AC 2011-2457: AN INTERESTING APPLICATION OF OPTICAL MEASUREMENT TECHNIQUES

Bijan Sepahpour, The College of New Jersey

Bijan Sepahpour is a registered Professional Engineer and Professor of Mechanical Engineering at TCNJ. He is currently serving as the chairman of the ME department. He is actively involved in the generation of design-oriented exercises and development of laboratory apparatus and experiments in the areas of mechanics of materials and dynamics of machinery for undergraduate engineering programs. Professor Sepahpour did his undergraduate studies at TCNJ and has degrees from New Jersey Institute of Technology (NJIT). He has served as the Chair of ASEE Divisions of Experimentation and Laboratory Oriented Studies (DELOS) in 2006-07 and the Mechanical Engineering in 2007-08. Professor Sepahpour is an active member of ASME and ASEE.

An Interesting Application of Optical Measurement Techniques

Abstract

An experiment and apparatus are designed to utilize "Optical Measurement Techniques" for obtaining the "Angle of Twist" of round bars in a first measurement engineering laboratory course. The advantages and unique characteristics of optical devices in measurement applications are discussed. The process and the setup for conducting the experiment are presented. The control of the parameters influencing the degree of precision and accuracy of the experiment are discussed. The significance of this approach "as an example" of application of optics in measurements is presented. The components and the specifications of the different parts of the apparatus are provided. This includes detailed parts list and the associated costs and sources for obtaining them. Junior Engineering students have been collaborating with the authors in the "Design of the Experiment" and the "Fabrication of the Apparatus". Fruits of the involvement of these students are discussed. Assessment of how the experiment and this unique approach have improved the learning curve of the participants is presented. The handout for setting and conducting the experiment, as well as the "Blueprints" for fabrication of the apparatus are included in the Appendices. It is hoped that the Engineering Education Community considers the adoption of this experiment, apparatus and approach in the Laboratory Curriculum.

I – Introduction

Optical measurement techniques have potential to become reliable and widespread tools for engineering applications. This class of measurements are characterized by being free from ambient electrical interference, non contact, non destructive, accurate and reproducible. As a result, an engineering graduate should not only have appreciation for these valuable techniques, but also develop sufficient understanding of their inner workings to allow for the creation/adaptation of such measurement methods as needed in a research or an industrial environment.

Numerous optical techniques are available for both quantitative and qualitative measurements. Many use sophisticated and expensive setups that include imaging components. A set of precise techniques are based on a combination of inexpensive diode lasers, mirrors, and prisms. It is on adapting these techniques to laboratory experiments that this team will focus on.

The following figures display the components of a preliminary design for creation and testing of an apparatus for measurement of the angle of twist of bars by application of torque. A mirror attached to the free end of the bar reflects the laser beam back on a scale before and after the application of the torque. Using laws of optics and simple trigonometric relations, the angle of twist is easily measured-with high resolution and nearly zero noise.

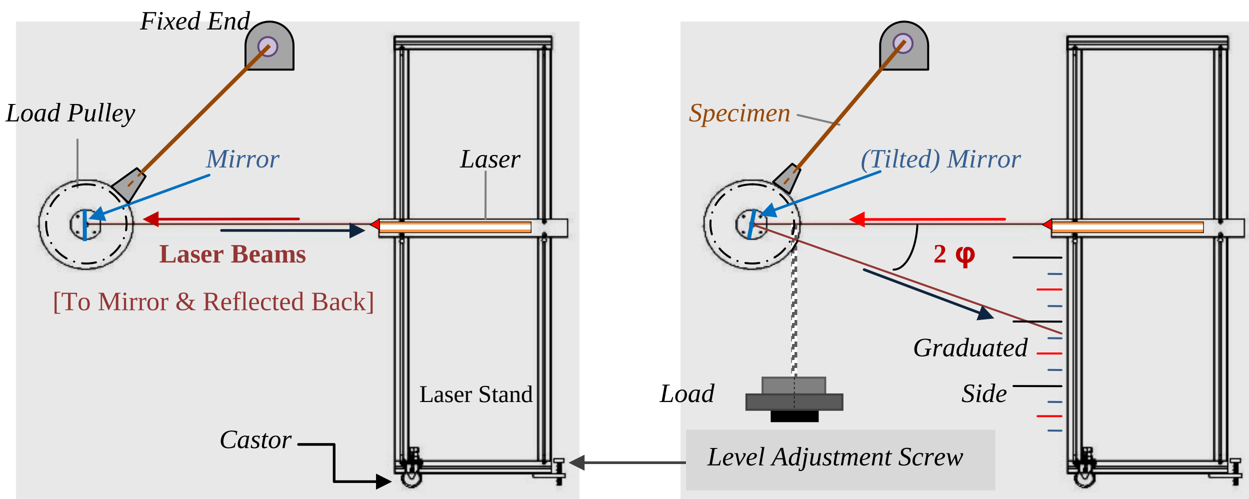
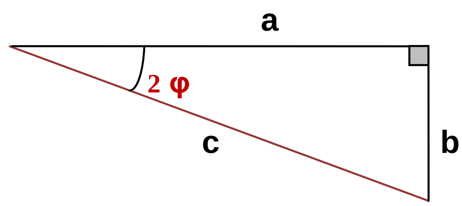


Figure 1. Setup for the *"Torsion Experiment"* Using *"Optical Measurement System"*

$$\begin{cases} \tau = T.r / J & (1) \\ \varphi = T.L / G.J & (2) \end{cases}$$



$$2\varphi = Tan^{-1} (\overline{b} / \overline{a})$$

Where:

τ = *Shear Stress*, *T= Torque*, *r = radius of the round bar*, *G = Shear Modulus of Elasticity*,	*J = Polar Moment of Inertia*, φ = *Angle of Twist*, *L = Length of the Bar.*

II - Objectives of the Experiment and the Project

The following major objectives were set at the inception of the project:

1. To develop an experiment and apparatus in order to measure the torsion of bars of several different materials using an "optical measurement process/system".

2. To create an opportunity for collaborative research and design efforts between the undergraduate engineering student(s) and the faculty.

3. To design, produce, test, and optimize a cost-effective, reproducible apparatus with outstanding features.

4. To make all information necessary for fabrication of the apparatus and conducting the experiment available to engineering programs nationwide.

It was decided to design an apparatus and experiment that would be feasible for replication in other educational institutions within a budget of about $2,000 for materials and components. Another important consideration (in the design process) was to minimize machining requirements. The target was set at machining and assembly times between 12-15 hours.

III-Student Collaboration

The authors invited three rising junior engineering students for collaboration. The parameters in successful implementation of the processes (for achieving the above goals) were discussed, outlined, and a preliminary Gantt chart was generated. Through three weekly scheduled meetings, alternative designs and approaches were evaluated, ranked, and chosen. It took two and a half weeks to fabricate, modify, and test the reliability of the apparatus and its feasibility for replication in other institutions. Another week was necessary to test the degree of precision and the accuracy.

A survey of alumni from the College of Engineering at the University of Delaware reveals that *"Alumni with research experience were more likely to pursue graduate degrees, and they reported greater enhancement of important cognitive and personal skills. In addition, respondents who had been involved in research were much more likely to have reported that they had a faculty member play an important role in their career choice."* [1]

Two of the (original three) students involved in the design and development of this project have successfully completed their graduate studies. Additional students have continuously contributed to the improvement of the project and redesign of several components and aspects of the apparatus.

IV- Design of the Experiment and the Apparatus

1. Pedagogy

This project has been designed for sophomore level students. Pedagogical measures have been taken for its realistic effectiveness (nation-wide). Therefore, the framework of the project has been set at a level that *sophomores* may: *a) succeed in its implementation and b) develop some degree of understanding and appreciation for the optical measurement processes and potential applications.*

2. Design of the Apparatus

The design of the apparatus is premised on meeting/delivery of the following characteristics:

1. Simple to Operate,
2. Cost-Effective,
3. Safe,
4. Highly Precise and Accurate (to +/- 5% of Error),
5. Relatively Simple to Construct and Replicate at other Institutions,
6. Light but Sturdy,
7. Independent, and Portable,
8. Durable,
9. Environmentally sound, and
10. Aesthetically Pleasing.

As shown in *Figures (2) and (3)*, the apparatus has the following major components;

1. The "Load Pulley" with the Precision Mirror,
2. The Clamping Ends to support the specimen and allow for "Length Adjustment",
3. A Portable Frame that its Casters allow for being locked and prevent rotation,
4. The Laser,
5. The Stand to support the Laser and allow for its "Height Adjustment".

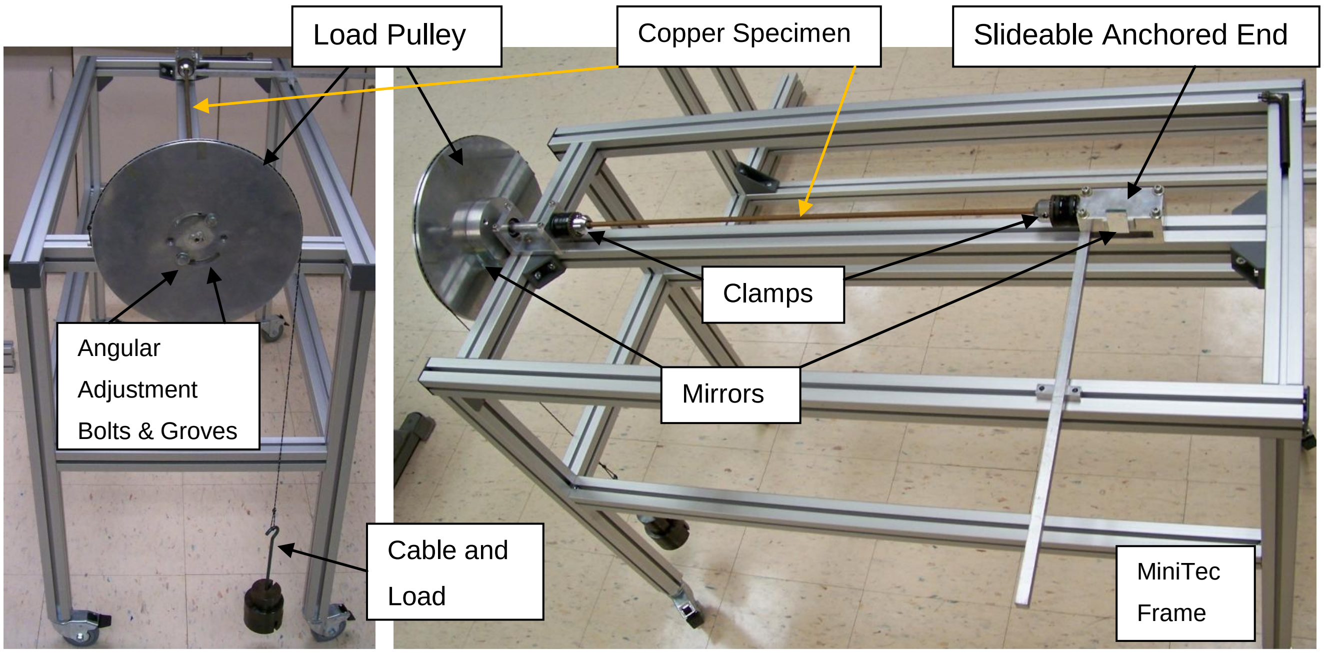


Fig 2. Major Components of the Apparatus

3. Procedure for the Set up

The set up of the experiment starts with the specimen secured firmly in the clamping jaws at a desired length using the adjustable/ sliding feature of the anchored end. The pulley wheel is rotated until the mirror is normal to the ground. Then the bolts on the pulley are torqued to maintain this orientation (of the mirror).

The laser is then set a known distance from the mirror. "*Laser Safety Goggles*" are put on to protect the eyes. The laser is turned on and its height on the "Laser Stand" is adjusted to shoot the beam at the mirror. Care must be taken to insure that the laser is level at all times. The reflected beam from the laser needs to hit the "Graduated Bar" at the same height (and preferably at the same location) as the shooting point of the laser.

Application of a set of known loads will generate a set of known torques. These set of different torques in turn, will cause the specimen to experience different (angles of) twists.

Fig 3. Laser and the Stand

Figure (4) clearly displays how the distances of the reflected laser beam increase (from the reference shooting point) as the magnitude of the applied loads/torques increase. *Figure (5)* depicts the simple geometry of this "optical approach" which may lead to easily obtaining the values of the "angle(s) of twist. It should be obvious that the larger the distance between the laser and the mirror ["***a***"(in the equation below)], the higher the resolution.

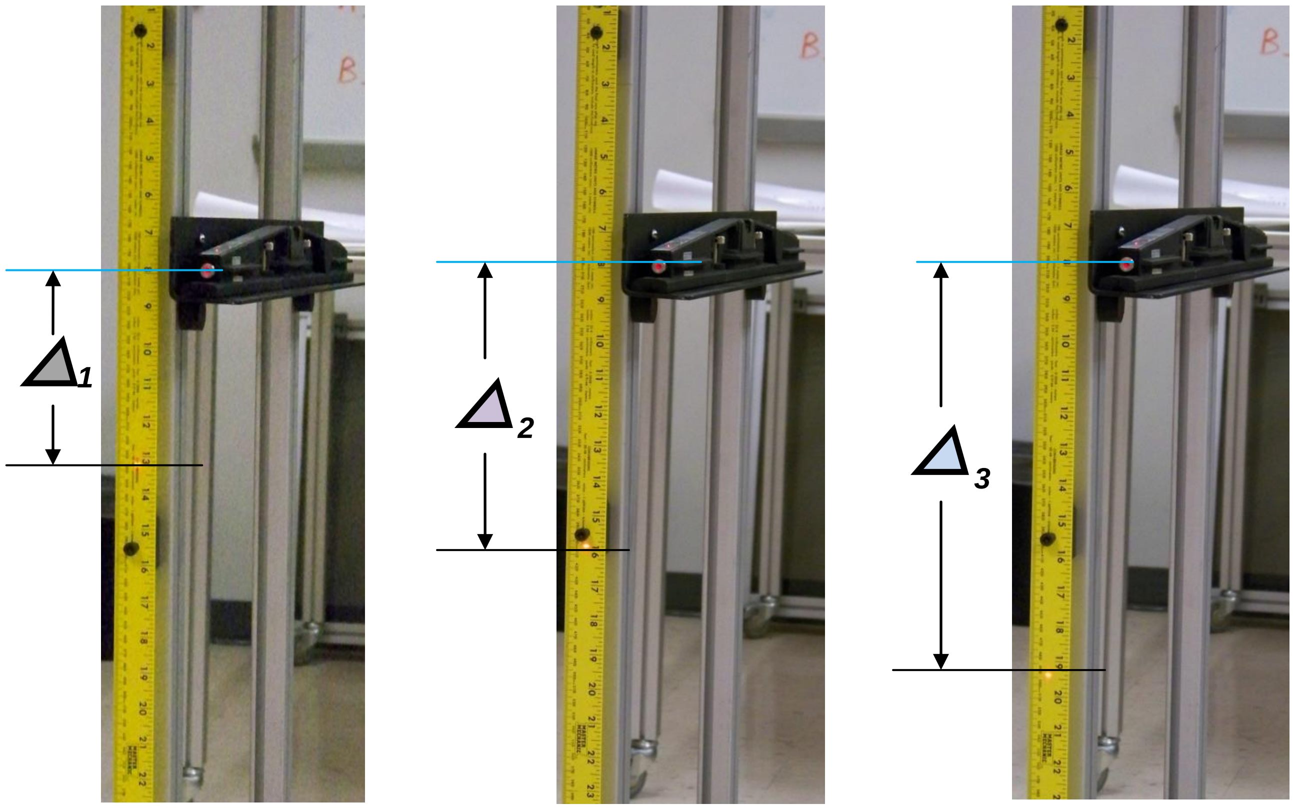


Fig 4. Reflected Laser Beam Changing Position due to application of Changing Torques.

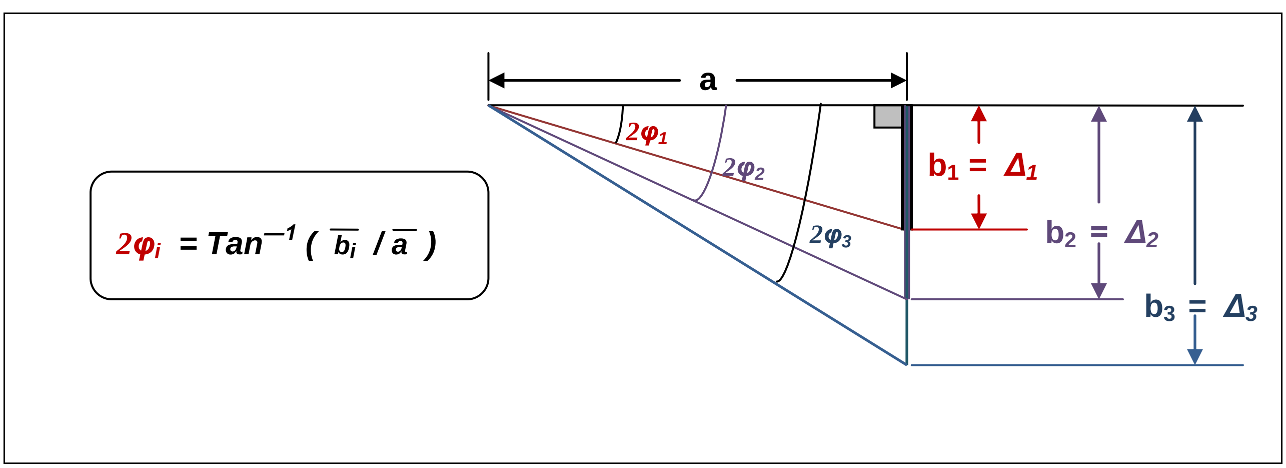


Fig 5. Display of the Simple Geometry and the Equation for Obtaining the Angle of Twist

4. The Choice of the Mirror

There is a large variety of mirrors to choose from. It is clear that whatever the choice, it needs to be a flat unit. The cost may be the dominating factor in the selection process. This group recommends a mirror available from "Edmund Optics" that has proven satisfactory based on the results obtained from a significantly large number of trials. *[Specifications of this mirror are provided in Table (4).]*

5. Size, Material, and the Number of Specimens

The "time required" for running the experiment is an important consideration. This parameter becomes more critical when the space and the number of apparatus are more limited. As a result, one of each samples of (Stainless) Steel, Aluminum, and Copper should suffice. See *Table (1)*.

Table 1. Specifications of the Specimens

Material	**Diameter**	**Length**	**Modulus of Elasticity (E)**	**Poisson's Ratio (ν)**
Stainless Steel	3/8"	35"+	196 GPa	0.305
Aluminum 6061-T6	3/8"	35"+	68.9 GPa	0.330
Non-Oxygenated Copper 101	3/8"	35"+	115 GPa	0.310

Unless it is desired to (deliberately) bring inconsistency into the process, we do not recommend the use of a "Brass" specimen as the behavior of this material in this exercise will prove problematic.

3/8" diameter samples of the recommended materials [with an original length of 35"+] have been successfully tested by this group and the results are consistent enough for comparison with those listed in reliable literature.[2]

6. Adjusting the Mirror's Plane

Achieving a perfectly perpendicular (to the ground) plane is a tedious task. If both the "line of action of the laser ray" and the "plane of the mirror" (on the Load Pulley) are not well controlled, both the accuracy and the precision of the measurement process will be compromised. In order to insure this critical requirement, *a) the laser must be first leveled and b) the plane of the mirror must be adjusted to perpendicular to the ground.*

Additionally, at the initially unloaded state; when the laser's beam is reflected back, the height of this (reflected/returning) point needs to be the "same" as that of the shooting point of the laser and preferably as close to the location of the shooting point. An example of achieving such condition is shown in *Figure (6)* below. Note that "line AB" serves as the Datum for the measurements.

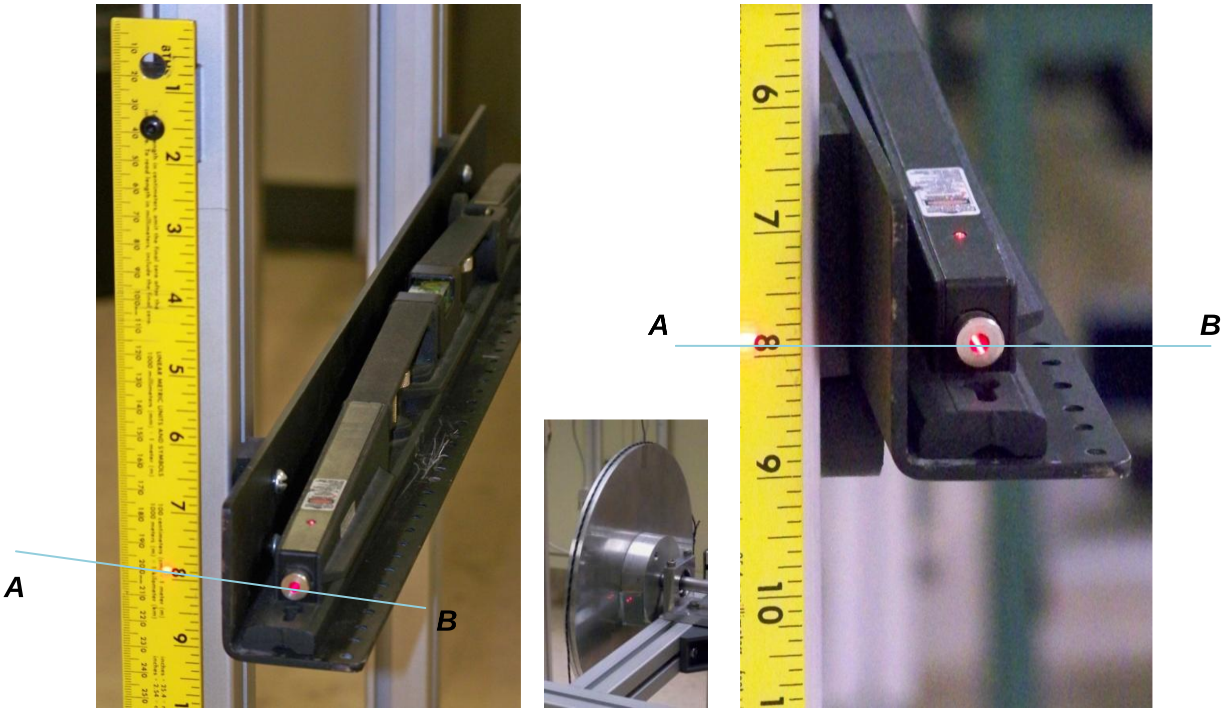


Figure 6. Depiction of the Required “Initial” Setting of the shooting and the Reflected Beams

7. Concern about the Movement of the Rear/ Fixed End

Should there be (angular) movement in the Rear/Fixed End of the apparatus, the measurement will not be accurate without taking this effect into account. The inclusion of this observation and the measurement of this “offset” value may add more interest to the challenging aspects of this experiment.

A “second” mirror may be added which in the initially unloaded state would also be perpendicular to the ground (and parallel to the mirror on the Load Pulley). Upon loading the system, if there would be an offset, it may be measured. *See Figure (7)*. It goes without saying that this “offset” angle would be subtracted from the value of the angle obtained originally. It should be clear that for increasing load values, there would be increasingly different values of the offset angle.

Alternatively, to suppress the potential existence of such an effect, a (Physical) “Moment Arm” may be added to this end as shown in *Figure (7)*. This group has conducted the experiment in both modes. Interestingly and as expectedly, the net (measurement) results are nearly identical in comparison.
We have left the option of “inclusion” or “suppression” of the potential offset up to the students. This is easily achieved by the “insertion” or “removal” of the “Support Block” from the system. *See Figure (7).*

8. Selection of the Laser

When this group first explored the possibility of using optics for creating a “Torsion of Bars Experiment and Apparatus”; a 15” long educational grade laser was purchased that has its own source of (DC) power and a beam splitter that may rotate. This highly affordable unit may be easily leveled and has proven reliable. Front and rear views of this unit are shown in *Figure (7)*. Although “Safety” is strictly enforced, this class-II laser may pose minimal potential harm.

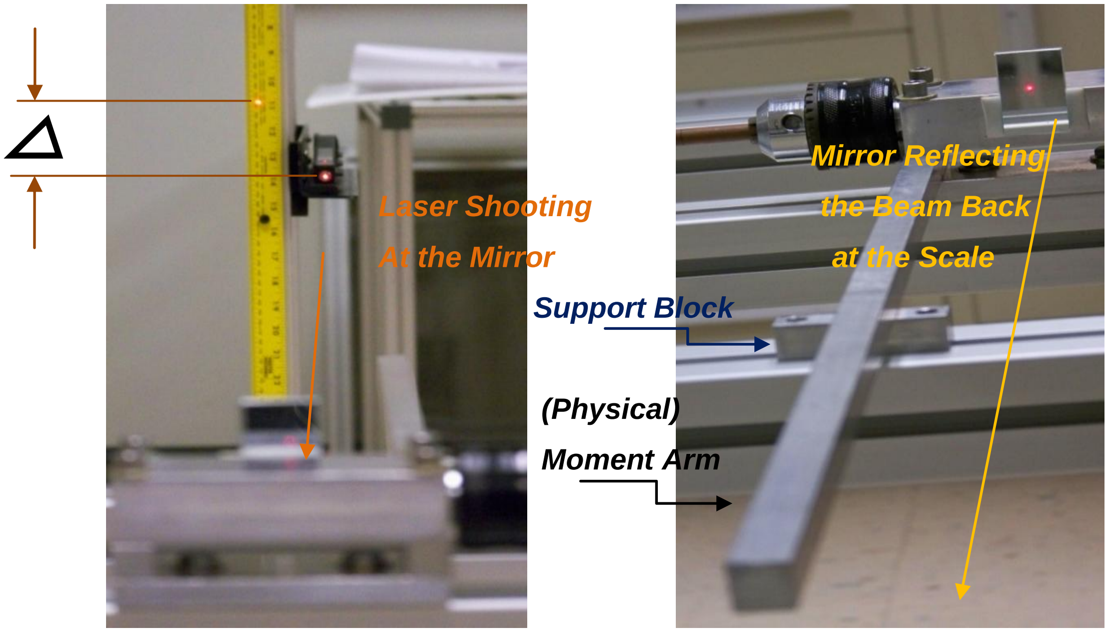


Figure 7. Depiction of the potential means to control the movement of the back support

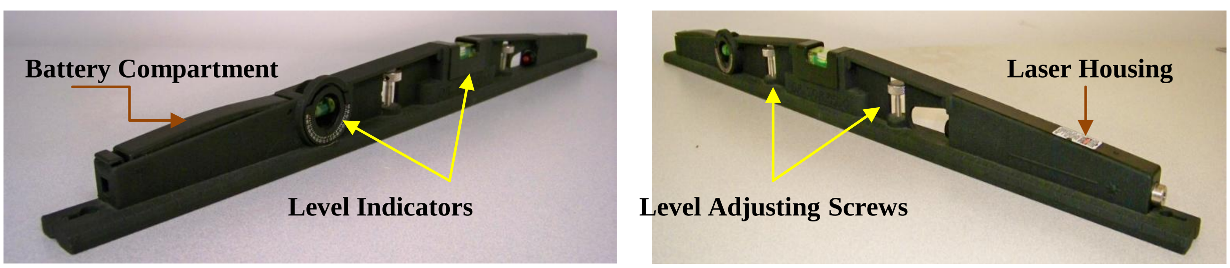


Figure 8. Compartments and features of the "Dr. Torpedo" Laser

There are now significantly more compact and lighter lasers that are "self leveling". They may also come with the pin-pointing advantage of shooting two beams simultaneously in a cross line orientation as shown in *Figure(9).* We recommend either of the following two commercial lasers with their specifications listed in *Table(2).*

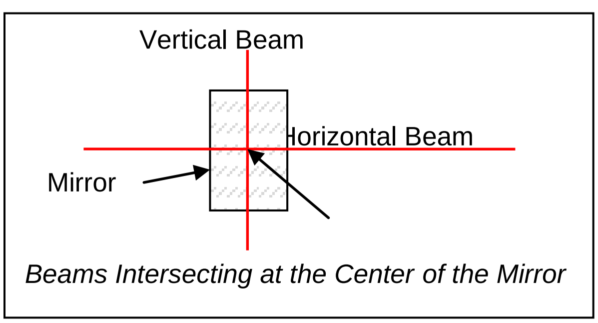
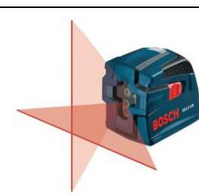


Figure 9. Cross line advantage

Table 2 . Two recommended lasers

Bosch Cross Line Self-Leveling Laser Level	
Model # GLL2-10	**Model # GLL2-40**
	

9. Laser Stand

A simple and cost-effective stand is recommended for this application. Depending on the type of the laser chosen, the design may be slightly modified. Since the bases of most lasers are magnetic, it may be advantageous to create and install a platform made out of steel in order to secure the laser. The platform should be easily adjustable in height to allow the beam of the laser target the mid-point of the mirror on the Load Pulley.

10. Parts and Materials List

Table (4), on the next page, provides comprehensive listing of the components of the apparatus and the sources for obtaining them. It also reflects on the associated costs for the samples, the required materials, and the components.

V- Total Cost

Laboratory apparatus is generally expensive due to low production levels, specialized features and significantly higher *Design Costs* built into the final cost. However, if blueprints of the designs of a (desired) apparatus are available, and on site machining capabilities exist, a major cut may be expected in the final cost.[3] The blueprints of the major parts of the apparatus are enclosed in *Appendix (C)*. Additional information may be obtained from the first author.

Table (3) takes the additional factors of machining and assembly requirements into account for the "total cost" of the proposed apparatus. A comparison of the associated costs with those of the Commercially available units reveals potential savings between 100-200%.

Table 3. Breakdown of the cost and the Required Hours for Machining and Assembly

1	**Overall Cost of the Materials, Samples and the Components**		≤ ***$ 1615***	
2	**Required Machining Time**	**I - Average Machining at $25/Hr.**	***About 6 Hrs.***	***$150***
		II - Above Average Machining at $50/Hr.	***About 4 Hrs.***	***$200***
3	**Required Assembly Time at $15/Hr.**		***3 - 4 Hrs.***	***$60***
	Total Cost		***$ 2,025***	

Table 4. Parts List and Cost for the Two Frames, Samples and the Components of the Apparatus

Part	Source	Quantity	Price ($)	Sub Total ($)
Main Frame of the Apparatus 18" Wide x 48" Long x 42" High With Mid. Shelf and Locking Castors	Mini Tec Inc.	1	NA	640
Stand for Supporting the Laser 14" Wide x 18"Long x 62" High	Mini Tec Inc.	1	NA	120
1/2" x 2.5" x 24" Precision Aluminum 6061-T6 Flat	OnLine Metals	1	14.11	14.11
0.625" x 12" x 12" Precision Aluminum 6061-T6 Plate	OnLine Metals	1	72.30	72.30
3/8" Dia. x 36" Long Precision Stainless Steel Rod	OnLine Metals	2	18	36
3/8" Dia. x 36" Long Precision Aluminum 6061-T6 Rod	OnLine Metals	2	18	36
3/8" Dia. x 36" Long Precision Copper (C101) Rod	OnLine Metals	2	20.44	40.88
½ Dia. Jacobs Drill Chucks with	McMaster-Carr Part# 2812A39	2	85.02	170.04
Hardware	McMaster-Carr	-	15	15
Cord: Extra-Strength Polyester 0.060" Diameter, 180 lb Capacity	McMaster-Carr Part# 2812A39	1 (100 ft)	16.57	16.57
Precision Laser with Splitting Beams in Vertical and Horizontal Directions	Bosch Online Sources/ Home Depot	1	99	99
Precision Mirror	**Edmund Optics**	2	35	70
8' Telescopic Bar / Philadelphia Bar	**LOWS**	1	52	52
Flat Weights/ Large Slotted Mass Set	PASCO Scientific	1 Set	129	129
Shipping and Handling				100
			Total ≅ $1615	

VI- Assessment

Completion of a "*Rating and Assessment"* form is an integral part of the requirements for this laboratory exercise. This form is included in *Appendix "B"*. The main objective of the survey is the continuous fine-tuning of this activity for further improving the learning curve in the future iterations.

Table 5. Summary of the Results for the *First* Measurable Question on the Project Assessment Form

Question # 1: *How would you rate the time required for completion of this Project?*							
xxxxxxxxxx			Rating				
Semester	Section #	# of Students [N]	Too Short	Short	About Right	Long	Too Long
Spring 2010	*1*	16	-	-	12	4	-
	2	15	-	-	11	4	-
	3	15	-	1	11	3	1
	4	13	-	-	10	3	-
	5	16	-	-	12	3	-
Spring 2009	*1*	14	-	-	12	2	-
	2	16	-	-	13	3	-
	3	12	-	-	11	1	-
	4	15	-	-	12	3	-
Total	***9*** *Sections*	*132*	-	*1**	*104*	*26*	*1**
Percentage			-	-	***80 %***	***20 %***	-

* *Considered to be an Outlier*

The survey was conducted for four (4) section of the course in the Spring of 2009 and five (5) sections in the Spring of 2010. The total number of the surveyed students in the nine (9) sections was 132. *Tables (5) through (10)* provide detailed summaries of the results for five of the (more measurable) questions on the project's assessment form.

Table 6. Summary of the Results for the *Second* Measurable Question on the Project Assessment Form

Question # 2: *If you had to do this experiment/activity again, how long would it take the second time? Use the Percentages listed below.*

XXXXXXXXXX			Rating							
Semester	Section #	# of Students [N]	30-40 %	40-50 %	50-60 %	60-70 %	70-80 %	80-90 %	Almost The Same	Can Not Predict
Spring 2010	1	16	-	1	3	11	1	-	-	-
	2	15	-	-	4	10	1	-	-	-
	3	15	-	-	4	11	-	-	-	-
	4	13	-	-	3	9	1	-	-	-
	5	16	-	-	2	10	2	1	-	1
Spring 2009	1	14	-	1	3	9	-	1	-	-
	2	16	-	1	3	11	1	-	-	-
	3	12	-	-	2	8	1	-	1	-
	4	15	-	-	3	10	1	1	-	-
Total	*9 Sections*	*132*	-	*3*	*27*	*89*	*8*	*3*	*1**	*1**
Percentage			-	*2*	*20*	*68. 5*	*6*	*2*	-	-
					88.5 %					

* *Considered to be an Outlier*

About 88% of the 132 surveyed students believe that they would be able to complete the same task between half to 70 percent of the time it took them in the first trial. Nearly all would incorporate an activity of this nature should they get the opportunity to teach a first course in measurement. The assessment results clearly reflect on the fact that there is (nearly perfect) consensus that the project is a balanced activity that is highly valued by the members of the nine (9) surveyed sections.

Table 7. Summary of the Results for the *Third* Measurable Question on the Project Assessment Form

Question # 3: *Would the experience gained in this activity help you optimize your approach the next time you have to deal with a similar task?*							
Semester	Section #	N	Rating				
			Highly Unlikely	Unlikely	Probably	Very Likely	Definitely
Spring 2010	*1*	16	-	-	1	3	12
	2	15	-	-	-	4	11
	3	15	-	1	-	3	11
	4	13	-	-	-	3	10
	5	16	-	1	1	3	11
Spring 2009	*1*	14	-	-	-	3	11
	2	16	-	-	-	6	10
	3	12	-	-	-	4	8
	4	15	-	-	-	6	9
Total	*9 Sections*	*132*	*-*	*2*	*2*	*35*	*93*
Percentage			*-*	*1.5*	*1.5*	***26.5***	***70.5***

Table (10) reflects on the level of performance and the scores achieved for this exercise. The results are highly indicative of the effectiveness of the proposed technique and activity for improving the learning curve in this interesting area for the engineers to be.

Table 8. Summary of the Results for the *Fourth* Measurable Question on the Project Assessment Form

Question # 4: *How would you rate the overall Value of this Experiment and Project?*							
Semester	Section #	N	Rating				
			Very Low	Low	Medium	High	Very High
Spring 2010	*1*	16	-	-	-	4	12
	2	15	-	-	-	3	12
	3	15	-	-	-	2	13
	4	13	-	-	-	2	11
	5	16	-	1	1	1	13
Spring 2009	*1*	14	-	-	-	4	10
	2	16	-	-	-	5	1 1
	3	12	-	-	-	3	9
	4	15	-	-	-	5	10
Total	*9 Sections*	*132*	-	*1**	*1**	*29*	*101*
Percentage			-	-	-	***22 %***	***78 %***

* *Considered to be an Outlier*

Table 9. Summary of the Results for the *Fifth* Measurable Question on the Project Assessment Form

Question # 5: *If you get to teach a similar course, would you incorporate such an activity in your course? If yes, what changes would you recommend or introduce?*							
Semester	Section #	N	Rating				
			Highly Unlikely	Unlikely	Probably	Very Likely	Definitely
Spring 2010	*1*	16	-	-	1	4	11
	2	15	-	-	-	4	11
	3	15	-	-	-	3	12
	4	13	-	-	-	2	11
	5	16	-	1	-	3	12
Spring 2009	*1*	14	-	-	-	6	8
	2	16	-	-	-	7	9
	3	12	-	-	-	2	10
	4	15	-	-	-	5	10
Total	*9 Sections*	*132*	-	*1**	*1**	*36*	*94*
Percentage			-	-	-	*28 %*	*72 %*
						≅ 100 %	

VII- Possible Future Application

Mechanical and Civil Engineering students get exposed to the Euler's (long) column buckling equation in their Mechanics/Strength of Materials courses. We recall that with the derivation of the equation, it may be mathematically shown that the eigen vectors of the differential equation will lead to the establishment of several modes of "Bucking".

$$\mathbf{P_{cr.} = n\pi^2 E\, I / (KL)^2}, \quad \textit{Where:}$$

E = Modulus of Elasticity,	*K = (Column) End Condition Factor,*
I = Area Moment of Inertia,	*L = Actual Length of the Column.*

Table 10. Summary of the Performance Record of the Four-Member Teams

Semester	Section #	Number of Students [N]	Number of Teams	Range (%)	Average (%)
Spring 2010	*1*	16	4	85- 96	92
	2	15	4*	87 - 98	94
	3	15	4*	86 - 93	91
	4	13	4***	88 - 94	92
	5	16	4	82 - 94	86
Spring 2009	*1*	14	4**	93- 100	89
	2	16	4	86 - 94	91
	3	12	3	85 - 100	90
	4	15	4*	88 - 97	93
Total	***9 Sections***	*132*	*35*	*82 - 100*	***90.9***

** One 3-Member Team, ** Two 3-Member Teams. *** Three 3-Member Teams.*

Although these modes may also be "physically" demonstrated [as shown in *Figure (10)*, below], it is "the first" mode of buckling (with ***n* = *1***) that is of significant interest and importance in both structural and mechanical design.

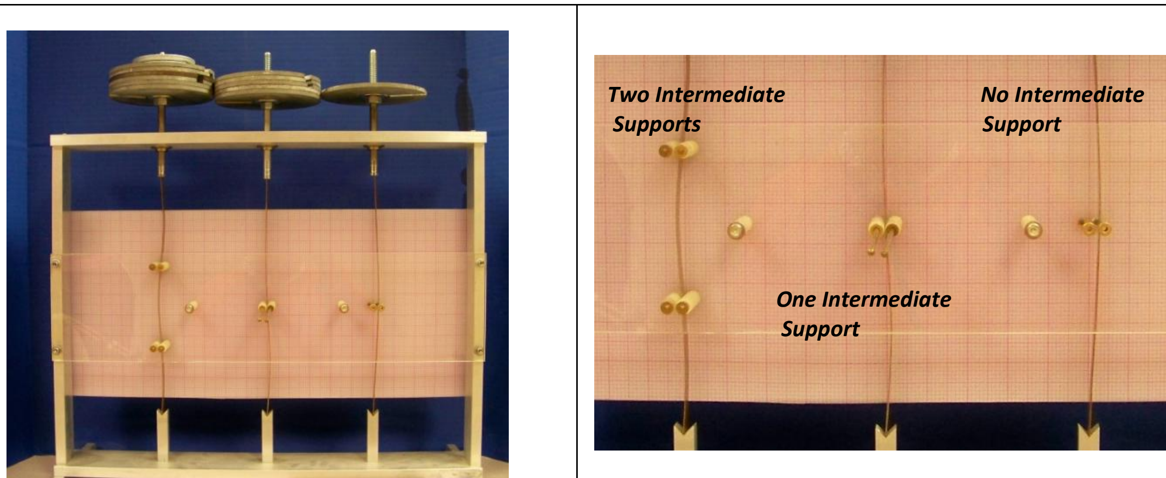


Fig 10. Load Carrying Capacity of Three Identical Columns with different intermediate supports.

Based on the data collected and analyzed in the past several centuries, it is possibile to obtain relatively acceptable (and conservative) analytical estimates of the “Critical Buckling Load” for a large array of scenarios. However, it is quite challenging to “physically”establish what is the exact load at which the buckling is “first” initiated. This group is hoping that they may design and produce an “Optical Measurement” technique and apparatus to achieve this goal.

VIII – Summary and Conclusions

An interesting application of the optical measurement techniques in design of an experiment for the measurement of the angle of twist in round bars has been presented. Complete details about the parameters in the design of the experiment and the associated apparatus for accurately conducting the necessary measurements have been presented. The advantages and unique characteristics of optical devices in measurement applications have been discussed. The steps and the reasoning in the setup for conducting the experiment have been fully explored. Parameters influencing the degree of precision and accuracy of the experiment have been examined. The significance of this approach “as an example” of application of optics in measurements has been discussed. As a first exposure of the sophomore level students, the number of components and the complexity of the design and the experiment have been well controlled and kept at a challenging level that sophomores may succeed. Parameters influencing the choice of the samples have been explored. Detailed cost analysis has been presented for the components of the apparatus, the materials, and the chosen specimens. Blueprints of the critical parts of the apparatus are included for potential replication at other institutions. The data collected from nine (9) sections of the first measurement course at TCNJ have been organized to assess how the experiment and this “Optical Approach” have improved the learning curve of the students. A potential future application of optics for experimentally determining the “Critical Buckling Load” is briefly discussed. The “tested” handout for conducting the experiment is included in the Appendices for reference and potential modifications. The outcomes of the collaboration of the junior engineering students with the faculty in the design of the experiment and the fabrication of the apparatus have been discussed. It is hoped that the engineering educators find this exercise worthy of being added to the archives of the experiments/projects in their undergraduate programs and share their experience(s) with the authors.

Acknowledgments

The authors expresses special thanks to Alexander Michalchuk (department senior technician and machinist) and Joseph Zanetti (Machine Shop Coordinator) for their continuous support and dedication to the project. They also thank all of the collaborating students for their contributions, especially those made by: James Giacchi, Matthew Kinback, and Christopher Allen. They certainly made a true difference.

References

1. Zydney, et al. 2002. “Impact of Undergraduate Research Experience in Engineering”, *Journal of Engineering Education.* 91(2): 151-157.
2. Shigley, Joseph E. Mechanical Engineering Design, Third Edition, McGraw Hill, 1980.
3. Sepahpour, B., “Involving Undergraduate Students in Design of Experiments”, *Proceedings of ASEE 2002 National Conference, Montreal, Canada, June 2002.*

Appendix A: Outline of the Experiment and the Project

Measurement Laboratory – I
Torsion of Round Bars Experiment

Task 1:
To investigate the relationship between the torque, length, and the angle of twist.

Task 2:
To determine the shear modulus of (stainless) steel, copper, and aluminum.

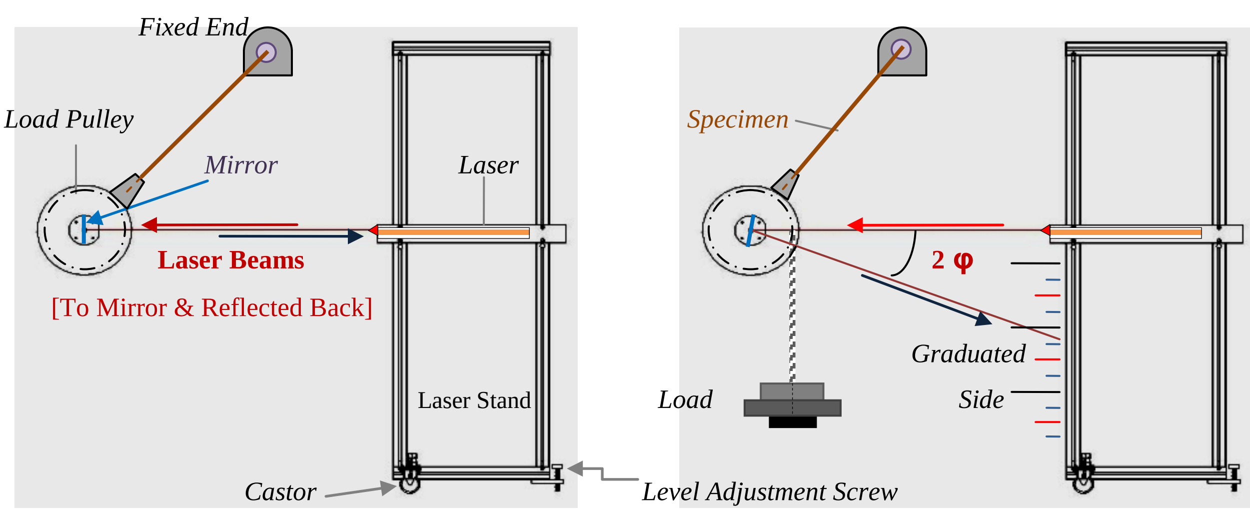


Figure 1. Components and the Setup for the *"Torsion Experiment"* Using *"Optical Measurement System"*

Introduction
In this experiment, we will use an "Optical Measurement System" to measure the angle of twist of several round bars made of different material. The apparatus is comprised of a laser that shoots a beam onto a flat mirror that is attached to a pulley through which load would be applied to the specimen. The specimen is fixed at one end and free to rotate at the other end upon the application of a torque (T). The beam of the laser and its reflection are initially set parallel to the ground. As the load is applied to the pulley/bar, the reflected beam will form an angle with respect to the reference. *Figure (1)* (above) shows the general setup and geometry of the optical system.

Procedure 1a:

Investigate the relationship between torque and angle of twist.

1. A test specimen of stainless steel is fastened into the specimen clamp closest to the pulley. The jaw is first hand tightened and then tightened further using a Chuck key/wrench until the specimen is firmly griped.

2. The mounting plate on the second jaw is then slid forward and the rod inserted into the jaws until the length of the rod reaches the desired 800 mm. The mounting plate screws are tightened first, the clamp jaws are then hand tightened and further fixed into position by the Chuck wrench. The pulley wheel is rotated until the mirror is normal to the ground. Then the bolts on the left side of the pulley are torqued to maintain the geometric orientation of the mirror. The loosening and tightening of these bolts are necessary for each set up (why?).

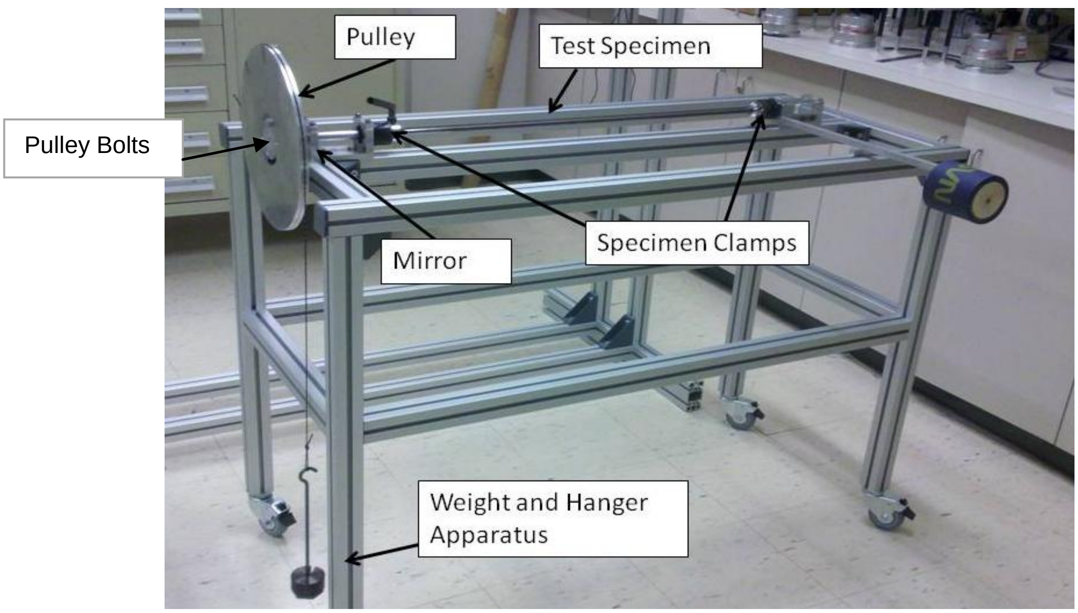


Figure 2. Relative location of the Components of the Apparatus W/R to each other

3. The laser is set a distance (D) of three (3) to four (4) meters from the apparatus aiming at the mirror on the load pulley.

4. The lights in the room are dimmed and the laser is turned on (by pressing the red switch on the back of it) after the "<u>Laser Safety Goggles</u>" are put on to protect the eyes.

5. The bracket holding the laser is then adjusted up or down until the laser's light hits the center of the mirror. It is important to keep an eye on the level that is located on the laser mount to be sure that the device is level and parallel to the ground.

6. The laser device can then be angled until the reflected beam from the laser hits the "Graduated Bar" located on the front of this device. The reflected beam needs not to hit above or below the light source. The two beams must be the same distance from the ground.

7. The ruler on the device is then adjusted so that the beam hits a multiple of a hundred (say, 200 mm) mark. This mark will be the H_i.

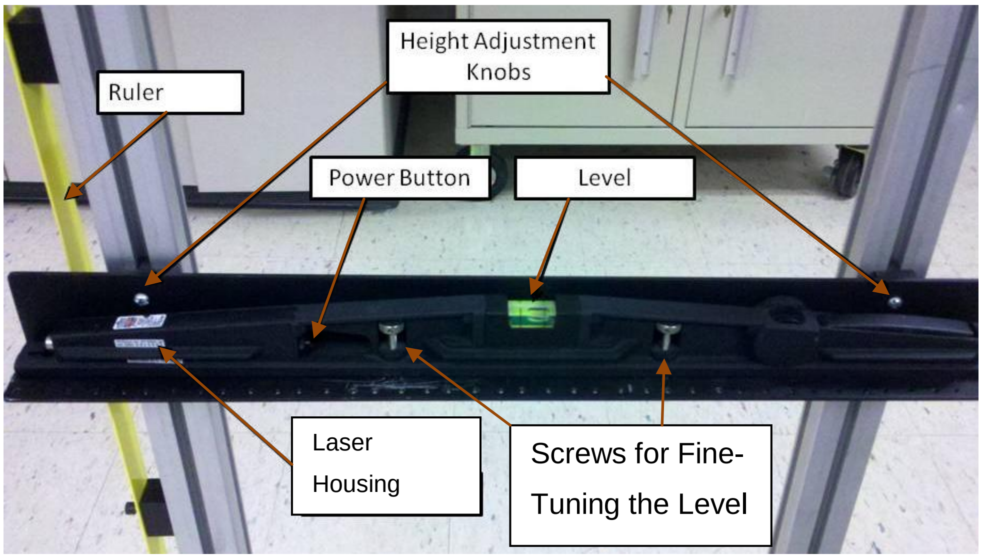


Figure 3. Class-II Laser on the stand with the manual leveling features

8. Apply the first load by attaching the ***200 g*** hanger on the pulley cable and observe the new location *(**H**)* of the reflected laser beam on the ruler. Vary the Load as seen in *Table (1)* using *Equation (1)* to calculate the angle of twist (φ).

$$2\varphi = Tan^{-1}\frac{H_i - H}{D} \qquad (1)$$

Table (1)

Load (N)	H — H_i (mm)	φ (Deg.)	Torque (N·mm)
7			
12			
22			
32			

9. Using the results from the table, generate a graph to show the correlation between the torque and the angle of twist.

Procedure 1b:

Investigate the relationship between clamping length and angle of twist.

1. A test specimen of stainless steel is mounted.
2. Load with 22 N (ONLY).
3. Vary the clamping length as shown in *Table (2)* and calculate the angle of twist using *Equation (1)*.

Table (2)

Load N	H - H_i	φ	Torque
600mm			
800mm			

4. Using the results from the table, plot the correlation between the length and the angle of twist.

Procedure 2:

Determine shear modulus of stainless steel, copper, and aluminum.

The following relationships will be used for this step of the activity.

$$\varphi = {TL}/{I_p G} \cdot \left({180}/{\pi}\right) \qquad (2)$$

$$G = {E}/{2(1+\nu)} \qquad (3)$$

Where:

$$T = F \cdot r \qquad (4)$$

For Solid Circular Sections:

$$I_p = \pi(d^4)/32 \qquad (5)$$

$$\tau = \frac{Tr}{J} = \frac{16T}{\pi d^3} \qquad (6)$$

φ = Angle of Twist (degrees)

F = Load (N)

L = clamping length (mm)

I_P = Polar Moment of Intertia (mm^4)

G = Shear Modulus (N/mm^2)

T =Torsional Stress ($N/mm^{2)}$

T= Torque (N·mm)

1. The span is set at 800mm. ***Procedure 2-Cont.***
2. A test specimen of stainless steel is fastened.
3. Load as indicated in *Table (4)* and calculate the values for the corresponding angles.
4. Repeat the test with specimens of copper and aluminum.
5. Complete *Table (3)* by calculating the shear modulus from *Equation (3).* Apply the numerical values listed in *Table (3)* for the Modulus of Elasticity (E) and the Poisson's Ratio (v).
6. Is it possible to estimate the "G" values experimentally? If so, obtain them and compare them with those calculated in *Table (3).*
7. Estimate Torsional Shear Stress using *Equation (6)*.

Table 1

Material	Modulus of Elasticity (**E**)	Poisson's Ratio (**v**)	Shear Modulus (**G**)
Stainless Steel	196 GPa	0.305	
Aluminum 6061-T6	68.9 GPa	0.330	
Non-Oxygenated Copper 101	115 GPa	0.310	

Table 2

Material	**Load, F (N)**	**Torque, T (N· mm)**	**Torsional Shear Stress, τ KPa**	**Angle of Twist, φ (Deg.)**	**Shear Mod. of Elasticity, *G* GPa**	**G_{avg} GPa**
Steel	7					
	12					
	17					
Aluminum	7					
	12					
	17					
Copper	7					
	12					
	17					

Sources of Error

Identify and comment on ALL the potential sources of error during the measurement leading to the final values of the Angle of Twist. How is it possible to further increase the precision and accuracy of the measurements with the use of the “same” apparatus?

Comparison of the Results

Compare the experimental values for the shaded boxes in *Table (4)* with those of theoretical values. Run a “Deviation” analysis.

Application of Optical Measurement

Can your group come up with an experiment or a measurement process utilizing an Optical Measurement Approach?

Report

Each group must prepare a brief professional report, describing in your own words the objectives of the experiment, the procedure followed, results, percent error, and your conclusions. It is necessary to discuss the probable sources of error in the experiment. Complete the “Assessment” form of the project and the group.
Refer to the handout for the *Report Requirements*.

Appendix B: Rating and Assessment Form of the Activity

RATING AND ASSESSMENT

1. *How many members formed your group? [ ]*

2. *Indicate the number, duration, and place of EACH of your meetings. (Use the following TABLE for tabulation)*

Meeting #	***DATE***	***DAY***	***TIME***	***PLACE***
Total Time Expended:				

3. *How would you rate the time required for completion of this Project?*

Too Short	*Short*	*About Right*	*Long*	*Too Long*

4. *If you had to do this experiment/activity again, how long would it take the second time? Use the Percentages listed below.*

(30-40)%	*(40-50)%*	*(50-60)%*	*(60-70)%*	*(70-80)%*	*(80-90)%*	*Almost The Same*	*Can't Predict*

5. *Would the experience gained in this activity help you optimize your approach the next time you have to deal with a similar task?*
(Use the Rating and the Space provided below)

Highly Unlikely				Definitely
1	2	3	4	5

6. *How would you rate the overall value of this Experiment and Project?*

Lowest				Highest
1	2	3	4	5

7. *If you get to teach a similar course, would you incorporate such an activity in your course? If yes, what changes would you recommend or introduce? (Use the Rating and the Space provided below)*

Highly Unlikely	*Unlikely*	*Probably*	*Very Likely*	*Definitely*
Recommended Changes:				

Appendix C: Detailed Drawings of the "Load Pulley" and the "Laser Stand"

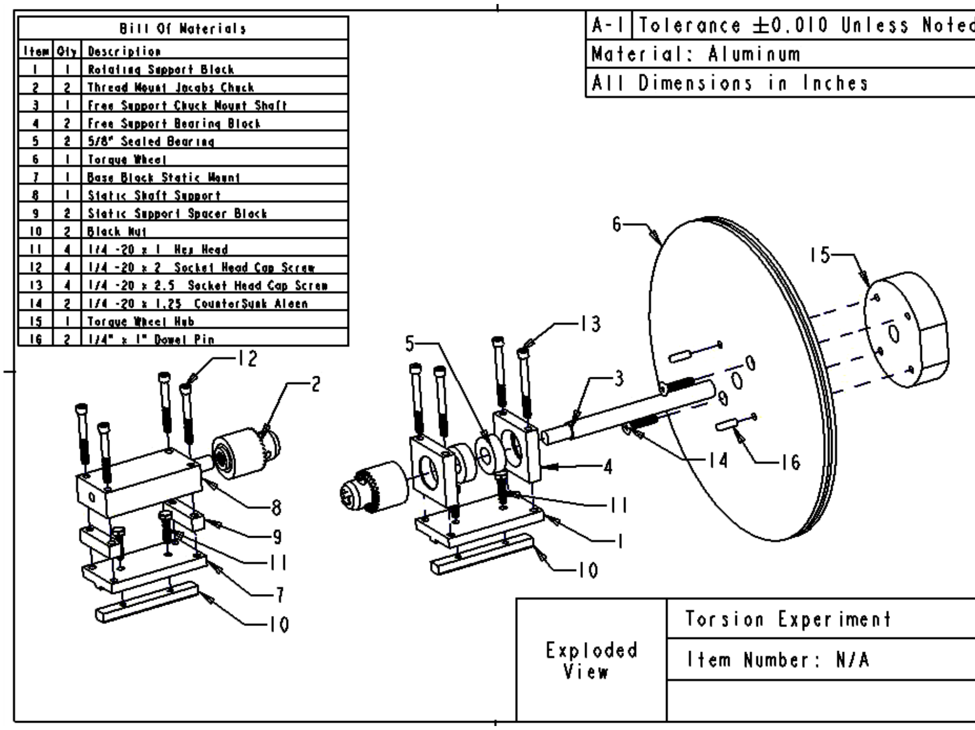


Figure C-1. Exploded View of the Components of the Apparatus

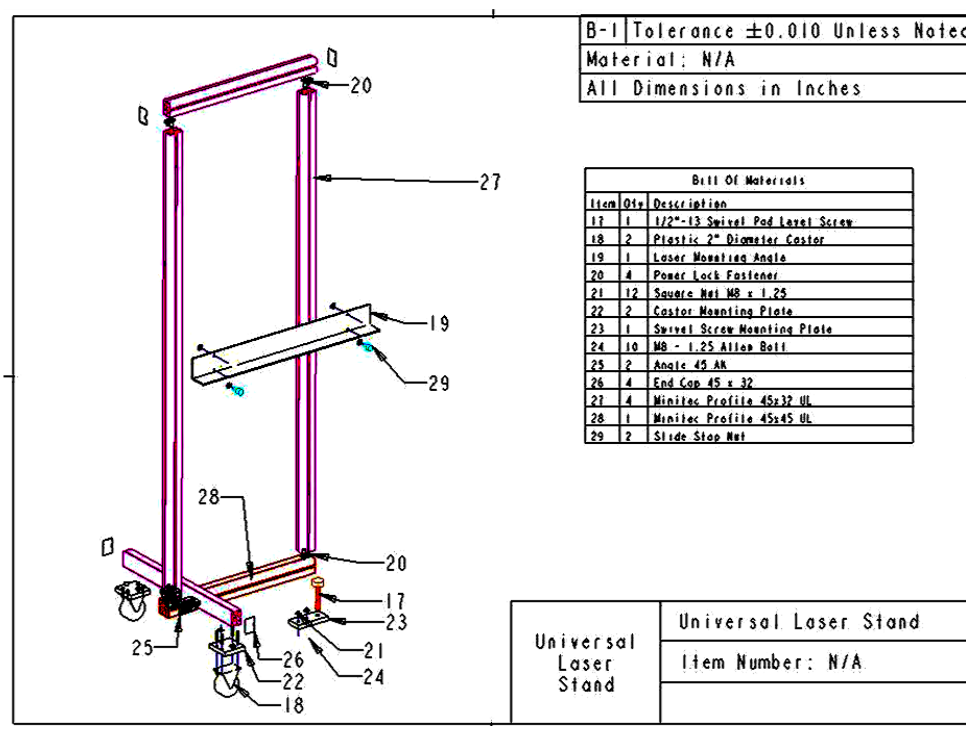


Figure C-2. Exploded View of the Laser Stand of the Apparatus