Immediate linking of tolerance theory to hardware fabrication in a sophomore design course.

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Abstract

This paper describes a teaching methodology where in order to bring a sense of importance to the potentially “dry topic” of tolerances, classroom theory is linked immediately to practical machining and assembly exercises. An introductory sophomore design course at the U.S Coast Guard Academy involves a substantial laboratory element embracing basic drafting and more advanced 3D CAD instruction followed by several weeks of machine shop/laboratory immersion and hands on technical instruction. In previous years basic tolerance theory has been taught in the CAD part of the class and a small percentage of this theory was then realized in machining exercises later in the course. The result has been somewhat “hit and miss” in the educational goal of passing on an appreciation of tolerances let alone an enthusiasm for including them in subsequent work. The new methodology described in this paper links tolerances with some very specific machining exercises that were then undertaken within the same academic week. The functionality of parts produced was directly related to successful adherence to drawing tolerances much more clearly than any class paper exercise. The end result was a dramatic improvement in both machining work and the appreciation of the importance of engineer specified tolerances for both performance and manufacturing cost implications. The use of tolerances was also seen more frequently in subsequent course design exercises.

Introduction

The U.S Coast Guard Academy mechanical engineering four year degree program like most other accredited courses has significant focus on engineering design. Figure 1 shows a sequence of primarily design oriented courses in which the intention is to ‘arm’ students with the basic tools of design with so called ‘instructive’ courses and then as students core skills are enhanced with exposure to various analytical type courses (e.g Thermodynamics, Fluids, Materials Science etc) the nature of the courses becomes more ‘demonstrative’. Culmination of the sequences is the two semester Capstone course where students undertake their own unique projects, creating specifications, generating alternatives and developing chosen solutions. Foley (2007) discusses the design process used at the Academy in more detail.

This paper however discusses a particular methodology of ‘rapid fire’ theory to hardware realization in a unique sophomore design course. The outcomes were ambitious and initially a little open ended, but once correctly indentified were seen to have been achieved.

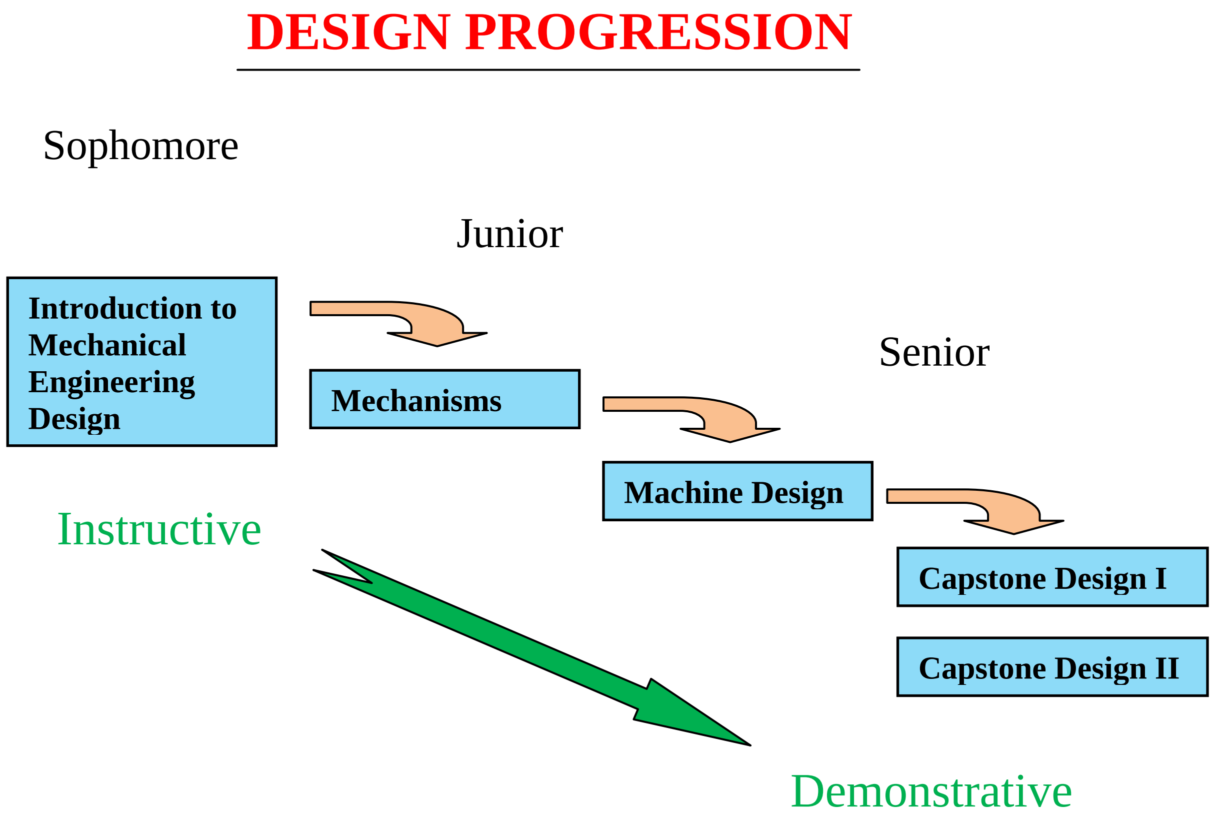

Figure 1 :
Design course progression through four year Mechanical Engineering Program

Course Objectives

The introduction to mechanical engineering design (IMED 1208) course is ambitious in its practical goals and in its significant contribution to numerous ABET outcomes. E.g. ED03, an ability to design a system, component or process to meet desired needs, ED05, an ability to identify, formulate and solve engineering problems, and most importantly, ED11, an ability to use techniques, skills, and modern engineering tools necessary for engineering practice.

This last outcome emphasizes the importance of seamlessly integrating the use of the vast array of engineering tools. In particular, this paper focuses on the integration of theory with communication and then ultimately realization. The particular example chosen is the integration of class room tolerance theory with CAD communication and then finally, machine shop fabrication and assembly of hardware. The sequence and relation is illustrated in the sequential objective timeline below:

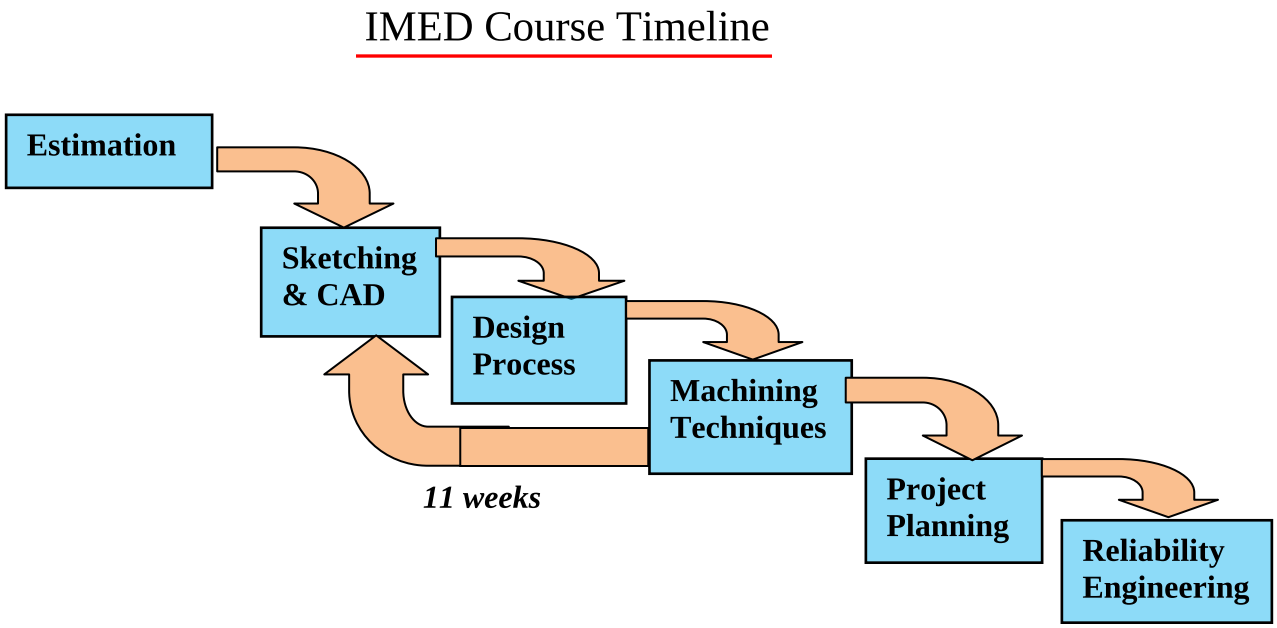

Figure 2 :
Introduction to engineering design course timeline. (15 week course)

Within central 11 week CAD, Design and machining instruction of the IMED course there are two separate evolutions. The first involves the drafting, and subsequent fabrication of 'practice parts' and the second is the design and fabrication of an operational air engine.

Theory to CAD

The practice parts are shown in figure 3. One part was designed to be 'mill' intensive and the other to be 'lathe' intensive, the intention being that students should have practice in using two of the primary machine shop tools. In outlining respective machining process guides, students gain insight to specific equipment limitations and progressions.

Almost as an afterthought a hole and shaft, identified in Figure 3 as features A, were incorporated into the parts such that the parts could be assembled. Although these were practice parts and the intention was that they be machined to a general tolerance of ± 10 thousandths, failure to meet the tolerance had in previous years seemed of little real consequence to students. By requiring that the parts now have to assemble together, the importance of the tolerances is immediately brought to bear.

Prior to fabrication of the practice parts the students first received a series of lectures on tolerance theory including a complete hour on metal fits from Shigley et al (2004). The purpose of the practice parts is, however, primarily to give practice in the use of the machining equipment. Unsurprisingly, the quality of the test parts results in tolerances averaging ± 50 thousandths and assemblies that either don't fit together or are obviously too loose for the desired free running fit (H9/d9). There is however a lot to be said for the old adage , 'learn from your mistakes', and fortunately within the course schedule there is a subsequent major fabrication exercise, an air engine, involving multiple component integrations with relatively tight tolerances. In order for the second fabrication exercise to function, successful attainment of tolerance theory must be realized. Figure 4 shows a CAD model of the air engine.

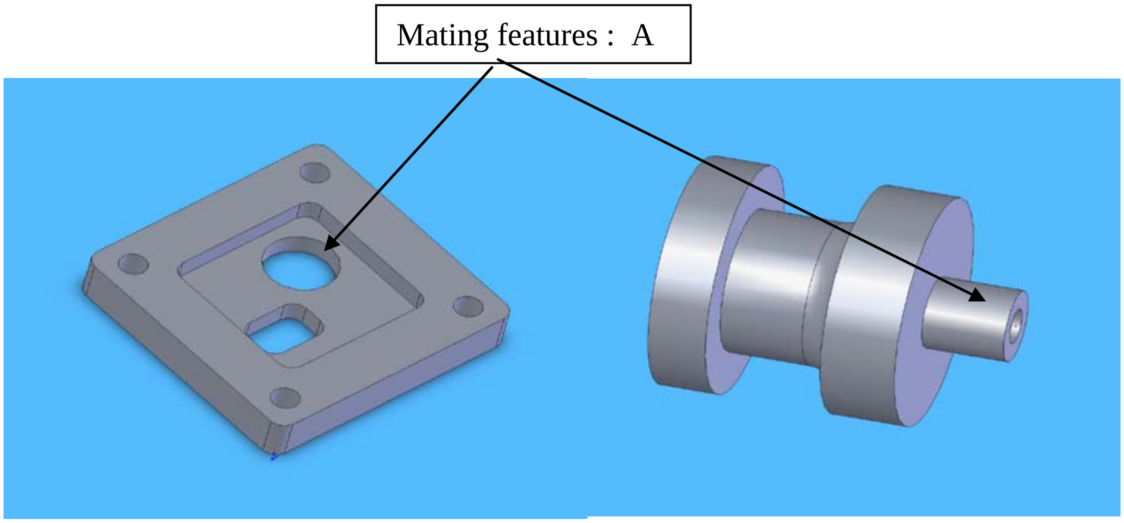

Figure 3 : Test parts for Mill and Lathe

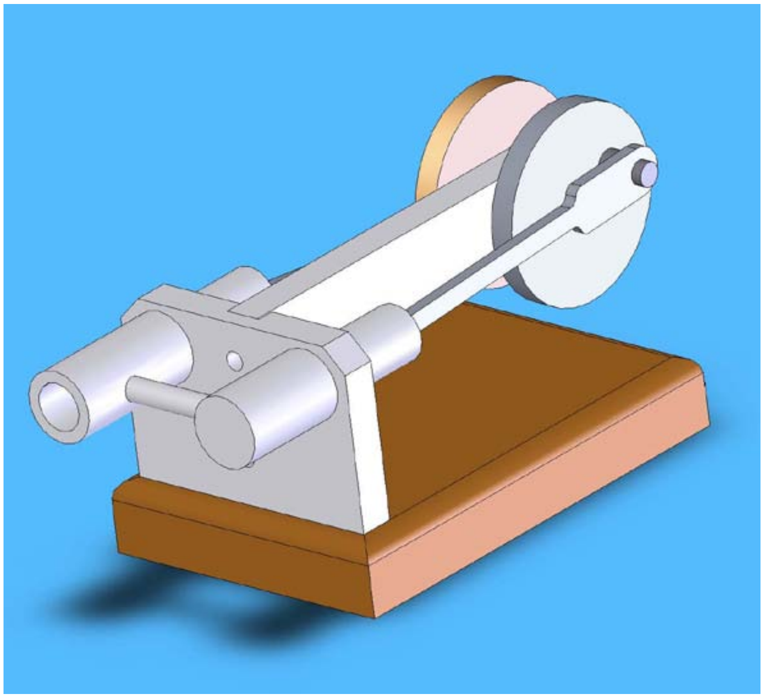

Figure 4 : Air Engine Assembly

Machining

The USCG Academy machine shop laboratory has a comprehensive range of machine tools, including industrial CNC mills, lathes, plasma cutters, hydraulic presses, metalworking, and a fully outfitted weld shop. While some exposure to these more exotic tools is given, the primary tools for the IMED class are 6 mills and 6 lathes dedicated to student use. (See photograph, figure 5, below). As previously mentioned the second major fabrication exercise students are required to complete in teams of 3 is to produce all the CAD drawings, tolerances and assembly drawings of an operational small air engine. As a team they are then required to fabricate and assemble all the parts before ultimately testing the engine. The importance of tolerances is again reemphasized and the students are told that their air engines operation and power output would be influenced by their ability to accurately design integrated component tolerances and fabricate within these tolerances.

Figure 6 shows a sectional view of the engine and highlights two of the critical sliding fits within the engine. While results are generally better for this second exercise students are however no longer working as individuals but now in teams. While improved machine skills exist, what is observed is that individuals will go and make the cylinder and the piston completely independently. While attempting to be within that parts tolerance they will invariably, due to inexperience, fail to meet tolerances in a cumulative manner. i.e. Cylinder bores will be oversized and pistons will be undersized resulting in ‘sloppy’ fits. The air seal in the engine will therefore be poor and the engine’s performance will be impaired. Occasionally students with prior machining experience or of a more cautious nature will realize that fabricating the parts in series and hence custom fitting the parts will result in an assembly that although potentially out of tolerance will still function correctly. (e.g. Having machined the cylinder bore oversize they can still turn the piston down to an enlarged diameter so as to still maintain the relative clearance required for a sliding fit.

Figure 5 : Typical Student Mill and Lathe workstation.

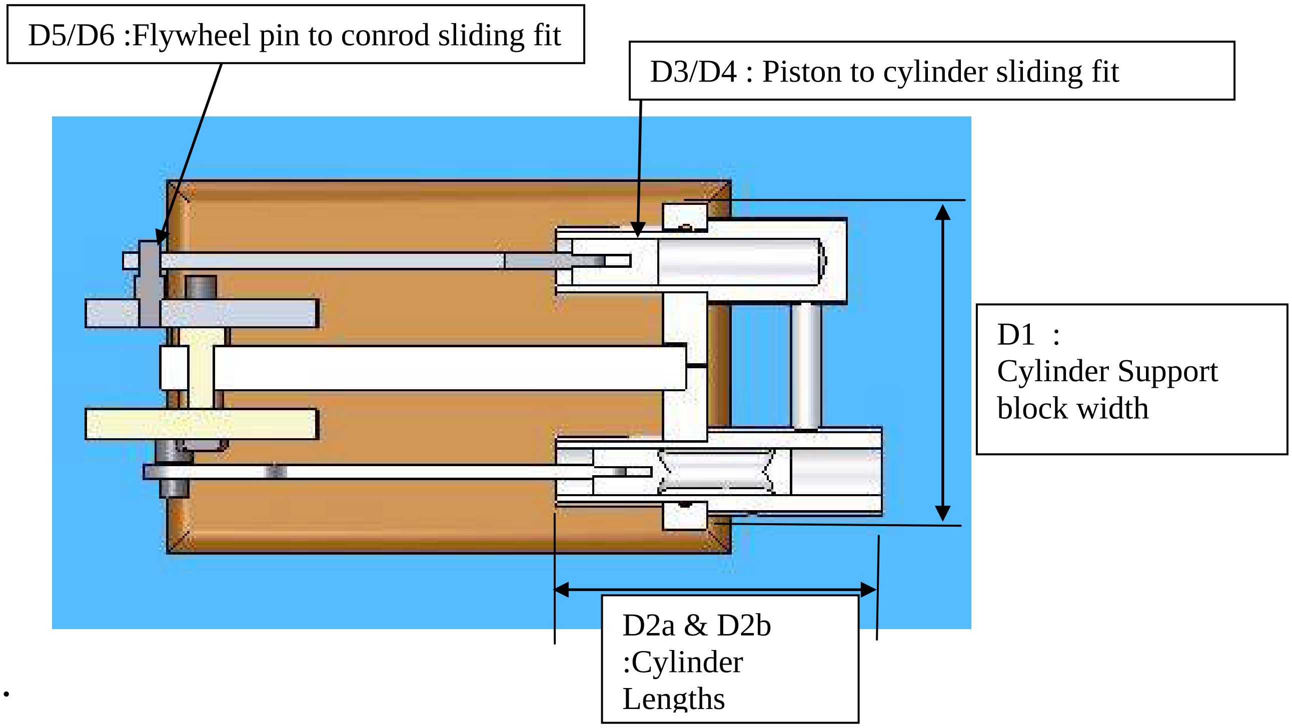

Figure 6: Sectional View of an Air Engine Assembly highlighting sample fits.

Results

The resulting sample dimensions corresponding to figure 4 are shown in table 1 for a sample batch of 9 engines. Each engine has two pistons, two cylinders and two flywheel conrod connectors which gives a total of 18 cylinder and piston dimensions.

The general tolerance level achieved for the linear milled and turned (D1 and D2) dimensions were found to be a disappointing ±50 thousandths based on a 90% confidence interval. This was considerably worse than the target of ± 10 thousandths but these dimensions were not critical for the engine operation and so the students in a way set their own tolerances based on functionality. For the turned parts the results were considerably better. The nominal cylinder/piston diameter was 0.500 inches and with a target H9/d9 free running fit this gave machined dimensions of 0.500 to 0.502 for the cylinder inner diameter and 0.498 to 0.496 for the piston diameter. The group average dimensions fell right at 0.505 for the cylinder and 0.496 for the piston, which results in an oversized cylinder and a minimum sized piston. The target ranges of 2 thou for the cylinder and the piston dimensions were matched by 10 thousandths for the cylinder and 12 thou for the piston. While these are obviously not at the desired level they are considerably better than the linear dimensions and respectable for a first attempt. The second set of fitted dimensions are D3 and D4 for the conrod attachment. Here the target was for a loose running fit H11/c11. This calls for a hole tolerance at nominal to +4 thou and a shaft diameter at -3 thousandths to -8 thousandths of nominal. i.e. A maximum tolerance range of 12 thousandths. The average achieved was a respectable 13 thousandths with a range of ± 10 thousandths. Again this means that well over half of a student sample set would be expected to be outside of tolerance but again there parts are effectively ‘getting in the ball park’.

	D1	*D2a*	*D2b*	*D3*	*D4*	*D3-D4*	*D5-D6*
Engine No.	**Cross Frame Width**	**Intake Cylinder Length**	**Power Cylinder Length**	**Cylinder Inner Diameter**	**Piston Outter Diameter**	***Tolerance A***	***Tolerance B***
1	2.773	2.813	2.49	0.508	0.499	0.009	0.007
				0.507	0.499	0.008	0.015
2	2.759	2.817	2.486	0.502	0.484	0.018	0.025
				0.506	0.496	0.01	0.016
3	2.801	2.79	2.501	0.51	0.496	0.014	0.014
				0.504	0.491	0.013	0.01
4	2.801	2.799	2.502	0.508	0.506	0.002	0.007
				0.495	0.494	0.001	0.007
5	2.819	2.879	2.515	0.503	0.491	0.012	0.01
				0.512	0.502	0.01	0.011
6	2.816	2.796	2.501	0.509	0.497	0.012	0.012
				0.508	0.495	0.013	0.02
7	2.846	2.803	2.494	0.509	0.501	0.008	0.017
				0.509	0.5	0.009	0.007
8	2.801	2.804	2.565	0.492	0.484	0.008	0.02
				0.503	0.497	0.006	0.009
9	2.805	2.791	2.492	0.506	0.492	0.014	0.017
				0.507	0.49	0.017	0.018
Average	2.802	2.810	2.505	0.505	0.496	0.010	0.013
Std Deviation	0.025	0.027	0.024	0.005	0.006	0.005	0.005

Table 1. Dimensions measured in Air Engine Project

Conclusions

Initially there was some disappointment amongst the faculty at the results obtained but in hindsight it was probably the expectations that were unrealistic. In the grand scheme of things students had all become competent in basic part modeling and assembly using a 3D commercial grade CAD package. Students understood how to determine what kind of fit an assembly required and then how to put such dimensions onto a CAD drawing. Students also became reasonably skilled setting up and safely operating the primary shop tools. The expectation that parts could be milled or turned to within the required tolerances however was not completely realized and as this is a skill that comes invariably with extensive practice this should not have been surprising. In future years the importance of all dimensions being within tolerance will be reemphasized and further instruction on how to achieve the last thousandth or so of a dimension will be given. If nothing else this exercise has also given a healthy appreciation of a skilled machinist's trade.

As discussed in the introduction, students within the four year program, have several more opportunities to design and fabricate projects and once more apply these skills. A random sample of one of the current years senior capstone design projects made at the time of print showed that not only was an appreciation of tolerances achieved but that in most cases parts were being successfully made within tolerance. In conclusion these students are unlikely to be machine operators in their careers and the primary objective of having an appreciation of the importance of tolerances is believed to have been achieved.

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