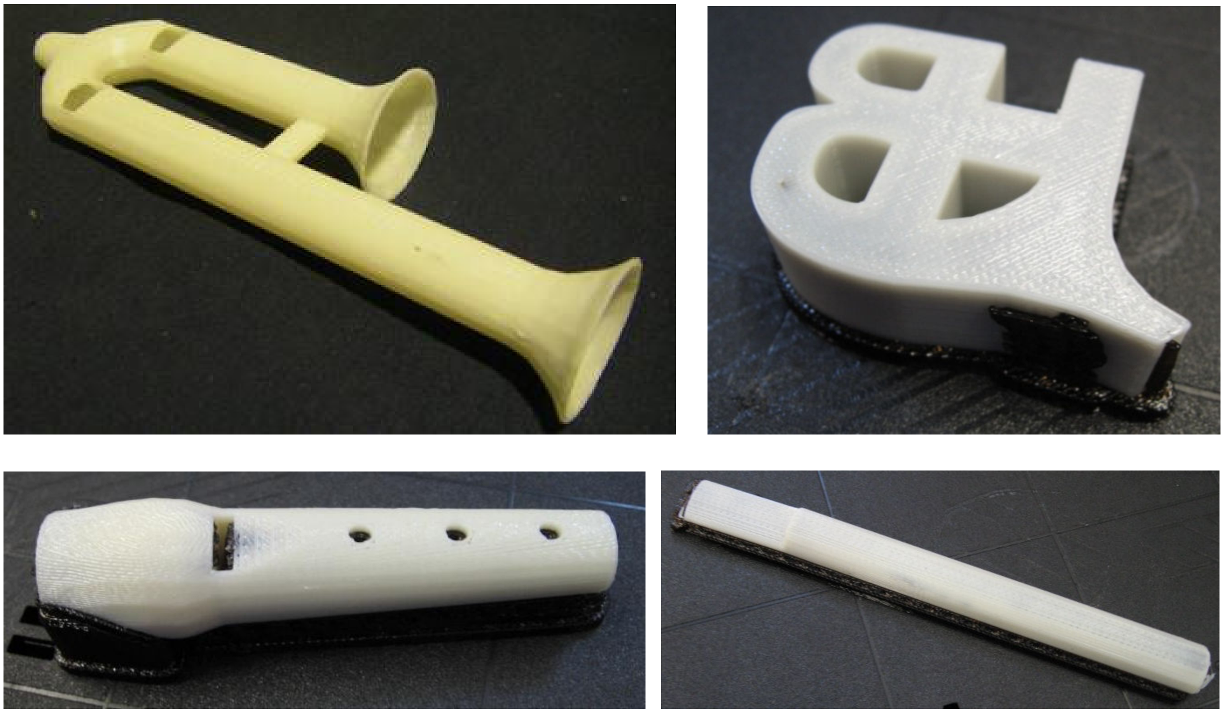


Figure 1. Whistles designed by students in Advanced CAD course.

However, only 7/16 of the whistles produced sound, as demonstrated by the frequency spectra in Figures 2 and 3. Several students commented in their reports that they should have done more benchmarking and research on instrument design. Other student comments expressed the students' perception of the benefits of the project.

> "I found this project to be very fulfilling. It was nice to end up something tangible for the work you put into the project. It also makes you more aware of how careful you have to be."
> "By doing this project the benefits of rapid prototyping were realized. It is a relatively inexpensive way to quickly manufacture a part to see if the design actually meets the design goals."
> "Despite the whistle failing to whistle I believe this project was a success in prototype design and learning from failure."

When surveyed (in retrospect) about the project, the students rated the following outcomes on a scale of 1 (not important) to 4 (very important).

Outcome	**Score**
Seeing the physical model	3.25
Testing the physical model	3.25
Becoming familiar with the RP technology	2.9
Understanding the design process	3.25
Enhancing my visualization skills	1.75
Understanding manufacturing constraints	4.0

While the students felt that it was important to test their designs, they did not seem to recognize the importance of the geometric modeling to the function of their whistles. Since the students were left to conduct their own research on instrument design, whereas the course included lecture on manufacturability, it is concluded that the students oversimplified or ignored the effect of geometry on performance, relying on personal experience or perceptions of the parameters exhibited by whistle shapes and features. In future offerings of this project, shape design will be more heavily emphasized.

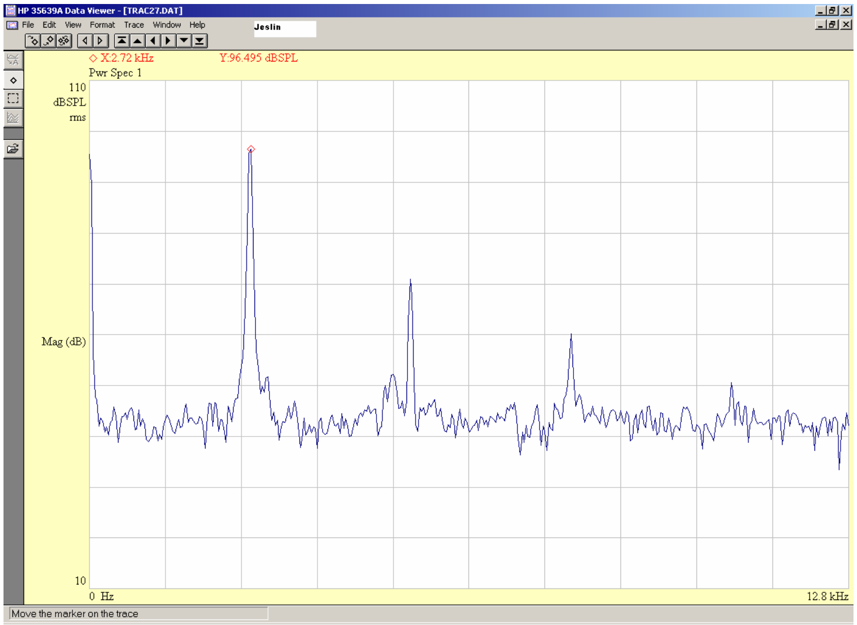


Figure 2. Frequency spectrum for successful whistle design.

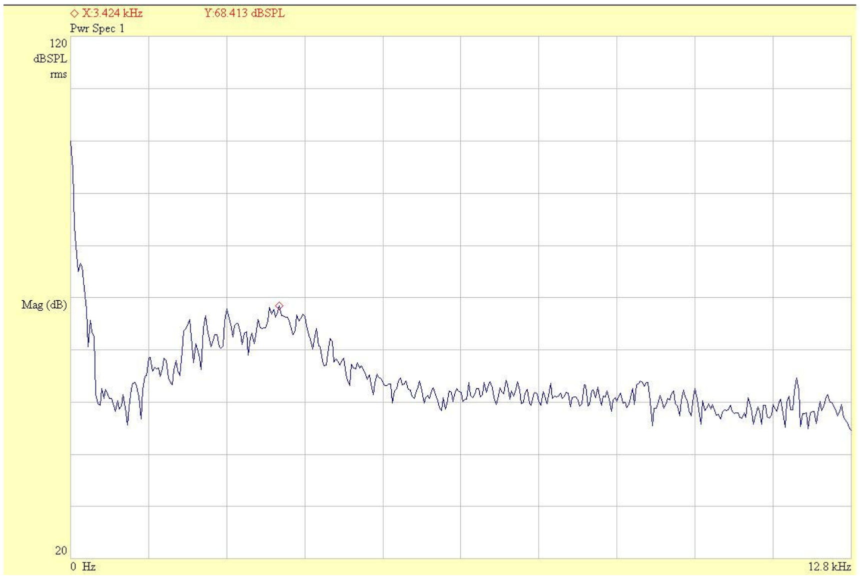


Figure 3. Frequency spectrum of an unsuccessful whistle design.

Senior Design Projects

The RP machine has been on campus for only the fall semester, and most senior design projects are not completed until spring. Thus, only about 10 teams have used the RP machine. When surveyed, the respondents almost unanimously indicated that they chose to use the machine because it was easy and inexpensive. Additionally, some teams indicated that they appreciated the quick turn-around and accuracy of the parts. One team stated that the RP machine allowed them to easily manufacture complex shapes that would have been very difficult to create using conventional machining methods. These limited results indicate that the use of RP technologies empowers students who may have limited manufacturing skills and short timelines to complete more complex design projects due to the relatively quick and easy manufacturing capabilities of the RP systems.

Conclusion

Rapid prototyping has been shown to be a successful tool in teaching engineering design at all levels. A variety of learning objectives can be achieved, including simply familiarizing students with the technologies, enhancing visualization and aesthetic evaluation of designs, and enabling students to complete more complex experiments or design projects. RP technologies can be used not only to achieve objectives related to manufacturing and design, but also to facilitate other learning objectives such as understanding and verifying advanced analysis and experimentation. Advantages of these technologies are the low cost, ease of use, and short lead times to make small models with simple to complex geometries. Limited material availability and lack of high precision are potential drawbacks.

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