Université Concordia University
Department of Mechanical & Industrial Engineering

THEORY OF MACHINES I

LABORATORY MANUAL

MECH 343

2011 Winter

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General Laboratory Safety Rules

Follow Relevant Instructions

- Before attempting to install, commission or operate equipment, all relevant suppliers'/manufacturers' instructions and local regulations should be understood and implemented.

- It is irresponsible and dangerous to misuse equipment or ignore instructions, regulations or warnings.

- Do not exceed specified maximum operating conditions (e.g. temperature, pressure, speed etc.).

Installation/Commissioning

- Use lifting table where possible to install heavy equipment. Where manual lifting is necessary beware of strained backs and crushed toes. Get help from an assistant if necessary. Wear safety shoes appropriate.

- Extreme care should be exercised to avoid damage to the equipment during handling and unpacking. When using slings to lift equipment, ensure that the slings are attached to structural framework and do not foul adjacent pipe work, glassware etc.

- Locate heavy equipment at low level.

- Equipment involving inflammable or corrosive liquids should be sited in a containment area or bund with a capacity 50% greater that the maximum equipment contents.

- Ensure that all services are compatible with equipment and that independent isolators are always provided and labeled. Use reliable connections in all instances, do not improvise.

- Ensure that all equipment is reliably grounded and connected to an electrical supply at the correct voltage.

- Potential hazards should always be the first consideration when deciding on a suitable location for equipment. Leave sufficient space between equipment and between walls and equipment.

- Ensure that equipment is commissioned and checked by a competent member of staff permitting students to operate it.

Operation

- Ensure the students are fully aware of the potential hazards when operating equipment.

- Students should be supervised by a competent member of staff at all times when in the laboratory. No one should operate equipment alone. Do not leave equipment running unattended.

- Do not allow students to derive their own experimental procedures unless they are competent to do so.

Maintenance

- Badly maintained equipment is a potential hazard. Ensure that a competent member of staff is responsible for organizing maintenance and repairs on a planned basis.

- Do not permit faulty equipment to be operated. Ensure that repairs are carried out competently and checked before students are permitted to operate the equipment.

Electricity

- Electricity is the most common cause of accidents in the laboratory. Ensure that all members of staff and students respect it.

- Ensure that the electrical supply has been disconnected from the equipment before attempting repairs or adjustments.

- Water and electricity are not compatible and can cause serious injury if they come into contact. Never operate portable electric appliances adjacent to equipment involving water unless some form of constraint or barrier is incorporated to prevent accidental contact.

- Always disconnect equipment from the electrical supply when not in use.

Avoiding Fires or Explosion

- Ensure that the laboratory is provided with adequate fire extinguishers appropriate to the potential hazards.

- Smoking must be forbidden. Notices should be displayed to enforce this.

- Beware since fine powders or dust can spontaneously ignite under certain conditions. Empty vessels having contained inflammable liquid can contain vapor and explode if ignited.

- Bulk quantities of inflammable liquids should be stored outside the laboratory in accordance with local regulations.

- Storage tanks on equipment should not be overfilled. All spillages should be immediately cleaned up, carefully disposing of any contaminated cloths etc. Beware of slippery floors.

- When liquids giving off inflammable vapors are handled in the laboratory, the area should be properly ventilated.

- Students should not be allowed to prepare mixtures for analysis or other purposes without competent supervision.

Handling Poisons, Corrosive or Toxic Materials

- Certain liquids essential to the operation of equipment, for example, mercury, are poisonous or can give off poisonous vapors. Wear appropriate protective clothing when handling such substances.

- Do not allow food to be brought into or consumed in the laboratory. Never use chemical beakers as drinking vessels

- Smoking must be forbidden. Notices should be displayed to enforce this.

- Poisons and very toxic materials must be kept in a locked cupboard or store and checked regularly. Use of such substances should be supervised.

Avoid Cuts and Burns

- Take care when handling sharp edged components. Do not exert undue force on glass or fragile items.

- Hot surfaces cannot, in most cases, be totally shielded and can produce severe burns even when not visibly hot. Use common sense and think which parts of the equipment are likely to be hot.

Eye/Ear Protection

- Goggles must be worn whenever there is risk to the eyes. Risk may arise from powders, liquid splashes, vapors or splinters. Beware of debris from fast moving air streams.

- Never look directly at a strong source of light such as a laser or Xenon arc lamp. Ensure the equipment using such a source is positioned so that passers-by cannot accidentally view the source or reflected ray.

- Facilities for eye irrigation should always be available.

- Ear protectors must be worn when operating noisy equipment.

Clothing

- Suitable clothing should be worn in the laboratory. Loose garments can cause serious injury if caught in rotating machinery. Ties, rings on fingers etc. should be removed in these situations.

- Additional protective clothing should be available for all members of staff and students as appropriate.

Guards and Safety Devices

- Guards and safety devices are installed on equipment to protect the operator. The equipment must not be operated with such devices removed.

- Safety valves, cut-outs or other safety devices will have been set to protect the equipment. Interference with these devices may create a potential hazard.

- It is not possible to guard the operator against all contingencies. Use commons sense at all times when in the laboratory.

- Before staring a rotating machine, make sure staff are aware how to stop it in an emergency.

- Ensure that speed control devices are always set to zero before starting equipment.

First Aid

- If an accident does occur in the laboratory it is essential that first aid equipment is available and that the supervisor knows how to use it.

- A notice giving details of a proficient first-aider should be prominently displayed.

- A short list of the antidotes for the chemicals used in the particular laboratory should be prominently displayed.

In case of an emergency use the internal phone to call security by dialing 811. Security will connect you to the appropriate emergency service and immediately dispatch security personnel.

Or you can use your cellular phone to call 848 3717.

The civic address is:
Concordia University, 1455 De Maisonneuve West, H3G1M8
Room____________

The technician responsible/ in charge of this laboratory is: **Mr. Brad Luckhart** tel: **3149**

Safety Regulations for Students in All Mechanical and Industrial Engineering Laboratories;

Standard lab safety must be followed in all laboratories.

a. First discuss your experiment regarding possible hazards or problems, with the demonstrator, or the MIE technical staff, or your professor.

b. Do not work alone. Work with another person in a lab that has running machinery, machine tools, conveyors, hydraulics, lifting equipment, voltage hazards, or where chemicals are in use.

c. Safety glasses must be worn in the vicinity of pneumatics, machine tools grinders, power saws, and drills.
Users of lasers need special safety glasses for the particular wavelength of the laser.

d. No equipment or machine may be operated by anyone unless they have received adequate instruction from a qualified instructor eg. machine tools, hydraulics, chemicals, lasers, running machinery, robots. Undergraduate students may not use any machine or equipment unless a Department technical staff member is present. Graduate students are the responsibility of their immediate academic supervisor.

e. Workplace Hazardous Material training must be obtained before using chemicals or compressed gasses. Contact Dainius Juras tel: 848 3128 for training.

f. All appropriate safety accessories (lab coats, safety glasses, gloves, etc..) must be used when handling chemicals. No open toe shoes are permitted in laboratories.

g. No chemicals to be left unattended or unlabeled according to WHMIS. All chemicals must be stored properly.

h. Long term unattended tests must be fail safe.

i. When the university is officially closed, you may not work in a lab unless your supervisor or a technical staff member is present.

j. No eating in laboratories.

k. Major accidents and injuries must be reported at once to Security tel: 811, the Safety Officer (tel: 3128), the Professor (Supervisor) or the Department Administrator (tel: 7975) should then be informed.

l. During working hours all minor accidents should be reported to the Safety Officer (tel: 3128), the Professor (Supervisor) or the Department Administrator (tel: 7975).

m. An "Incident Report" must be filled out by the person involved, for all accidents and injuries.

INTRODUCTION

The purpose of the kinematics and dynamics of mechanisms experiments is twofold. First, they are intended to explain the student with machine elements and mechanical systems as well as provide an insight of techniques of Kinematic and dynamic analysis. This is part of the overall design process and it forms an integral part of a good engineering curriculum. Second, they provide a realistic environment within which the student can practice writing technical reports.

The teaching aspect is fulfilled by conducting the experiment and submitting a sample calculation sheet to satisfy the lab instructor that the concepts and methodology of each experiment are thoroughly understood. These experiments are frequently scheduled to be conducted preceding the lectures; however, since there is one setup per experiment, it is not uncommon for some groups to start with experiments not yet covered in class. This will give the students the opportunity to prepare for their labs on their own, and discuss with the lab demonstrator if further clarification is essential.

The second objective is slightly challenging and requires hard work on the part of the student. Each group is expected to select one of the experiments performed and submit a formal report on it. In view of the following comments on technical writing, no guidelines shall be given as to how long or detailed the report should be. Treat the selected experiments as a realistic industrial assignment. It is your job to submit a full report of your findings to an engineering audience. Do not feel compelled to follow a particular format other than the broad structural composition discussed next. The arrangement of the material within each main section is left to your discretion.

GUIDELINES IN PREPARATION OF THE LAB REPORT

In general terms, the role of engineers in society is to translate technological advances into new products. To achieve this function successfully, engineers need a sound technological background together with the ability to communicate well with their co-workers. The latter aspect is often compounded by the fact that engineers frequently are faced with the problem of explaining technical topics to people with very little knowledge and understanding of engineering principles.

Despite the recognized importance of proper report writing, very little formal training exists in this field, either in industry, or in university curricula. The lack of formal instruction could be traced to the widely accepted philosophy that good report writing is a skill that can be acquired through practice and determination. To achieve this goal, an engineer must be thoroughly familiar with the technical aspects of the problem and also hold the ability to communicate his thoughts accurately.

THE ELEMENTS OF A REPORT

1. THE LANGUAGE

The author must at all times keep in mind the limitations of the readers of his work. If his message is well understood, then the report is an unqualified success. The text may not be a literary showpiece but then again this is not the goal of engineering writers. We are not advocating the proper grammatical construction and style should be neglected. These aspects play a secondary role in assessing the effectiveness of a technical report. To summary an old rule, in technical writing the message is the important thing and not the medium.

2. THE INTRODUCTION

How should the report be structured? Since the author needs to bring the reader into focus quickly, a report should commence by a statement of the case being considered. This helps create the appropriate atmosphere by repeating the terms and conditions which led to the investigation in the first place. Next, there should be a brief outline of the process followed to arrive at the solution and a summary of the main conclusions reached.

3. THE MAIN BODY

The core of the report should contain all the relevant details that were considered during the investigation. It should discuss the background information necessary to the understanding of the problem, describe the experimental set up used if measurements were taken, briefly describe what you did during experiment,(don't copy the procedure in lab manual), present the data collected and show how this information was used to perform whatever calculations were necessary. The main body is a detailed account of everything that was done during the experiment. It should be extensive to the point that the solution to the problem becomes obvious without actually stating it. For clarity of presentation, it is advisable to leave lengthy derivations or complex arguments out of the main part of the report. These, if essential should be separate appendices.

4. THE CONCLUDING REMARKS

The final section of the report sets out the solution to the problem defined in the introduction. It contains the conclusions reached at the end of the investigation. It does not present new data. It simply restates the arguments made in the main body of the report as conclusions. In effect the intent of this section is to convince the reader that the original assignment has been successfully carried out. Not all assignments are answered successfully. A good percentage of investigations fail either due to inadequacies of the investigator or because the problem considered may not have a practical solution within the present experimental set-up. Under such circumstances, the concluding section should contain an analysis of the reasons which are responsible for the apparent failure of the assignment. These quasi-conclusions could be employed to define the scope of a later investigation which will look into specific aspects of the problem, and thus eventually arrive at a normal answer.

In summary the following format can be followed:

TITLE

OBJECTIVE

INTRODUCTION (Theory)

PROCEDURE (concisely and briefly)

RESULTS (SAMPLE CALCULATION)

DISCUSSIONS AND CONCLUSIONS

DATA SHEETS

EXPERIMENT 1

- **Simple Four-Bar Linkage Mechanism**
- **Slider Crank Mechanism / Scotch Yoke Mechanism**

1. Simple Four-Bar Linkage Mechanism

1. 1. Definitions

In the range of planar mechanisms, the simplest groups of lower pair mechanisms are four bar linkages. A *four bar linkage* comprises four bar-shaped links and four turning pairs as shown in Figure 1.1.

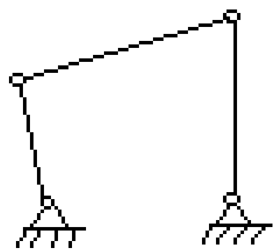


Figure 1.1: Four bar linkage

The link opposite the frame is called the *coupler link*, and the links which are hinged to the frame are called *side links*. A link which is free to rotate through 360 degree with respect to a second link will be said to *revolve* relative to the second link (not necessarily a frame). If it is possible for all four bars to become simultaneously aligned, such a state is called a *change point*.

Some important concepts in link mechanisms are:

1. **Crank**: A side link which revolves relative to the frame is called a *crank*.
2. **Rocker**: Any link which does not revolve is called a *rocker*.
3. **Crank-rocker mechanism**: In a four bar linkage, if the shorter side link revolves and the other one rocks (*i.e.*, oscillates), it is called a *crank-rocker mechanism*.
4. **Double-crank mechanism**: In a four bar linkage, if both of the side links revolve, it is called a *double-crank mechanism*.
5. **Double-rocker mechanism**: In a four bar linkage, if both side links rock, it is called a *double-rocker mechanism*.

1. 2. Classification

Before classifying four-bar linkages, we need to introduce some basic nomenclature. In a four-bar linkage, we refer to the *line segment between hinges* on a given link as a **bar** where:

- *s* = length of shortest bar
- *l* = length of longest bar
- *p, q* = lengths of intermediate bar

Grashof's theorem states that a four-bar mechanism has *at least* one revolving link if

$$s + l <= p + q \quad (1.1)$$

and all three mobile links will rock if

$$s + l > p + q \quad (1.2)$$

The inequality 1.1 is *Grashof's criterion*.

All four-bar mechanisms fall into one of the four categories listed in Table 1.1:

Table 1.1 Classifications of Four-Bar Mechanisms

Case	**l + s** vers. **p + q**	**Shortest Bar**	**Type**
1	<	Frame	Double-crank
2	<	Side	Rocker-crank
3	<	Coupler	Double- rocker
4	=	Any	Change point
5	>	Any	Double-rocker

From Table 1. 1 we can see that for a mechanism to have a crank, the sum of the length of its shortest and longest links must be less than or equal to the sum of the length of the other two links. However, this condition is necessary but not sufficient. Mechanisms satisfying this condition fall into the following three categories:

1. When the shortest link is a side link, the mechanism is a crank-rocker mechanism. The shortest link is the crank in the mechanism (Figure 1.2).
2. When the shortest link is the frame of the mechanism, the mechanism is a double-crank mechanism (Figure 1.3).
3. When the shortest link is the coupler link, the mechanism is a double-rocker mechanism (Figure 1.4).

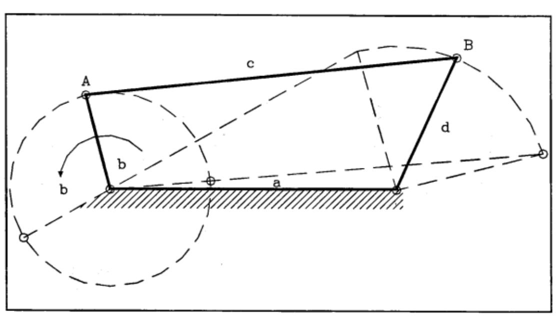


Figure 1.2: Crank and Rocker Mechanism

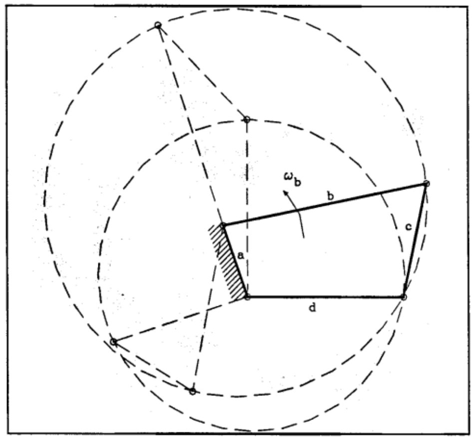


Figure 1.3: Drag Link Mechanism

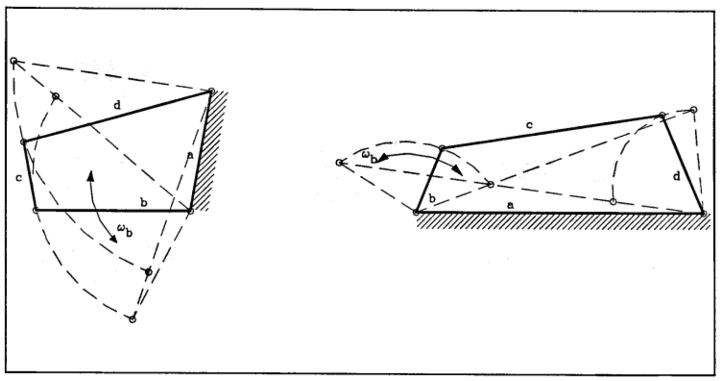


Figure 1.4: Double Rocker Mechanism

1. 3. Transmission Angle

In Figure 1.5, if *AB* is the input link, the force applied to the output link, *CD*, is transmitted through the coupler link *BC*. (That is, pushing on the link *CD* imposes a force on the link

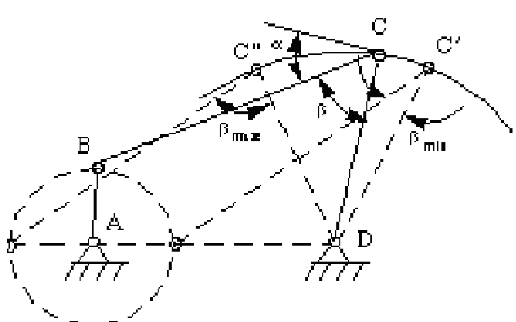


Figure 1.5: Transmission angle

AB, which is transmitted through the link *BC*). The angle between link BC and DC is called *transmission angle*, β, as shown in Figure 1.5. For sufficiently slow motions (negligible inertia forces), the force in the coupler link is pure tension or compression (negligible bending action) and is directed along *BC*. For a given force in the coupler link, the torque transmitted to the output bar (about point *D*) is maximum when the transmission angle approaches to π /2.

When the transmission angle deviates significantly from $\pi/2$, the torque on the output bar decreases and may not be sufficient to overcome the friction in the system. For this reason, the *deviation angle* $\alpha = |\pi/2 - \beta|$ should not be too great. In practice, there is no definite upper limit for α, because the existence of the inertia forces may eliminate the undesirable force relationship that is present under static conditions. Nevertheless, the following criterion can be followed.

$$\alpha_{\max} = |90^o - \beta|_{\min} \langle 50^o \qquad (1.3)$$

1. 4. Dead Point

When a side link such as *AB* in Fig 6, becomes aligned with the coupler link *BC*, it can only be compressed or extended by the coupler. In this configuration, a torque applied to the link on the other side, *CD*, cannot induce rotation in link *AB*. This link is therefore said to be at a *dead point* (sometimes called a *toggle point*). In order to pass the dead points a flywheel is usually connected to the input shaft particularly.

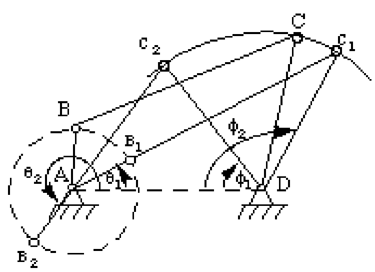


Figure 1. 6: Dead point

In Figure 1.6, if *AB* is a crank, it can become aligned with BC in full extension along the line AB_1C_1 or in flexion with AB_2 folded over B_2C_2. We denote the angle *ADC* by Φ and the angle DAB by θ. We use the subscript 1 to denote the extended state and 2 to denote the flexed state of links *AB* and *BC*. In the extended state, link *CD* cannot rotate clockwise without stretching or compressing the theoretically rigid line AC_1. Therefore, link *CD* cannot move into the *forbidden zone* below C_1D, and Φ must be at one of its two extreme positions; in other words, link *CD* is at an extreme. A second extreme of link *CD* occurs with $\Phi = \Phi_1$.

Note that the extreme positions of a side link occur simultaneously with the dead points of the opposite link.

1. 5. Objective and Fundamentals:

The experiment is designed to give a better understanding of the performance of the four-bar linkages in its different conditions according to its geometry.

Measuring the Dead point angles φ and transmission angles β at two positions when the constant bar a at two different positions 4″ and 6″

1. 6. Description of the Experiment:

The experimental setup consists of two four-bar linkage mechanism trains as shown in Figure 1.7. Careful examination of the setup should result in the correct categorization of the linkages. There is an arm following the coupler curve trace, a software generated linkage similar to the actual linkage is studied using the Working Model simulation package.

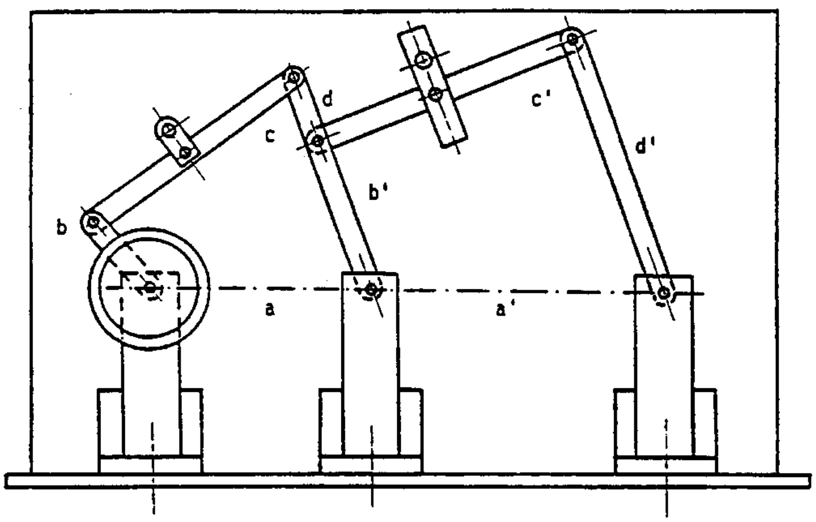


Figure 1.7: Four bar linkage Mechanism

1. 7. Experimental Procedure:

1. Set the fixed bar a at 4″.
2. Observe the movement of the four bar linkage mechanism.
3. Find the first dead point, then measure Dead point angle φ and transmission angle β.
4. Repeat step 3 for the second dead point.
5. Set the fixed bar a at 6″.
6. Repeat the steps 2, 3, 4.
7. Fill table (1).

Table (1)

Ground Length (in)	Transmission Angle (β)		Angle at Dead points (φ)	
	β_1	β_2	φ_1	φ_2
4				
6				

2. The Slider-Crank and Scotch- Yoke Mechanism

2.1. Theory

The Slider-crank (Figure 1.8) and the Scotch-yoke mechanism (Figure 1.9) setup is a single setup which can be adapted to function as one or the other, as shown in Figure 1.9.

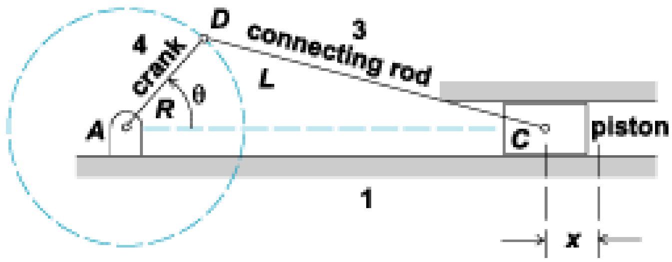


Figure 1.8: Slider crank Mechanism

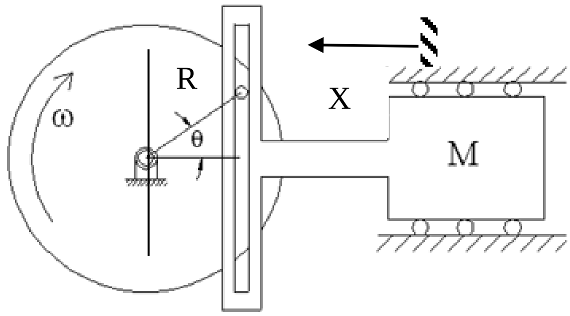


Figure 1.9: Scotch- Yoke Mechanism

The only difference is in link 3 which is replaceable depending on the type of mechanism required. It is important to study the Kinematic and dynamic response of the mechanism because of practical applications. It is also useful in determining the Kinematic equivalents of other mechanisms. While the motion of a Scotch-yoke mechanism is purely sinusoidal, that of the Slider-crank mechanism is not. The derivation of the equations used for describing the Kinematic motions (displacement, velocity and acceleration) of a simple Slider-crank mechanism can be seen on most mechanism text books. The final equation describing the displacement may be written as:

$$X = R + L - [R\cos\theta + L\left(1 - \frac{R^2}{L^2}\sin^2\theta\right)^{1/2}] \tag{1.4}$$

the velocity and acceleration can also be described by:

$$V = R\omega\left(\sin\theta + \frac{R\sin 2\theta}{2\left[L^2 - R^2\sin^2\theta\right]^{1/2}}\right)^{1/2} \tag{1.5}$$

$$a = R\alpha\left(\sin\theta + \frac{R\sin 2\theta}{2\sqrt{L^2 - R^2\sin^2\theta}}\right) + R\omega^2\left(\cos\theta + \frac{R\cos 2\theta}{\sqrt{L^2 - R^2\sin^2\theta}} + \frac{1}{4}\frac{R^3\sin^2(2\theta)}{(L^2 - R^2\sin^2\theta)^{3/2}}\right)$$

(1.6)

Similarly the motion analysis for the Scotch mechanism can be found in most mechanisms text books. For this case the displacement is given by:

$$X = R(1-\cos\theta) \tag{1.7}$$

and velocity and acceleration can be written as:

$$\dot{X} = R\omega\sin\theta \tag{1.8}$$

$$\ddot{X} = R\omega^2\cos\theta + R\alpha\sin\theta \tag{1.9}$$

2. 2. Objective:

Obtaining the position, velocity, acceleration for the Slider Crank and the Scotch Yoke mechanisms.

2. 3. Experimental procedure:

1. Set the slider crank at 0mm for the connecting rod, and 0° for the rotating disk.
2. Measure L the length of the connecting rod and R the radius for the rotating disk.
3. Change the angle for the disk by 30° each time until 360°, and each time measure X .
4. Fill the result in table (2).
5. Plot graphs between the angular displacement and the displacement X, velocity V, and the acceleration a.
6. Repeat for the Scotch Yoke and fill the results in table (3).

Table (2) Slider crank:

Angular Displacement (θ)	Experimental position X (mm)	Theoretical position X (mm)	Velocity V (mm/ sec)	Acceleration a (mm/sec^2)
0				
30				
60				
90				
120				
150				
180				
210				
240				
270				
300				
330				
360				

Table (3) Scotch Yoke:

Angular Displacement (θ)	Experimental position X (mm)	Theoretical position X(mm)	Velocity V (mm/ sec)	Acceleration a (mm/sec^2)
0				
30				
60				
90				
120				
150				
180				
210				
240				
270				
300				
330				
360				

2. 4. Results:

1. Show the difference of the results obtained in step 2 for Slider-Crank and Yoke Mechanisms.
2. Show the maximum value of velocity and acceleration given the equations describing the velocity and acceleration for both Slider-crank and Scotch-yoke mechanisms.
3. At what angular positions the maximum value of velocity and acceleration happen in both mechanisms?
4. Plot experimental and theoretical result for displacement versus angular displacement in the same graph, as well as theoretical velocity and acceleration versus angular displacement for both Slider-Crank and Scotch-Yoke mechanisms.

EXPERIMENT 2

Kinematic Analysis of Norton-Type Gearbox

1. General

Norton-type gear drives are used in feed systems of machine tools to provide sufficient speeds in a geometric progression. Figure 2.1 shows a schematic of the drive.

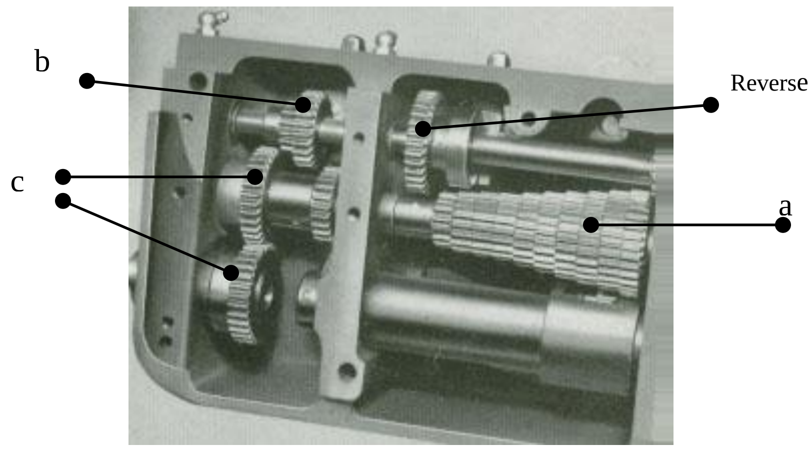


Figure 2.1: Norton-Type Gearbox, used in Lathes

It consists basically of a set of gears (a) of equal diametral pitch with decreasing tooth number arranged in a conical pattern as shown in Figure 2.1. A single mating gear (b) on a sliding arm provides a means of selecting the required speed ratio. The input motion is always given to the sliding gear (b) while the output motion is taken from the conical gear set (a).

2. Theory

The gear ratio (GR) in a gear train as shown in Figure 2.2 is defined as:

$$GR = \frac{ouput\ angular\ velocity}{input\ angular\ velocity}$$

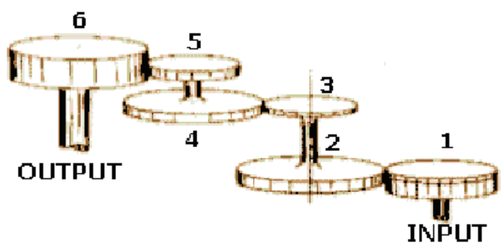


Figure 2.2: Compound Gear Train, Input, Output

The gear ratio between any two successive engaged gears, is inversely proportional to the teeth numbers, *n*, i.e.,

$$\frac{W_2}{W_1} = \frac{n_1}{n_2} \qquad (2.1)$$

The procedure to find the GR is to start with the input, and to calculate how the angular velocity propagates through each successive intermeshing pair of gears based upon the number of teeth. Consider a compound gear train shown in Figure 2.3.

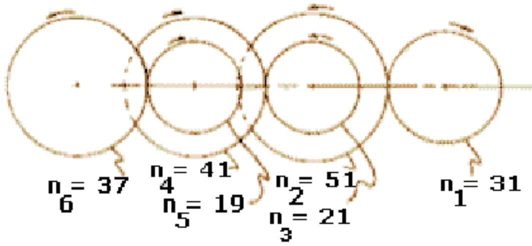


Figure 2.3: Compound Gear Train

Suppose that the input gear speed (rotation rate) is 1600 rpm clockwise, i.e.,

$$W_1 = +1600\,rpm \quad \text{(+ is clockwise)} \qquad (2.2)$$

Using Equation (2.1),

$$W_2 = \frac{n_1}{n_2} W_1 = -\frac{30}{50}(1600) = -960\,rpm$$
$$W_3 = W_2 = -960\,rpm \qquad (2.3)$$

where the negative sign represents for counter-clockwise direction. Similarly,

$$\frac{W_4}{W_3} = \frac{n_3}{n_4}$$

$$W_4 = \frac{n_3}{n_4} W_3 = -\frac{20}{40}(960) = 480\,rpm$$

$$W_5 = W_4 = 480\,rpm \qquad (2.4)$$

and

$$\frac{W_6}{W_5} = \frac{n_5}{n_6}$$

$$W_6 = \frac{n_5}{n_6} W_5 = -\frac{18}{36}(480) = -240\,rpm \qquad (2.5)$$

The final gear ratio GR can thus be obtained,

$$GR = \frac{ouput\ angular\ velocity}{input\ angular\ velocity} = \frac{-240}{1600} = -0.15 \qquad (2.6)$$

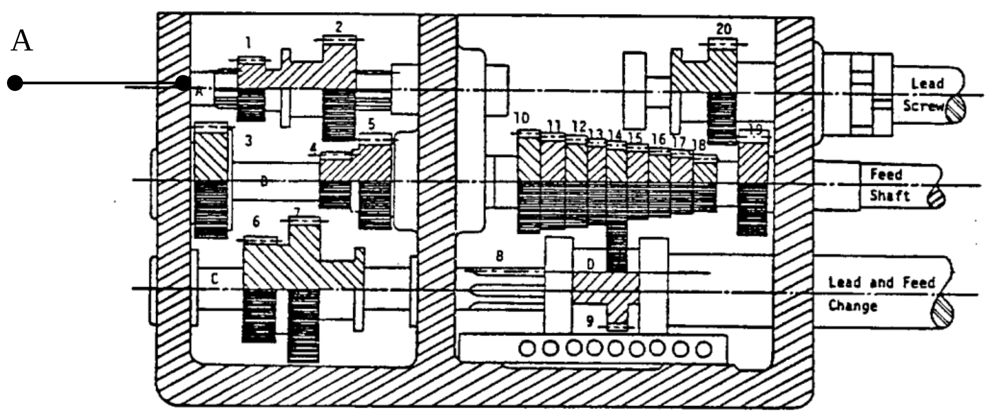
3. Objectives and Fundamentals

The experiment is designed to give a better understanding of the geometry of gear trains and their Kinematic analysis.
Measure the output velocity for the shaft, and calculate the gear train.

The schematic of Gear drive is shown in Figure 2.4. The construction of speed diagrams of gear drives is also illustrated in Figure 2.5.

4. General Data for Norton 36-Speed Gearbox

Motor speed: 1725 rpm.
Motor reduction unit ratio: 60: 1
Speed input to gearbox: 29.2 rpm.
Gearbox output speed range: 2.3 -34.4 rpm, (Fig 4)
Input torque to reduction unit: 277 in. lb.
Output torque range: 3510 -235 in. lb.



Gear	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Teeth	16	24	32	14	24	24	42	14	27	28	26	24	23	22	20	19	18	16	24	24

Figure 2.4: Schematic of Gear Drive

5. Experimental Procedure

1) Considering speed input to the gearbox from the motor is 29.2 rpm which goes to the input shaft A
2) Observe Figure 2-5 and match the gear numbers and shaft
3) Measure the output seed for the shaft.

4) Fill table (2.1): the experimental values.

Table 2. 1: Output results

Case #	Input	Output (rpm)				
		G-10		G-14	G-16	G-18
1	**1-3 3-6**	Theoretical				
		GR				
		Experimental				
		GR				
2	**2-5 3-6**	Theoretical				
		GR				
		Experimental				
		GR				
3	**2-5 4-7**	Theoretical				
		GR				
		Experimental				
		GR				

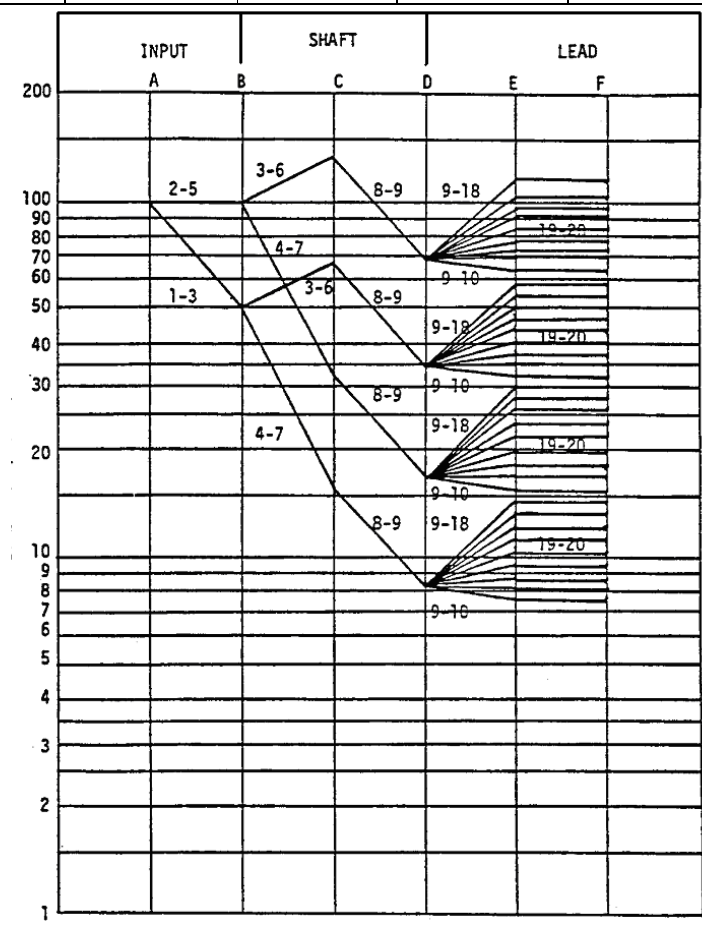


Figure 2.5: Speed Diagram

6. Experimental Result

1) Calculate the theoretical output speed, and show the calculation.
2) Calculate the gear ratio for all cases.
3) Plot speed diagram for the all cases depending on the one shown in Figure 2-5.

EXPERIMENT 3

Hook (Cardan) Joint or Universal Joint

1. Introduction:

The simplest means of transferring motion between non axial shafts is by means of one or two universal joints, also known as Cardan joints in Europe and Hook's joints in Britain. The shafts are not parallel to one another and they may be free to move relative to one another. For this reason, this very simple spherical mechanism appears in an enormous variety of applications. The most common application is Cardan joint used in the trucks as shown in Figure 3.1. A universal joint is a simple spherical four-bar mechanism that transfers rotary motion between two shafts whose axes pass through the concurrency points. The joint itself consists of two revolute joints whose axes are orthogonal to one another. They are often configured in a cross-shape member as shown in Figure 3.2.

2. Objective of Universal Joint

- Coupling is used to connect two intersecting shafts.
- Consists of 2 yokes and a cross-link.

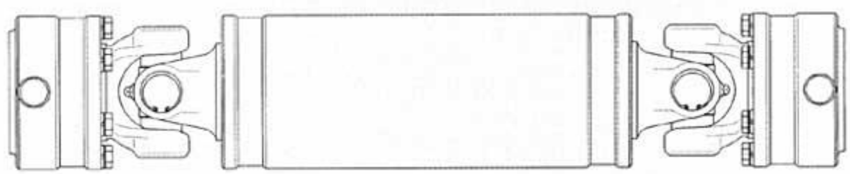


Figure 3.1: Cardan Joint, used in Trucks

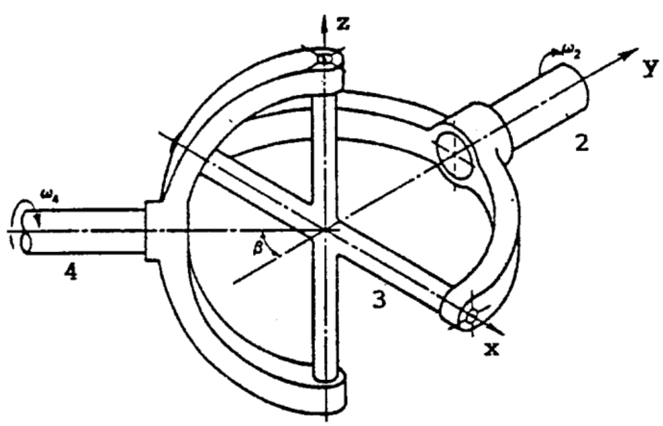


Figure 3.2: Schematic of Cardan Joint

The transmission behavior of this joint is described by Equation (3.1).

$$\alpha_2 = \arctan\left(\frac{1}{\cos\beta}.\tan\alpha_1\right) \qquad (3.1)$$

where α_2 is the momentary rotation angle of the driven shaft 2.

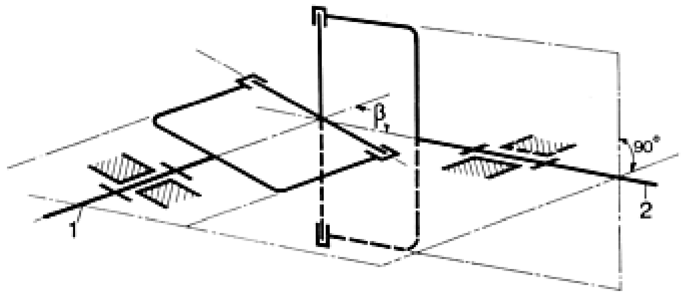


Figure 3.3: Schematic of Cardan Joint

The angular velocity ratio can be described by:

$$\frac{\omega_4}{\omega_2} = \frac{\cos\beta}{1-\sin^2\theta\sin^2\beta} \tag{3.2}$$

where β is the angular misalignment of the shafts and Θ is the angle of the driving shaft. It is noted that:

$$\frac{\omega_4}{\omega_2}\max. \quad \text{at } \theta = 90^o, 270^o$$

$$\frac{\omega_4}{\omega_2}\min. \quad \text{at } \theta = 0^o, 180^o, 360^o \tag{3.3}$$

if $\beta = 0 \rightarrow \frac{\omega_4}{\omega_2} = 1$ = constant at any Θ

$\frac{\omega_4}{\omega_2}$ will vary between a minimum and a maximum during each revolution.

$\omega_2 = \omega_4$ only at 4 instants as shown in Figure 3.4.

This is a very big disadvantage, in case of automotive vehicles, this means that rear wheels will rotate at variable speed.

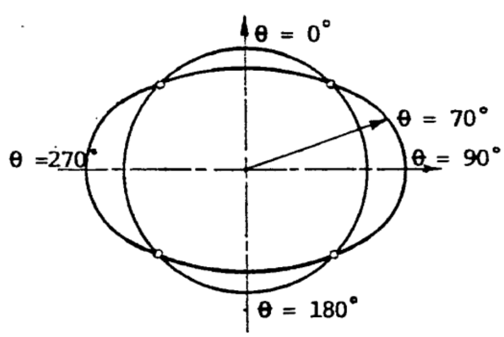


Figure 3.4: Relation between $\frac{\omega_4}{\omega_2}$ and Θ

ω_2 is constant (because engine and flywheel) speed of car cannot be variable each revolution because its inertia, and so this means tires will slip and severe wear will happen.

The effect of the angle β can be shown by plotting $\frac{\omega_4}{\omega_2}$ for different values of β (Figure 3.5).

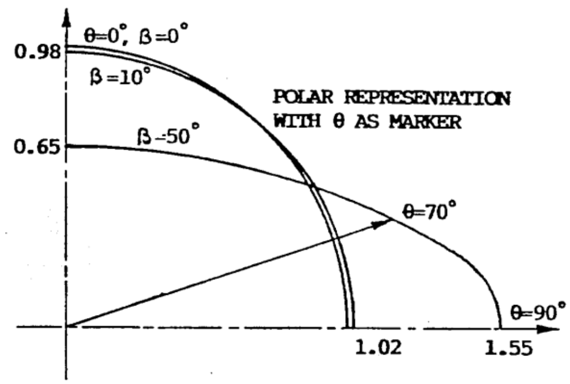


Figure 3.5: Relation between $\frac{\omega_4}{\omega_2}$ and β

The acceleration expression of the follower of universal joint for constant ω_2 is given by:

$$\alpha_4 = \omega_2^2 \frac{\cos\beta \sin^2\beta \sin 2\beta}{\left[1 - \sin^2\beta \sin^2\theta\right]^2} \tag{3.4}$$

Recall: $y = u(x)/v(x)$, therefore $y' = [vu' - uv']/v^2$.

For acceleration or retardation
-acceleration when 2Θ lies between 0 -180°
-deceleration when 2Θ lies between 180 -360°
Maximum acceleration occurs when $d\alpha_4 / d\Theta = 0$. Thus,

$$\cos 2\theta \cong \frac{-2\sin^2\beta}{2 - \sin^2\beta} \rightarrow gives\,\theta\; for\; \max.\alpha_4 \tag{3.5}$$

It is possible to connect 2 shafts by 2 Hook's couplings and an intermediate shaft that the uneven velocity ratio of the first coupling will be cancelled out by the second Condition (Figure 3.6).

$$\beta_2 = \beta_4 \tag{3.6}$$

Yoke 32 lies in plane containing shaft 2, 3
Yoke 34 lies in plane containing shaft 3, 4

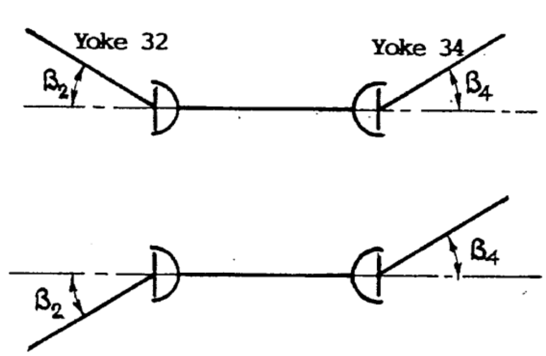


Figure 3.6: Two shafts by two Hook's couplings and an intermediate shaft

2. Objective:

Testing the affect of changing of the angle between the shaft and universal joint on the input and output shaft speed and calculate the speed ration between output and input shaft speed

3. Experimental Procedure

1) Fixing the input shaft angle $\beta_2 = 0^o$.
2) Setting the output shaft angle $\beta_4 = 15^\circ$.
3) Filter setting: cutoff freq. 4. Scope setting: ch1 500mv, ch2: 500mv, M 50ms. run scope, turn on motor. After stable fluctuate signal appear on screen, stop scope then turn off motor.
4) Check the input and output shaft speed by using Cursor: paired. We assume that at $\theta = 0$, N4 is min. setting paired cursor at this point as t=0 ms. Moving cursor along ch2 signal and record t and N4 by Δ: __ms, @:__v. Fill table 3-1. N2 is input shaft speed. It is constant.
5) Repeat step #2, setting the output shaft angle $\beta_4 = 30^\circ$. Fill table 3-2.
6) Plot the graph of velocity ratio during one cycle for both cases. Compare with theoretical plot using equation 3.2.

Table 3. 1: Test results of Cardan joint

$\beta_4 = 15^\circ$

θ (^{o})	0	45	90	135	180	225	270	315	360
t (ms)									
N4(v)									
N2(v)									
N4/N2									

Table 3. 2: Test results of Cardan joint

$\beta_4 = 30^\circ$

θ (^{o})	0	45	90	135	180	225	270	315	360
t (ms)									
N4(v)									
N2(v)									
N4/N2									

EXPERIMENT 4

Mechanical Oscillator for Measurement of Friction Coefficient

1. Introduction

The mechanical oscillator is an apparatus which allows the experimental determination of friction coefficient by measuring the period of an oscillating table. As shown in Figure 4.1 the apparatus consists of two counter rotating wheels upon which is placed a table of uniform weight.

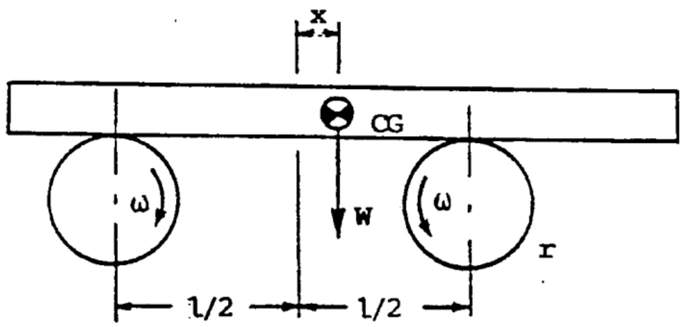


Figure 4.1: The mechanical oscillator

If the center of gravity of the table is not centered when it is placed on the rotating wheels, then more of its weight will rest upon one wheel than upon the other. Consequently the frictional forces will not be equal and the table will move in the direction of the larger of the two forces. But the inertia of the table will carry it too far past the center point and the other wheel will exert the larger frictional force. Thus the table will oscillate back and forth at a frequency which depends upon the coefficient of friction.

The basic step to find the equation of motion of the system is to construct the Free Body Diagram of the oscillating table. Figures 2(a), 2(b) and 2(c) show this procedure.

Summing the forces in the horizontal plane, we have

$$\frac{W}{g}\ddot{X} + \mu R_1 - \mu R_2 = 0 \tag{4.1}$$

or

$$\frac{W}{g}\ddot{X} + \left(\frac{2\mu W}{L}\right)X = 0 \tag{4.2}$$

hence,

$$\ddot{X} + \frac{2\mu g}{L}X = 0 \tag{4.3}$$

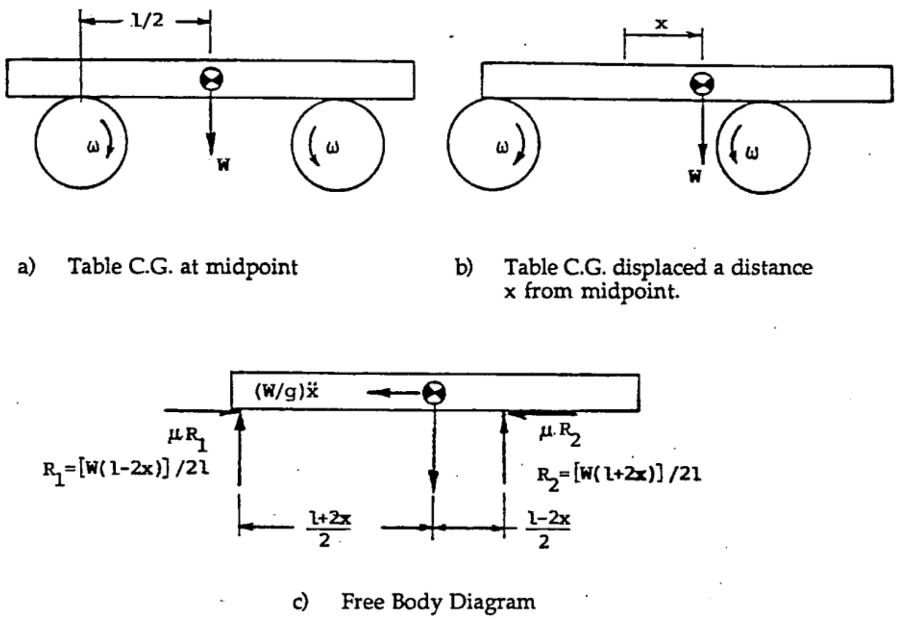


Figure 4.2: procedure of finding the equation of motion

Since the differential equation of motion of free vibration for a one degree of freedom system is of the form

$$\ddot{X} + \omega_n^2 X = 0 \tag{4.4}$$

where *n* is the natural frequency of the system, then

$$\omega_n^2 = \frac{2\mu g}{L} \tag{4.5}$$

But
$$\omega_n^2 = 4\pi^2 f^2 = \frac{2\mu g}{L} \tag{4.6}$$

where

f = the frequency of the oscillating table in cps.,
L = the distances between wheel centers in ft.,
g = gravity constant

hence
$$\mu = \frac{2\pi^2 L}{g} f^2 \tag{4.7}$$

The solution of the equation of motion can be written in the form

$$X = A\sin(\omega_n t) + B\cos(\omega_n t) \tag{4.8}$$

With the initial condition:

$$t = 0, \qquad X = X_O, and \quad \dot{X} = 0 \tag{4.9}$$

one gets
$$A = 0, \qquad and \quad B = X_o \tag{4.10}$$

The response of the oscillating table is therefore

$$X = X_o \cos\left(\frac{2\mu g}{L}\right)^{1/2} t \tag{4.11}$$

$$\dot{X} = -X_o\left(\frac{2\mu g}{L}\right)^{1/2}\sin\left(\frac{2\mu g}{L}\right)^{1/2} t \qquad (4.12)$$

$$\ddot{X} = -\left(\frac{2\mu g X_o}{L}\right)\cos\left(\frac{2\mu g}{L}\right)^{1/2} t \qquad (4.13)$$

Thus it may be concluded that the response of the oscillating table is governed by the initial displacement: X_0, the coefficient of friction μ, and the difference between wheel centers L.

2. Objectives

The experiment is designed to illustrate some of the direct applications of the theory of vibration to the measurement of physical quantities. The experiment also demonstrates the differences between mathematical models and actual physical systems.

Calculate the friction coefficient between the wheels and the bars.

3. Description of Experiment

The oscillating table apparatus consists of four grooved wheels mounted on two axels which are driven by a 1/20 H.P. electric motor and a gear reduction unit in opposite directions. The table consists of circular rods connected in a rectangular shape such that the rods are guided by the grooved wheels.

4. Experimental Procedure

1) Measure L the length between the centers of the two wheels.
2) Locate one of the bars on the wheels.
3) Select two different speeds for the wheels, and when it starts rotating and the bar moving calculate the time for 10 oscillations.
4) Calculate the experimental coefficient of friction μ, through the following equation: $\mu = \frac{2\pi^2 L}{g} f^2$. When; f is the frequency, g gravity acceleration. L the length between the centers of the two wheels. Fill table 4-1.
5) Find the theoretical coefficient of friction μ, for all bars.
6) Compare between theoretical and experimental coefficient of frictions μ.

Table 4. 1: Combinations for measuring the friction coefficient

Case #	Material of the bar	Speed (rpm)	Time taken for 10 oscillation	Frequency (f)	Coefficient of friction (μ)	Standard coefficient of friction
1	Steel					
2	Brass					
3	Aluminum					

EXPERIMENT 5

5-1: PLANETARY GEAR TRAIN KINEMATICS

1. Introduction

A planetary gear train is one in which the axis of some of the gears may have motion. A planetary gear set always includes a sun gear, one or more planet gears, and a planet carrier or arm which sometimes called as *sun-and-planet* planetary gear train as shown in Figure1.

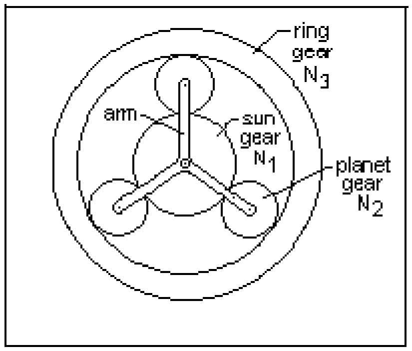


Figure 5.1: Planetary gear train

A planetary gear set, as shown in Figure 5.2, is one having two degrees of freedom. This means that the motion of each and every element of the mechanism is not defined unless the motion of two of its elements is specified. To make the planetary set a one degree of freedom gear train, one must fix the motion of one element of the mechanism.

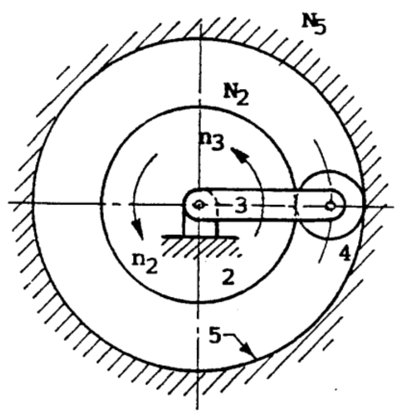


Figure 5.2: Sun-and-planet planetary gear train

2. Solution of Planetary Trains by Formula Methods

Figure 5.3 shows a planetary gear set which is composed of a sun gear 2, an arm 3, and planet gears 4 and 5:

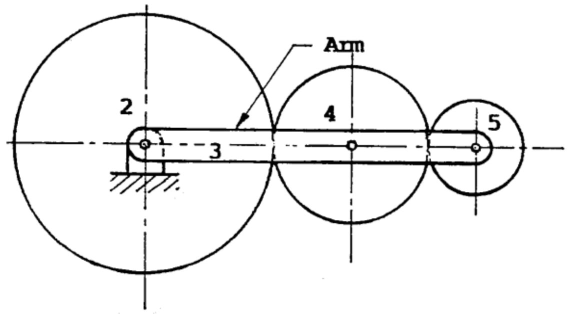


Figure 5.3: Compound Planetary Gear Set

We can express the velocity of gear 2 relative to the arm 3 in the form:

$$n_{23} = n_2 - n_3 \tag{5.1}$$

$$n_{53} = n_5 - n_3 \tag{5.2}$$

Dividing Equation (5.2) by (5.1) gives:

$$\frac{n_{53}}{n_{23}} = \frac{n_5 - n_3}{n_2 - n_3} \tag{5.3}$$

Since this ratio is the same and is proportional to the tooth numbers, it is equivalent therefore to the train value "*e*"

$$e = \frac{n_5 - n_3}{n_2 - n_3} \tag{5.4}$$

Or

$$e = \frac{n_L - n_A}{n_F - n_A} \tag{5.5}$$

where: n_F = rpm of first gear in train
n_L = rpm of last gear in train
n_A = rpm of arm.

The experiment is designed to demonstrate the fundamentals of planetary gear train and to show all possible motions that can be obtained with this type of gear trains.

3. Objective

Calculate the gear train ratio for the planetary gearbox; and the degrees of freedom that the system has.

4. Experimental Procedure

For the planetary gear trains mechanism shown in Figure 5.1:

1) Calculate the degree of freedom to the planetary gear system
2) Calculate the gear train ration through the following equation:

$$e = \frac{n_3 - n_2}{n_1 - n_2}$$

- When the outer ring is fixed.
- When the planet gears are fixed.

5-2: The Borg-Warner Model 35 Automatic Transmission Simulator

1. Introduction

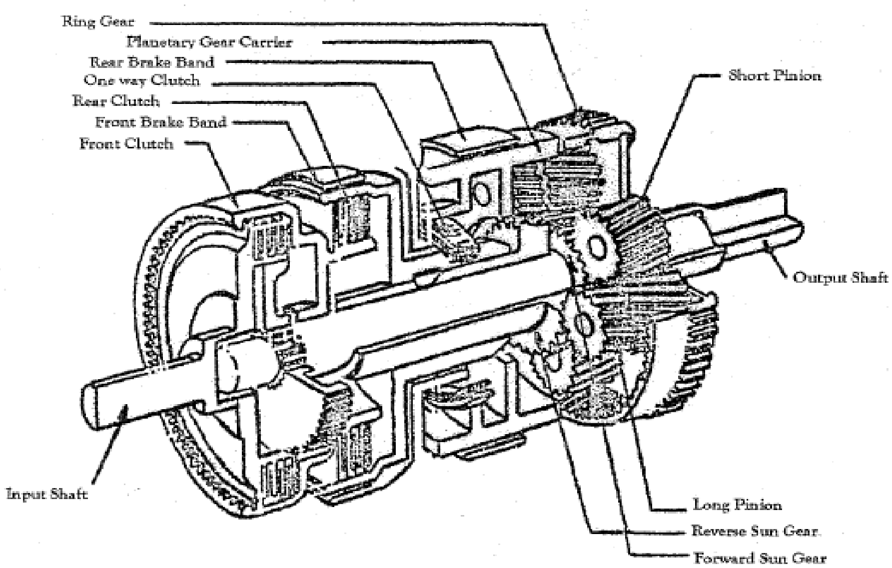
The Borg-Warner Model 35 Automatic Transmission comprises a three element torque converter--coupling and a planetary gear set to provide three forward ratios and reverse.

The planetary gear set consists of two sun gears, two sets of pinions, a pinion carrier and a ring gear.

Power enters the gear set via the sun gears. In all forward ratios, power enters through the forward sun gear. In reverse it enters through the reverse sun gear. Power leaves the gear set by the ring gear, and the pinions are used to transmit power from the sun gears to the ring gear.

In reverse, a single set of pinions is used, which causes the ring gear to rotate in the opposite direction from the sun gear. In forward ratios, a double set of pinions is used to cause the ring gear to rotate in the same direction as the sun gear.

The Carrier locates the pinions relative to the two sun gears and the ring gear, also forming a reaction member for certain conditions. The various mechanical ratios of the gear ser are obtained by the engagement of hydraulically operated multi-disc clutches and brake bands.



Power flow in each ratio is achieved by locking various elements of the planetary gear set, as follows:

1st Gear (Lockup selected)

The front clutch is applied, connecting the converter turbine to the forward sun gear. The rear band is also applied, holding the pinion carrier stationary. The gear set provides the reduction of 2.39 : l. The reverse sun gear rotates freely in the opposite direction to the forward sun gear.

1st Gear (Drive selected)

The front clutch is applied, connecting the converter turbine to the forward sun gear. The one-way clutch is in operation, preventing the pinion carrier from moving opposite to the engine rotation. The gear set again provides the reduction of 2.39 : 1. On the overrun, the one-way clutch unlocks and the gear set freewheels.

2nd Gear (Lockup or drive selected)

Again the front clutch is applied, connecting the converter turbine to the forward sun gear. The front band is applied, holding the reverse sun gear stationary. The pinions now 'walk' around the stationary sun gear and the gear set provides the reduction of 1.45 : l.

3rd Gear (Drive selected)

Again the front clutch is applied, connecting the converter turbine to the forward sun gear. The rear clutch is applied, connecting the turbine also to the reverse sun gear. Thus both sun gears are locked together and the gear set rotates as a unit, providing a ratio of 1: 1.

Neutral and Park

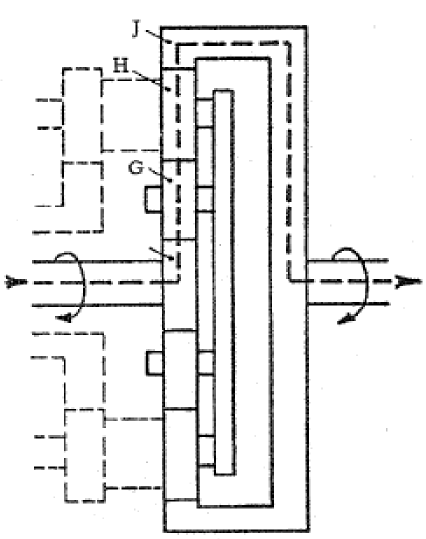
The front and rear clutches are released and no power is transmitted from the converter to the gear set.

Reverse

The rear clutch is applied, connecting the converter turbine to the reverse sun gear. The rear band is applied, holding the pinion carrier stationary, providing a reduction of 2.09 : l.

2. Gear Ratios

1st Gear



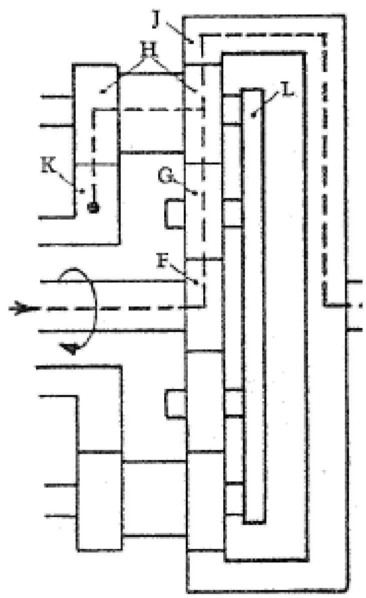
The carrier is held stationary to provide the reaction member and the gears operate as a Simple gear train

$$Gear\ Ratio: \frac{\theta_o}{\theta_i} = \frac{1}{2.39}$$

F	28 Teeth
G	16 Teeth
H	17 Teeth
J	67 Teeth

2nd Gear

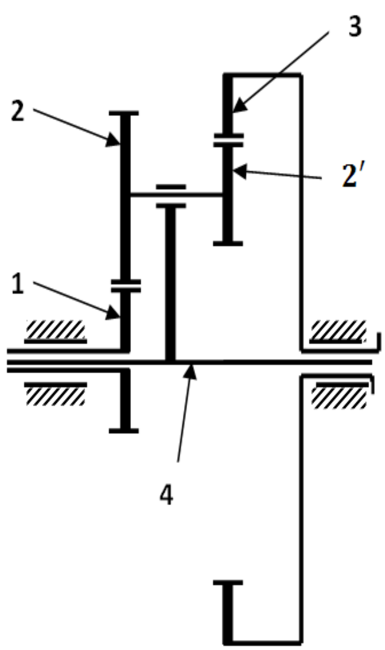
The reverse sun gear is held to that the gears now operate as an epicyclic gear train



F	28 Teeth
G	16 Teeth
H	17 Teeth
J	67 Teeth
K	32 Teeth

$$Gear\ Ratio: \frac{\theta_o}{\theta_i} = \frac{1}{1.45}$$

For an epicyclic gear train shown as following:



$$i_{13}^{4} = \frac{\omega_1 - \omega_4}{\omega_3 - \omega_4} = -\frac{Z_2}{Z_1}\frac{Z_3}{Z_2'}$$

For our transmission show as above:

$$i_{FJ}^{L} = \frac{\omega_F - \omega_L}{\omega_J - \omega_L} = -\frac{Z_G}{Z_F}\frac{Z_H}{Z_G}\frac{Z_J}{Z_H} = \frac{67}{28} \qquad (1)$$

$$i_{FK}^{L} = \frac{\omega_F - \omega_L}{\omega_K - \omega_L} = -\frac{Z_G}{Z_F}\frac{Z_H}{Z_G}\frac{Z_K}{Z_H} = -\frac{32}{28} \qquad (2)$$

Hence: $\frac{-\omega_L}{\omega_J - \omega_L} = -\frac{67}{68}\frac{28}{32}$

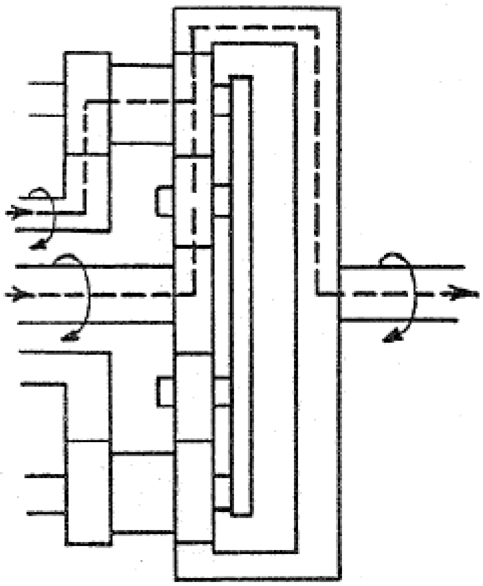
$$or \quad \omega_L \frac{32}{67} = \omega_J - \omega_L;\ \omega_J = \frac{99}{67}\omega_L$$

From (2) $\omega_F - \omega_L = \frac{32}{28}\omega_L;\ \omega_F = \frac{60}{28}\omega_L$

Therefore $i_{FJ} = \frac{\omega_F}{\omega_J} = \frac{60}{28}\frac{67}{99} = 1.45021645$

So: $\frac{\theta_o}{\theta_i} = \frac{1}{1.45}$

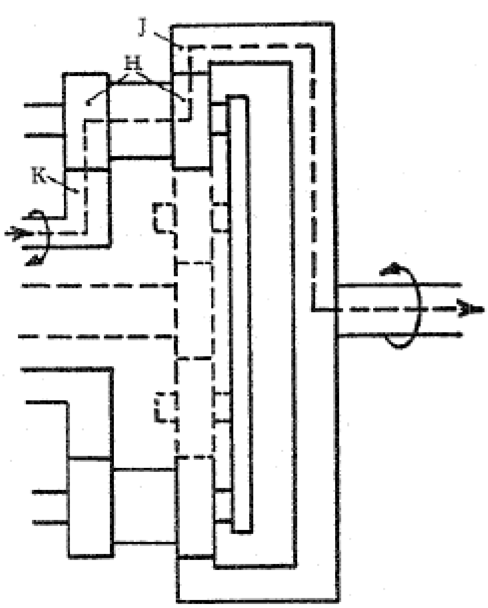
3rd Gear



Both sun gears are locked together and the gears set rotates as a unit.

$$Gear\ Ratio: \frac{\theta_o}{\theta_i} = \frac{1}{1}$$

Reverse Gear



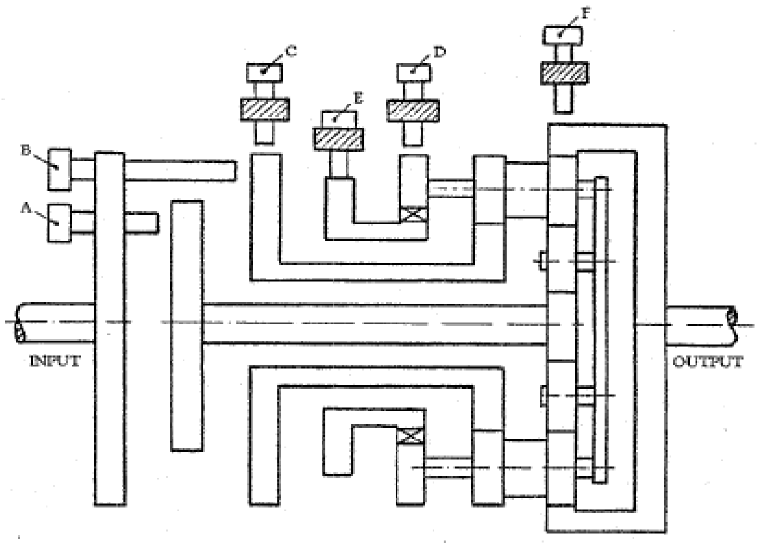
With the reverse gear engaged, power is applied to the reverse sun gear. The planet carrier is held stationary so that the planet gears rotate the ring gear in the opposite direction to the reverse sun gear.

$$Gear\ Ratio: \frac{\theta_o}{\theta_i} = \frac{1}{2.09}$$

H	17 Teeth
J	67 Teeth
K	32 Teeth

3. Experimental Procedure

Pins and slotted plates represent the multi-disc clutches and brake bands. The various gear ratios of the gear set may be obtained by inserting the appropriate pins as indicated below.



	A	B	C	D	E	F
Lockup 1/Drive 1	*			*	√	
Lockup 2/Drive 2	*		*			
Drive 3	*	*				
Reverse		*		*		
Neutral						
Park						*

Note:

1. Lose all pin and turn input shaft and output shaft, make sure input shaft disk and output shaft disk indicate to 0° , then lock pins for each case
2. Turn input shaft one turn (360°), read output disk (degree).
3. Fill out following table

	Input θ_i (degree)	Output θ_o (degree)
Lockup 1/Drive 1	360	
Lockup 2/Drive 2	360	
Drive 3	360	
Reverse	360	

4. Results

According to power flow and gear ratio figures for each case, referring to 2nd gear ratio calculation, derive and calculate gear ratios for 1^{st}, 3^{rd}, and reverse shift. Compare them with your experimental results.

EXPERIMENT 6

Static and Dynamic Balancing

1. Objective:

The objectives of this experiment are:

- Understanding the concept of static and dynamic balancing
- Understanding unbalance torque
- Justifying theoretical calculation for balancing with experiment
- Balancing the shaft by the four given masses.

2. Introduction

Unbalanced dynamic forces effects have profound influence on the working and of rotating machinery like turbines, compressors, pumps, motors etc. These forces act directly on the bearings supporting the rotor and thus increase the loads and accelerate the fatigue failure. These unbalanced forces induce further mechanical vibrations in the machinery and connected parts thereby creating environmental noise problem through radiation of sound. Hence it is desirable to balance all such uncompensated masses and thus reduce the effect of unbalance forces in a dynamics balancing machine.

Balancing is the technique of correcting or eliminating unwanted inertia forces which cause vibrations, which at high speeds may reach a dangerous level. An important requirement of all rotating machinery parts is that the rotation axis coincides with one of the principal axis of inertia of the body. After a roll is manufactured, it must be balanced to satisfy this requirement, especially for high speed machines. The condition of unbalance of a rotating body may be classified as static or dynamic unbalance.

2. 1. Static Unbalance

An idler roll is statically balanced if the roll doesn't rotate to a "heavy side" when free to turn on its bearings. Thus, the roll's center of gravity is on the axis of rotation. Static unbalance (Figure 6.1) creates a centrifugal force when rotating which causes deflection of the roll. Idler rolls are sometimes static balanced only when the roll operates at slow speeds.

The static unbalance usually happens because of errors in the manufacturing tolerances of the rotating parts. Therefore, static imbalance is essentially a weighing process in which the part is acted upon by either gravitational or centrifugal force. This type of unbalance could be easily reduced or removed by static balancing.

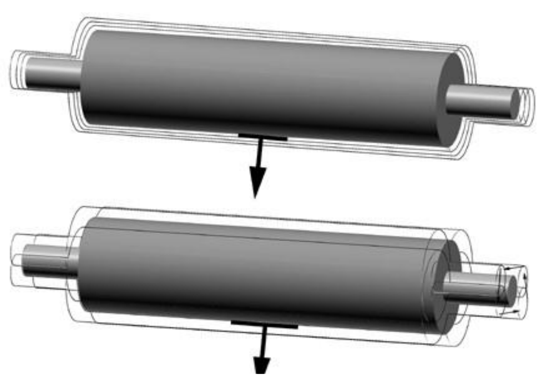


Figure 6.1: Static (or force) Unbalance

2. 2. Dynamic Unbalance

An idler roll may be in perfect static balance and not be in a balanced state when rotating at high speeds. A dynamic unbalance is a “couple” or twisting force in two separate planes, 180 degrees opposite each other (Figure 6.2). Because these forces are in separate planes, they cause a rocking motion from end to end. A roll that is unbalanced will cause 1) machinery vibrations, 2) web flutter, and 3) a decrease in bearing life due to unnecessary forces.

To dynamically balance a roll, it must first be statically balanced. Then, the roll must be rotated to its operating speed and have the dynamic unbalance eliminated by adding or subtracting weight. The determination of the magnitude and angular position of the unbalance is the task of the balancing machine and its operator. Balancing machines are provided with elastically supported bearings in which the idler roll may spin. Because of the unbalance, the bearings will oscillate laterally, and the amplitude and phase of the roll are indicated by electrical pickups and a strobe light.

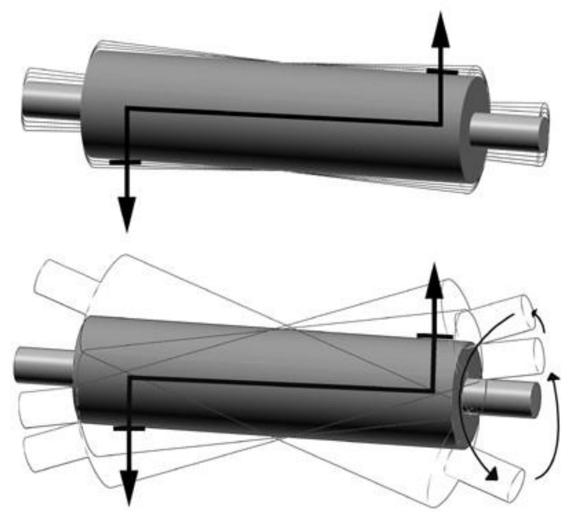


Figure 6.2: Dynamic (or couple) Unbalance

Figure 6.3 shows a long rotor which is to be mounted in bearing A and B. We might suppose that two equal masses m_1 and m_2 are placed at opposite ends of the rotor and at equal distances r_1 and r_2 from the axis of rotation. Since masses are equal on opposite sides of the rotational axis, the rotor is statically balanced in all angular positions. But, if the rotor is caused to rotate at an angular velocity ω rad/sec, the centrifugal forces $m_1r_1\omega^2$ and $m_2r_2\omega^2$ act, respectively, at m_1 and m_2 on the rotor ends. These centrifugal forces produce the equal but opposite bearing reactions F_A and F_B and the entire system of forces rotate with the rotor at the angular velocity ω. Thus the rotor is to be statically balanced and, at the same time, dynamically unbalanced.

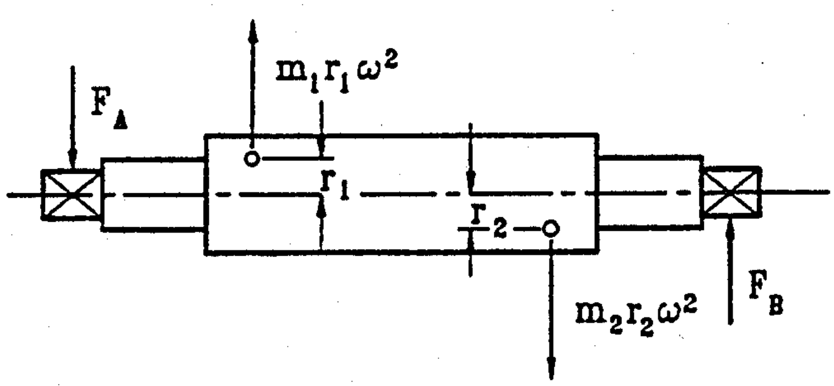


Figure 6.3: Dynamically Unbalanced Rotor

3. Principle and Theory of Operation

Consider a body of mass M rotating with a uniform angular velocity ω about **O** with eccentricity ***e***, as shown in Figure 6.4. The centrifugal force F_c acting on the axis of rotation is $Me\omega^2$. This force is therefore very sensitive to speed and hence there is a need to reduce this force either by operating at lower speeds or by decreasing the eccentricity as shown in Figure 6.5.

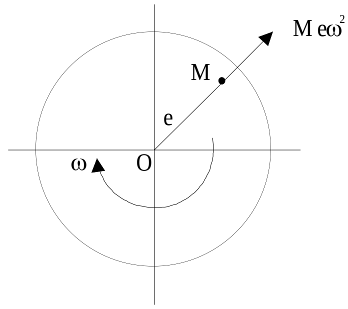


Figure 6.4: Unbalanced Disc

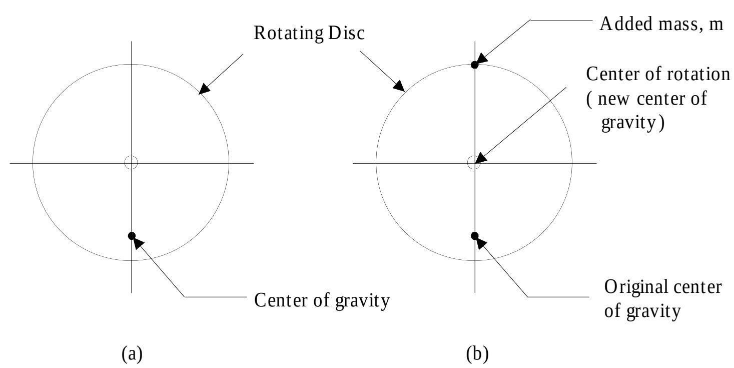


Figure 6.5: Illustration of The 'Simplest' Method of Static Balancing

In general, it is desirable to make ***e*** as low as possible. If the rotor thickness to diameter ratio is less than 0.5 and speed are below 1000 rpm, the rotor can be single plane balanced - otherwise two-plane balancing is necessary. In the single plane balancing technique, with a rotor of mass, m_i and radius r_i from the axis of rotation and lying in the same plane, the condition for static balance is used.

$$\sum m_i \tilde{r}_i = 0 \tag{6.1}$$

where i = 1, 2, ... which denotes the total number of masses and m denotes the mass. The vector $\tilde{r}_i$ represents the eccentricity e of the mass m_i from the axis of rotation.

When the bodies are rotating in several planes, the condition for dynamic balance has to be satisfied in addition to that for static balance. This is given by:

$$\sum m_i \tilde{z}_i \times \tilde{r}_i = 0 \tag{6.2}$$

where $\tilde{z}_i$ is the axial coordinate vector of the mass m_i measured for a chosen datum. In the two-plane balancing technique, instead of satisfying Equations (6.1) and (6.2) explicitly, Equation (6.2) is used with two different datum planes for $\tilde{z}_i$. Mathematically, if the distance between these two plane is $\tilde{z}_o$, then

$$\sum m_i(\tilde{z}_i + \tilde{z}_o) \times \tilde{r}_i = 0 \tag{6.3}$$

It is therefore, clear that Equations (6.2) and (6.3) imply the satisfaction of Equation (6.1). Conceptually, it means that if a system of bodies rotating in several planes is in dynamic balance with respect to two different datum planes, then the system is also in static balance. This is the principle of the two-plane balancing technique.

4. Description of Experimental Apparatus

Figure 6.6 shows the Static and Dynamic Balancing Apparatus. It consists of a perfectly balanced shaft with four rectangular blocks clamped to it. The shaft is mounted in ball bearings and it is driven by a 12 volt electric motor through a belt and pulley drive. The shaft assembly is mounted on a metal plate resting on four resilient rubber supports, which allow the mount to vibrate when the shaft is not balanced.

The rectangular blocks can be clamped to the shaft at desired out-of-balance moments by means of discs having eccentric holes of various diameters. The discs are fixed to the blocks by hexagon socket set screws. Any longitudinal and angular position of a block relative to the shaft can be set by linear and protractor scales provided. Adjacent to the linear scale is a slider which can be pushed against the block to read its longitudinal position. The slider also serves as a datum stop against which the blocks can be held when reading their angular position on the shaft.

The out-of-balance moments are measured by fitting the extension shaft and pulley to the main shaft. Each rectangular block is then clamped to the shaft in succession. A cord with a weight bucket at each end is hung on the pulley and bearing balls are placed in the bucket until the block has turned through 90°. The out-of-balance moment is proportional to the number of balls required to turn the block.

A Perspex dome serves as the safety cover. The shaft cannot be driven unless the dome is in position which is achieved by micro switches actuated by the dome. The motor switch on the front panel is spring loaded so that the motor cannot be left running. The motor requires a power supply of 12 volts at 2 amperes which is provided by E66/E90 speed controller.

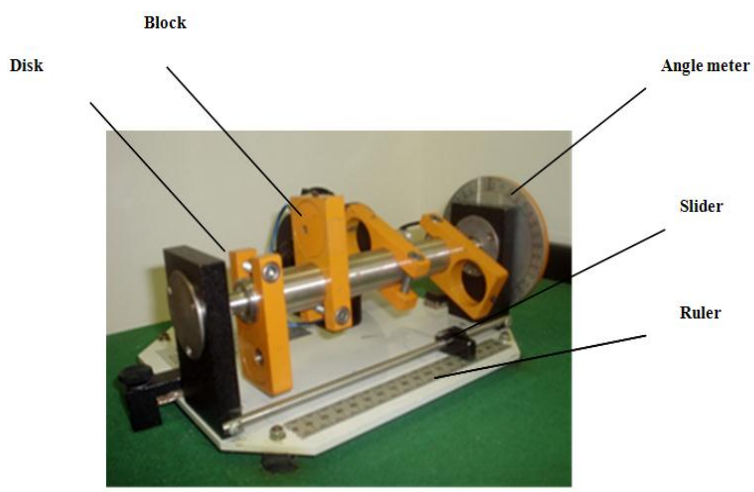


Figure 6.6: Static and Dynamic Balancing Apparatus

5. Experimental Procedure

5. 1. TEST 1: Static Balancing

1. Looking at the shaft from the side, the masses will be as shown in figure 6-7, each mass has an angle θ with horizontal

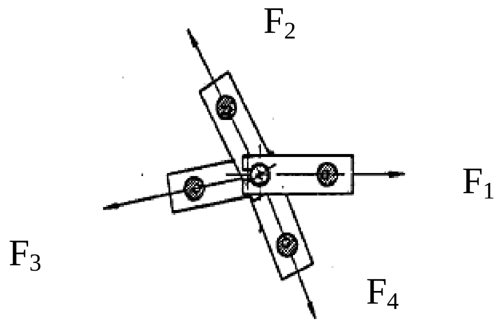
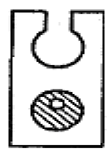
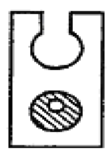
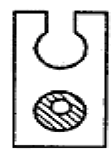
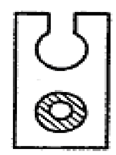


Figure 6-7 Shaft view from the side

2. The masses forces are given by the following table 6-1:

The masses values Table 6-1

				
BLOCK	1	2	3	4
Wr (balls)	88	82	74	64

3. In order to balance the shaft statically the sum of the forces will be equal zero as the following equations:

$$\sum F=0$$

$$F_1*\cos\theta_1+F_2*\cos\theta_2+F_3*\cos\theta_3+F_4*\cos\theta_4=0 \quad (1)$$

$$F_1*\sin\theta_1+F_2*\sin\theta_2+F_3*\sin\theta_3+F_4*\sin\theta_4=0 \quad (2)$$

4. Since we have just two equations with four unknown angles, we assume :

$$\theta_1=0^o, \quad \theta_2=90^o$$

5. Solving the two equations or using force polygon by AutoCAD, to find the θ_3, θ_4.

5. 2. TEST 2 Dynamic balancing

1. Looking for the shaft from in front, the masses create the forces as shown in figure 6-8, each mass has an arm X create a momentum.

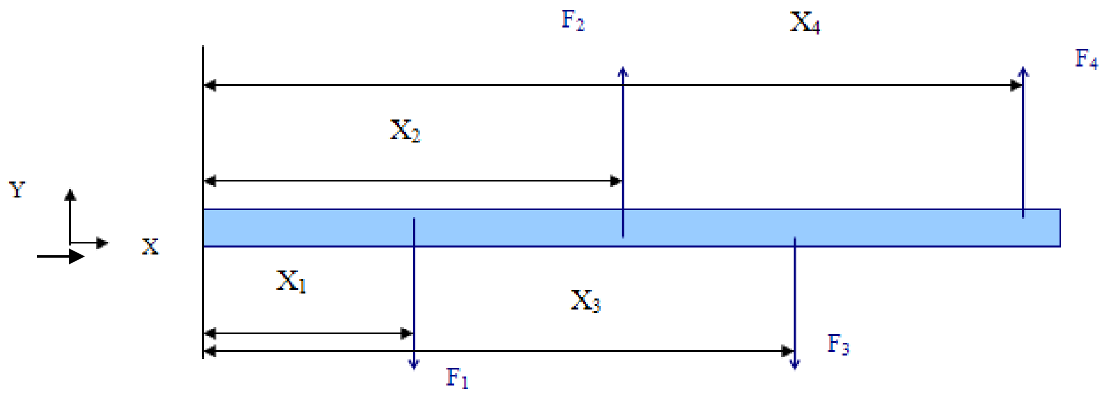


Figure 6.8: In front shaft view

2. In order to balance the shaft dynamically the sum of the momentum will be equal zero as the following equations:

$$\sum M=0$$

$$F_1*\cos\theta_1*X_1+F_2*\cos\theta_2*X_2+F_3*\cos\theta_3*X_3+F_4*\cos\theta_4*X_4=0 \quad (1)$$

$$F_1*\sin\theta_1*X_1+F_2*\sin\theta_2*X_2+F_3*\sin\theta_3*X_3+F_4*\sin\theta_4*X_4=0 \quad (2)$$

3. Since we have just two equations with four unknown arms, we assume:

$$X_1=50 \text{ mm}, X_2=100 \text{ mm}$$

4. Solving the two equations or using momentum polygon by AutoCAD, to find the X3, X 4.

TABLE 6. 2

Block	1	2	3	4
Mass	88	82	74	64
Angle θ(º)	0	90		
Arm X (mm)	50	100		

6. Typical Calculations

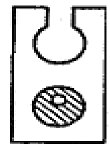
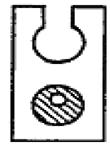
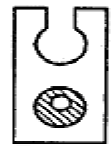
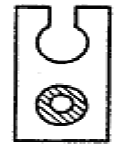
The basic equations that are used for balancing purposes are:

$$\sum W_i r_i = 0 \quad (6.3)$$

$$\sum a_i W_i r_i = 0 \quad (6.4)$$

Suppose that block (1) is placed 17 mm from the left end of the shaft at zero angular displacement and that block (2) is placed 100 mm from it at 120°. The measured out-of-balance moments are as follows:

TABLE 6. 3: OUT-OF-BALANCE MOMENTS

				
BLOCK	1	2	3	4
Wr (balls)	88	82	74	64

It is first necessary to draw the moment polygon of Wr values as shown in Figure 6.8 to determine the angular positions of blocks (3) and (4). W_1r_1 and W_2r_2 are known in both magnitude and direction. The vector W_1r_1 has been drawn at positive X-direction ($\theta = 0$). The lengths of vectors W_3r_3 and W_4r_4 are known and arcs can be drawn from the ends of W_1r_1 and W_2r_2 to get the directions of the unknown vectors.

Figure 6.9 shows the diagram of the angular positions and the corresponding longitudinal locations of the blocks on the shaft are 17 mm for the first, 117 mm for the second block.
.To find the longitudinal positions of the other two blocks we designate distance of block (3) by a_3 and distance of block (4) by a_4 measured from block (1); so block (1) is the reference and will not appear in calculations.

Draw a vector $a_2W_2r_2$ = 100 (82) units long parallel to r_2 and vectors $a_3W_3r_3$ and $a_4W_4r_4$ parallel to r_3 and r_4 respectively so that the moment polygon is closed. The lengths of vectors $a_3W_3r_3$ and $a_4W_4r_4$ can be measured and the magnitudes found by using the scale factor. From these a_3 and a_4 can be calculated.

Notice that the sense of vector $a_3W_3r_3$ is reverse. In order to maintain vector $a_3W_3r_3$ the only possible solution is to reverse a_3. So from the vector polygon (triangle) it follows:

a3 = -12 mm
a4 = 124 mm

This means that block (3) should be located 5 mm from the left end of the shaft. The blocks should be positioned as follows:

Block	Angular Position (Deg)	Longitudinal Position (mm)
(1)	0	17
(2)	120	117
(3)	190	5
(4)	294	141

The values of a_3 and a_4 can be found analytically using complex vector approach.
Real and imaginary components yield:

$100(82) \cos 120° + (74)\, a_3 \cos 190° + (64)\, a_4 \cos 294° = 0$
$100(82) \sin 120° + (74)\, a_3 \sin 190° + (64)\, a_4 \sin 294° = 0$

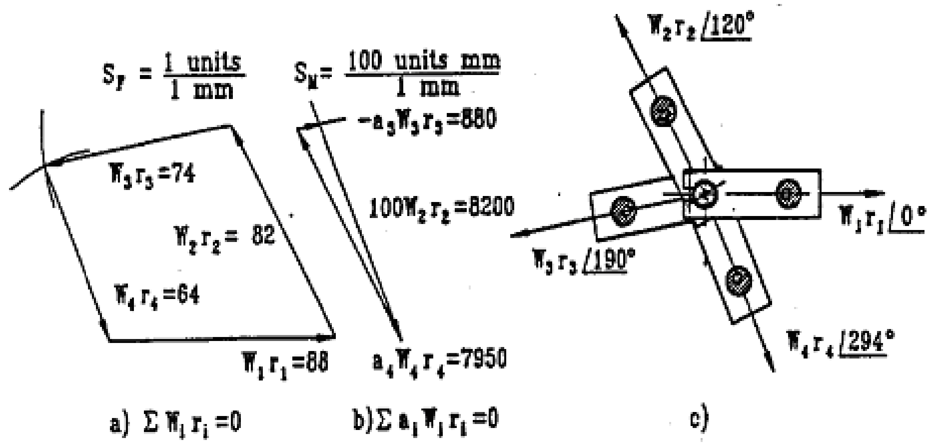
which reduce to

$4100 - 72.88\, a_3 - 26.03\, a_4 = 0$
$7101.4 - 12.85 a_3 - 58.47\, a_4 = 0$

Solving the two equations gives: $a_3 = -11.94$mm; $a_4 = 123.96$mm

The values compare very well with those obtained graphically.

In order to obtain independent results it is suggested that Wr values of the blocks are varied by using different positions of the discs with eccentric holes. The angular displacements between blocks (1) and (2) may also be varied.



a) Force Polygon
b) Moment Polygon
c) Angular positions of the blocks

Figure 6.9: Moment Polygon of Wr

EXPERIMENT 7

Machine Fault Simulator (MFS)

1. Theory

Refer to experiment number 6.

2. Description of Experimental Apparatus

Figure 7.1 shows the machine fault simulator. The rotor is driven by a variable speed motor via a flat belt and the rotor rotational speed is captured through a digital tachometer. The vibration due to the unbalanced rotor is measured and fed directly into the on-board processor of the machine.

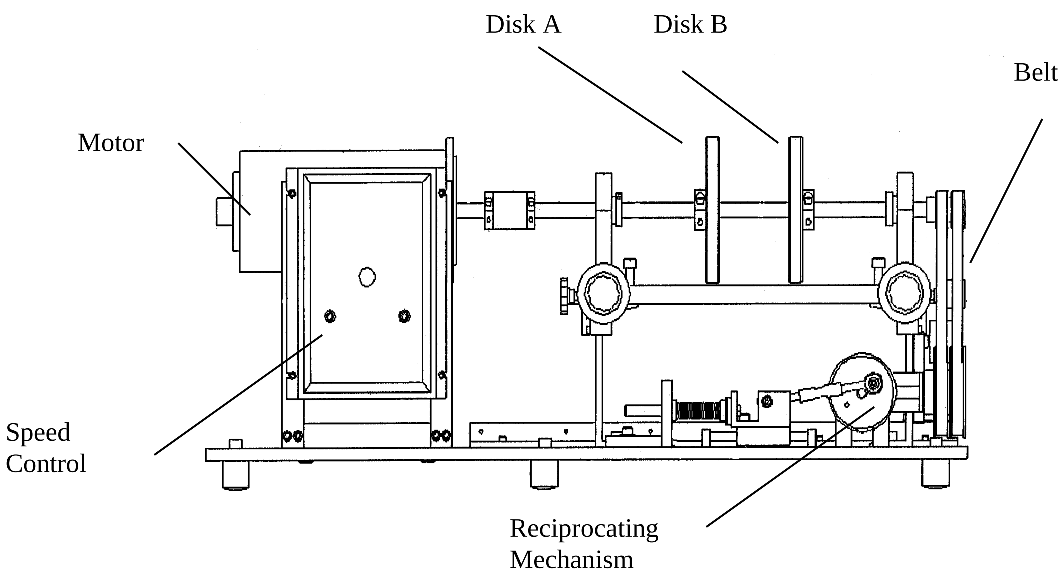


Figure 7.1: Machine Fault Simulator

3. Objective:

In this experiment we will study the reaction of the shaft and the motor when the shaft is balanced, and when it is unbalanced.

4. Experimental Procedure:

1) **Run the Vibro-Quest Software**:
   - Define a "**New Project**" (under root)
   - Fill up the window, select "**Project name**", click "**Next**"
   - Select "**None**" from the menu on the right side, click "**Next**"

- Review the table, (do not change the default), click "**Next**"
- Review the table, check the setting data, click "**Next**"
- Click "**Done**"
- Review the information provided, if they are not ok "**Go back**" to modify the data, then click "**Finish**"

2. Select "**Data**" from the toll bar on the computer.
3. Name the "**Test Title**" in the window. Insert the parameters used in the test and click "**Next**".
4. Review the information provided in the window and click "**Next**".
5. Chose 2000 as **Frequency limit**, 1600 for **Space line**. Leave the rest information as defaulted and "**GO DAQ**"

2) . Running the Machine Fault Simulator

Select the required speed (rpm) change it to frequency (Hz) using the following relation: $f(Hz) = 2\pi n(rpm)/60$

1. Run the machine using speed control system at desired speed
2. Wait about 15 seconds to stable the system
3. Click on" **START RECORDING**"
4. When the recording is finished save the file under the root of "**Data"** of base line at the subdirectory that you want to compare with the other data (for example if you are running the machine at 20 Hz, save the your file under 20 Hz subdirectory)
5. Now select the "**Project name"** from the left menu, all the relevant tests will appear at the right table under the "**Test Explorer**"
6. To compare the data from different files: Hold down the "**Shift**" key and select any two interested files that you are going to compare
7. Click on "**Compare**" to observe the difference between the unbalanced system with a base system
8. To observe more clearly the difference between the frequency responses of the different test click on "**Overlay**"

TEST 1: Imbalance Effects on Vibration response

- Install the defined weight in one of the taped hole in rotor disk A and tight it securely with a nut
- Close the cover of MFS
- Change the motor speed and record vibration level at each bearing. For this purpose you don not need to define new project for each speed. define a new project(follow steps 1-6 from section 3) then follow steps 1-2 for each speed from section 4
- Measure the average level of amplitude at each speed and Plot it against the speed
- Repeat steps 2-5 for 2 different weights at 2 different radius and angles

TEST 2: Balancing the Imbalance Rotor

- Add weight at different radius and angles using the “sample calculation” to balance the rotor.
- If the rotor is balanced, define a “**New project**” and follow steps 3-8 of Section 4
- Fill Table 7. 1

TABLE 7. 1

Unbalance weight on disc A: ____________ angular position: _______________

Mass Added on disk B, gr	r (mm)	θ	Amp base/Amp New %

EXPERIMENT 8

DETERMINATION OF SPUR GEAR EFFICIENCY

1. Objective

The main objective of the experiment is to determine the efficiency of the Spur gear and worm gear unit.

2. Introduction and theoretical background

2.1 Pinion gear

Two intermeshed toothed wheels make up a pinion gear. This type of gear permits a positive transmission of motion and torque. Wheel pairs are available in different shapes and shaft configurations. Figure 1 explains the various types of gears and their arrangements.

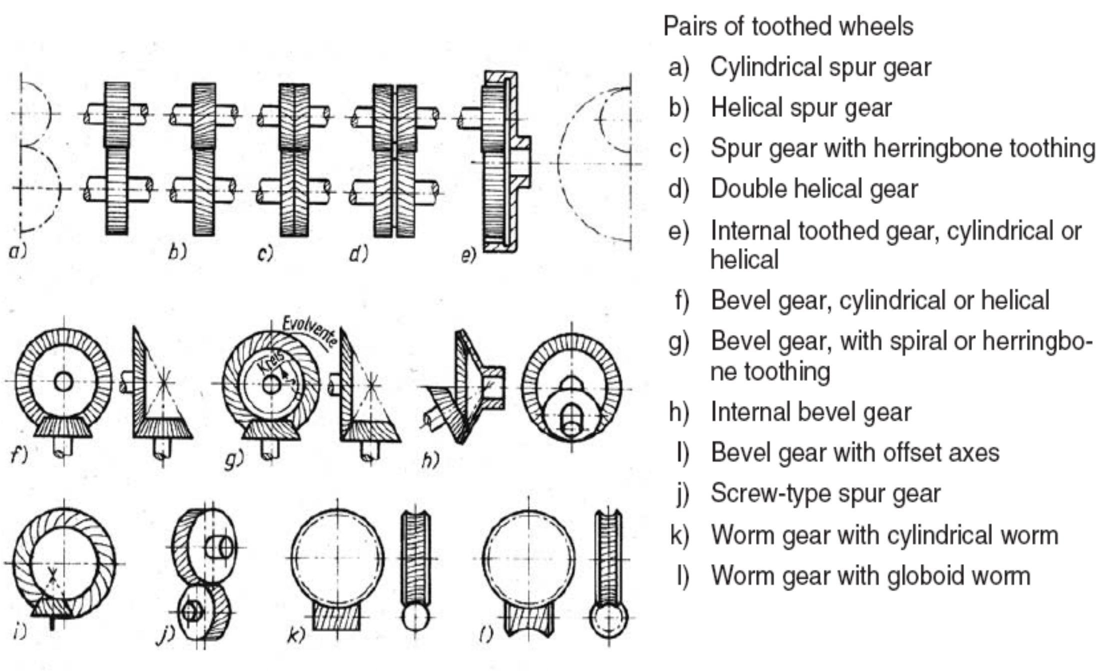


Fig.8. 1 Various types of gear arrangements

2.2 Worm gear

A worm gear is a screw-type transmission unit whose axes generally intersect at right angles. The worm and wheel make contact on a straight line. Normally, the worm has a cylindrical core and the wheel globoid toothing. Units with a very high performance consist of a globoid worm and globoid wheel. A worm gear with a cylindrical worm has the following special features:

- High load capacity compared with spur gears, due to linear contact.
- Low-noise operation and high absorption of vibrations
- Wide transmission range down to low i<110
- High efficiency at high transmission ratios; high efficiencies($\eta \leq 98$ %) can be achieved with very sophisticated designs under favorable operating conditions; a decrease in pitch angle (high transmission ratio) or speed is accompanied by a corresponding decrease in efficiency (to $\eta \leq 50$ %)
- Self-locking operation.
- Smaller and lighter design compared with spur bevel gear units possessing high transmission ratios.

2.3 Basic definitions:

Drive torque:

The drive torque is the product of the force F and the lever arm l on which the force acts.

$$M = F \times l \qquad (1)$$

M is in Nm, F is in N and l in m.

Drive power:

The drive power of a rotating shaft is the product of the torque M and angular frequency ω.

$$P = M \times \omega \qquad (2)$$

$$\text{and } \omega = \frac{2\pi n}{60} \qquad (3)$$

P is in W, n is in rpm.

Efficiency:

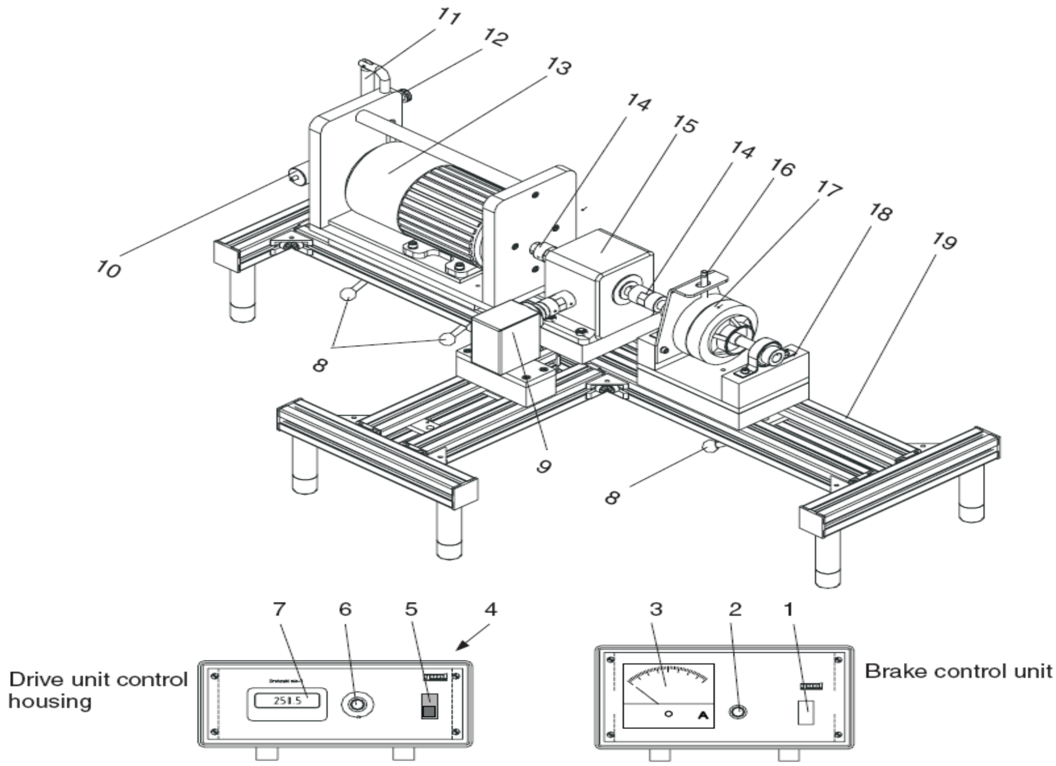
The efficiency is defined as the ratio between the output and input powers. It has a maximum theoretical value of 1.

$$\eta = \frac{P_{out}}{P_{in}} \qquad (4)$$

where speed $n_2 = \frac{n_1}{i}$.

3. Experimental set-up

Figure 2 shows the complete view of the experimental set up.



1	ON/OFF switch for the magnetic brake	11	Dynamometer
2	Potentiometer excitation current	12	Knurled screw for fastening the dynamometer
3	Excitation current indicator	13	DC motor
4	Switch for direction of rotation (rear panel)	14	Coupling
5	ON/OFF switch for motor control unit	15	Spur gear
6	Potentiometer for speed adjustment	16	Brake lever arm
7	Speed indicator	17	Magnetic powder brake
8	Clamping levers	18	Brake bearing
9	Worm gear	19	Frame
10	Balancing weight		

Fig.8. 2 Complete view of GUNT AT 200 experimental set up

The modules comprising the drive unit, spur gear, worm gear and magnetic powder brake are mounted on a profile frame. The DC shunt motor is designed for right-hand and left-hand rotation. The drive unit is electrically powered via control housing. The control unit adjusts the DC machine's speed via its armature voltage. Its target speed is set by means of a potentiometer on this housing. Its actual speed is measured and indicated by means of an inductive proximity switch and evaluation unit. The speed is measured inductively by a contactless sensor disc and indicated by a digital display element on the control unit. Electronic thyristor speed control with I x R compensation provides a high torsional rigidity. The reaction torque exerted on the drive housing is measured by means of a spring force meter connected to a lever arm.

The transmission units consist of a 2-stage spur gear with transmission ratio i = 13.5 and a single-stage worm gear with transmission ratio, i = 14.The transmission torque can be determined on the drive side as well as the brake side. To facilitate adjustment of the brake torque, the brake characteristic (current torque) is recorded in a preliminary experiment. Moments are determined through power measurements (spring balance) with a known lever arm. The moments, measured input speeds and transmission ratios are used to determine power and efficiency.

The magnetic powder coupling consists of two independently mounted rotors, i.e. a primary and a secondary rotor, both furnished with ball bearings. The primary rotor also serves as a coil carrier. If one of these two rotors is deactivated, the magnetic powder coupling can also be used as a brake. The air gap between the two rotors contains a special magnetic powder. If a direct voltage is applied to the excitation winding, the powder aligns itself with the resulting magnetic field lines to form a compact mass providing a frictional link between the primary and secondary rotors. The value of the torque depends on the adjusted current. When the current-proportional moment is exceeded, slippage occurs without any transition.

4. Experiments procedure:

As shown in Figure 8.2 the complete view of the experimental set up, for this experiment there is input as the motor speed and the output as excitation current, so that there is two steps for this experiment,

After making sure spur gear is connected as shown in Figure 8.3:

1) Fix the output excitation current at I= 50 mA, and change the speed of the motor as shown in the table (1), each time measure the motor force F_1, and the brake force F_2

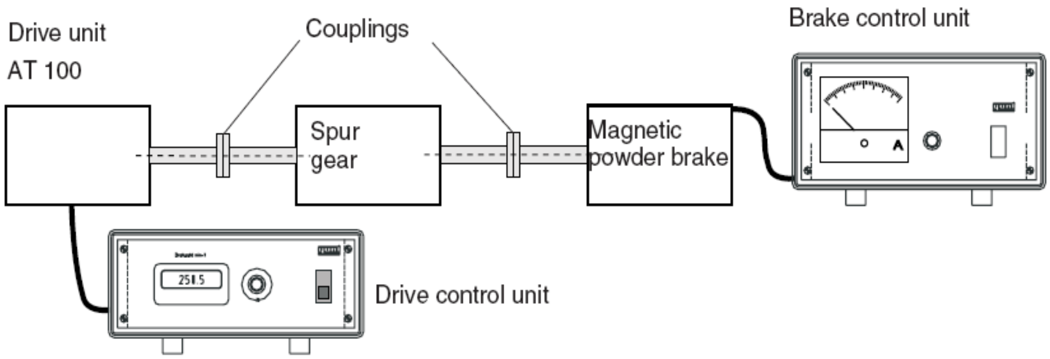


Figure 8.3 Configuration of spur gear unit experimental set up

Measurement data to determine the efficiency of Spur gear unit, Table (1) I = 50mA

Sl.No.	Motor speed (n_1) rpm	Motor holding force (F_1) N	Brake holding force (F_2) N	Efficiency (η)
1	500			
2	1000			
3	1500			
4	2000			
5	2500			

In order to find out the spur gear efficiency, we go through the following equations:

- The general equation for the spur gear efficiency is:

$$\eta = \frac{P_{out}}{P_{in}}$$

- The drive power of a rotating shaft is the product of the torque M and angular frequency ω. $P = M \times \omega$

- The drive torque is the product of the force F and the lever arm l on which the force acts.

$$M = F * Arm$$

When the arm for the motor Arm_1=25 mm, and for the brake Arm_2=50 mm

And the angular velocity from the following equation:

$$\omega = \frac{2\pi n}{60}$$

In order to find the speed for the brake we use this ratio, assuming i= 13.5

$$n_2 = \frac{n_1}{i}$$

2) Fixing the input n_1= 1500 rpm, and changing the output and filling table (2):

Recorded values of the excitation current and the force on the lever arm table (2)

Speed : n_1= 1500 rpm	
Excitation current , I (mA)	Force , F_2, on the lever arm (N)
50	
70	
90	
110	
130	
150	
130	
110	
90	
70	
50	

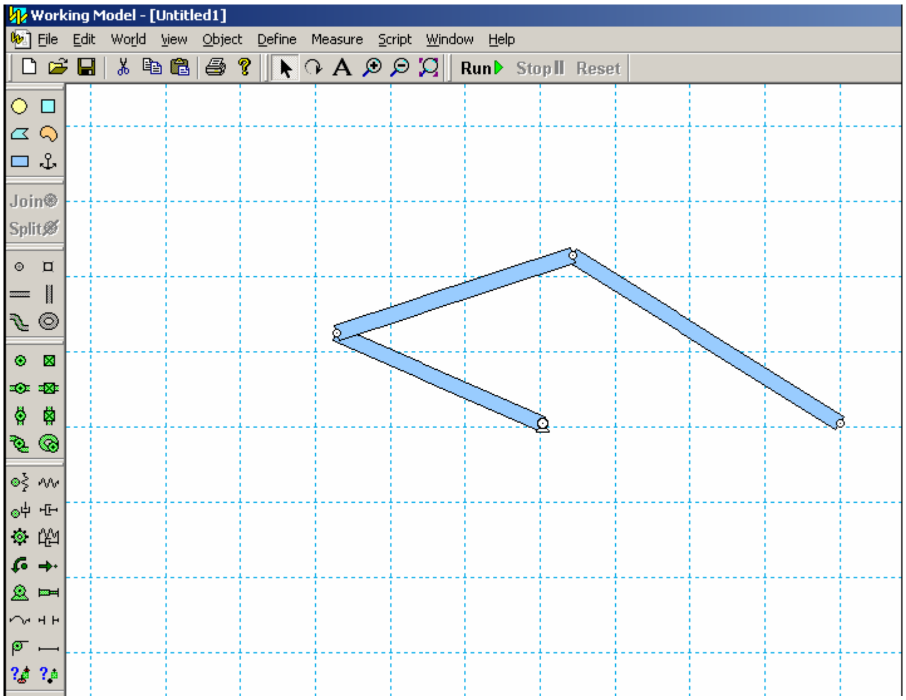
5. Experiments Results:

1) Plot the characteristics curve between the current I and the force on the lever arm F2.
2) Plot the characteristics curve between the current I and the torque M.
3) Determine the efficiency of the spur gear unit. Comment on the errors on the efficiency if the calculated efficiency deviates from the realistic values of 80 % - 90 %.

EXPERIMENT 9

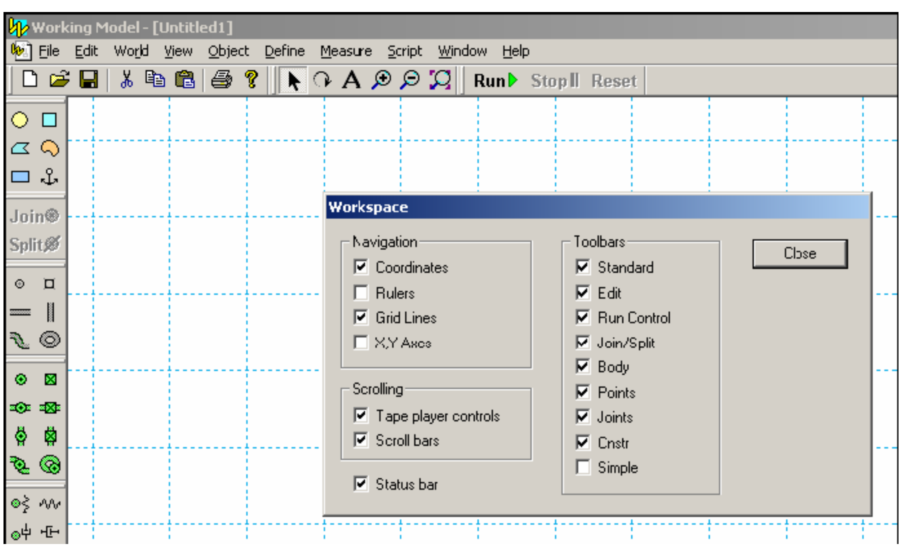
ANALYSIS OF LINKAGE MECHANISM

Try to build a linkage mechanism as the figure below:

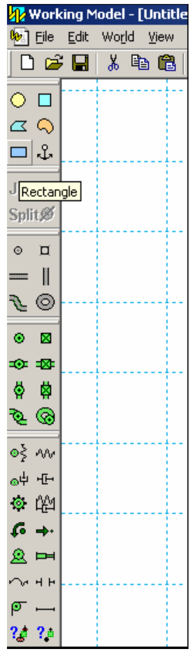


Steps:

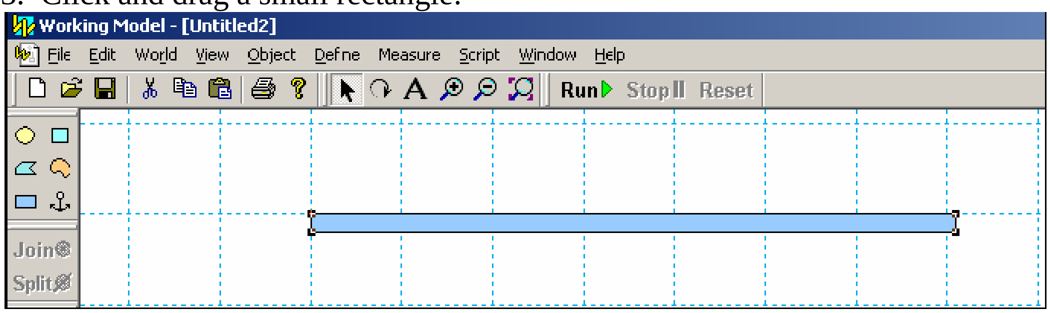
1. Turn on grid line from View-workspace-grid lines as below:



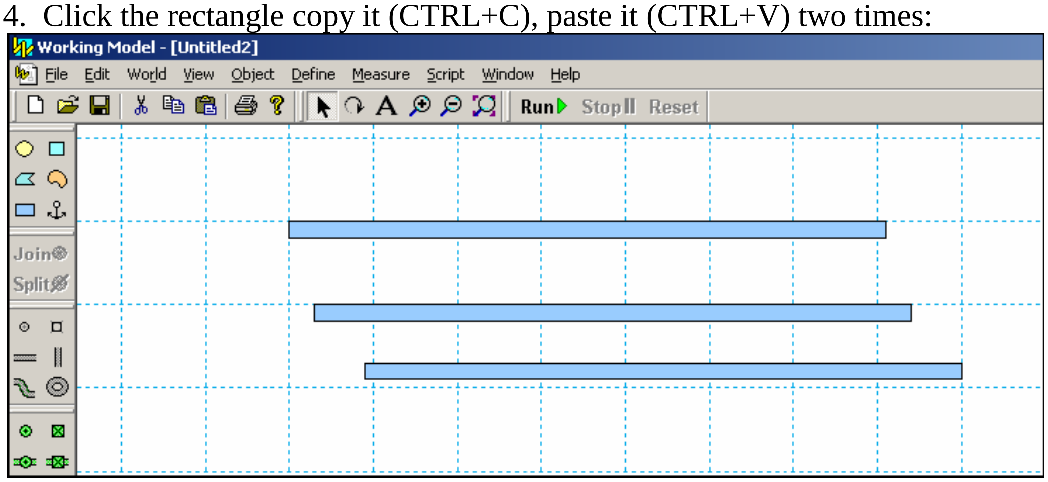
2. Select rectangle tool:



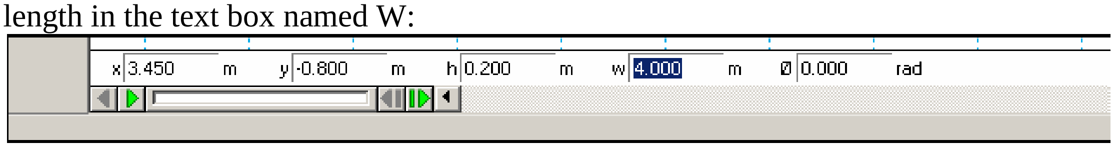
3. Click and drag a small rectangle:



4. Click the rectangle copy it (CTRL+C), paste it (CTRL+V) two times:

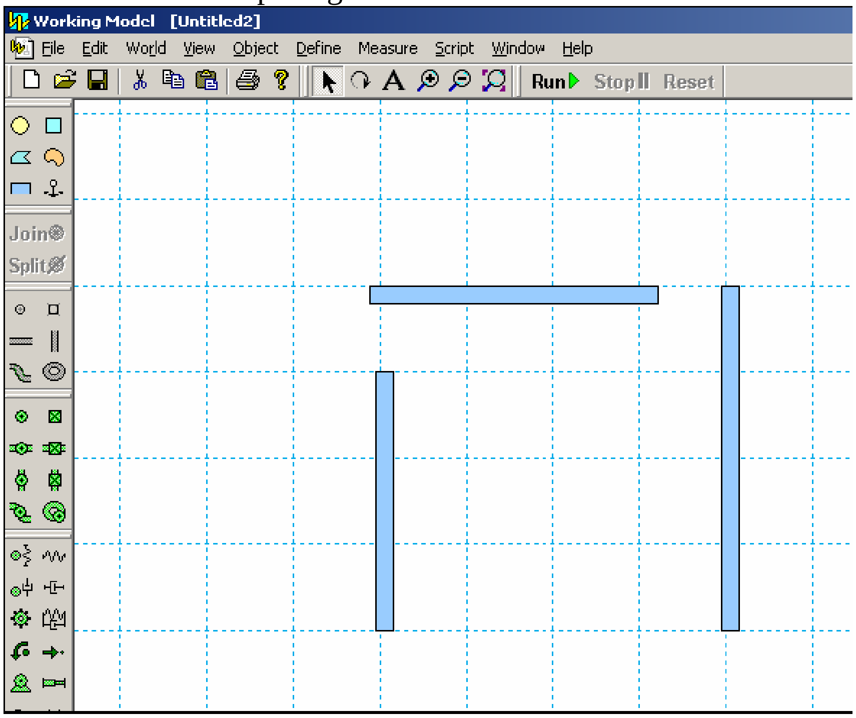


5. Change the length of each rectangle by selecting it, and writing down the desired length in the text box named W:

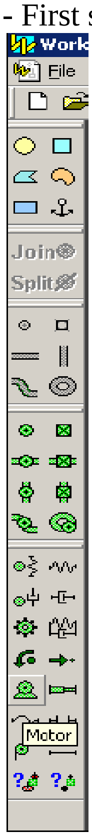


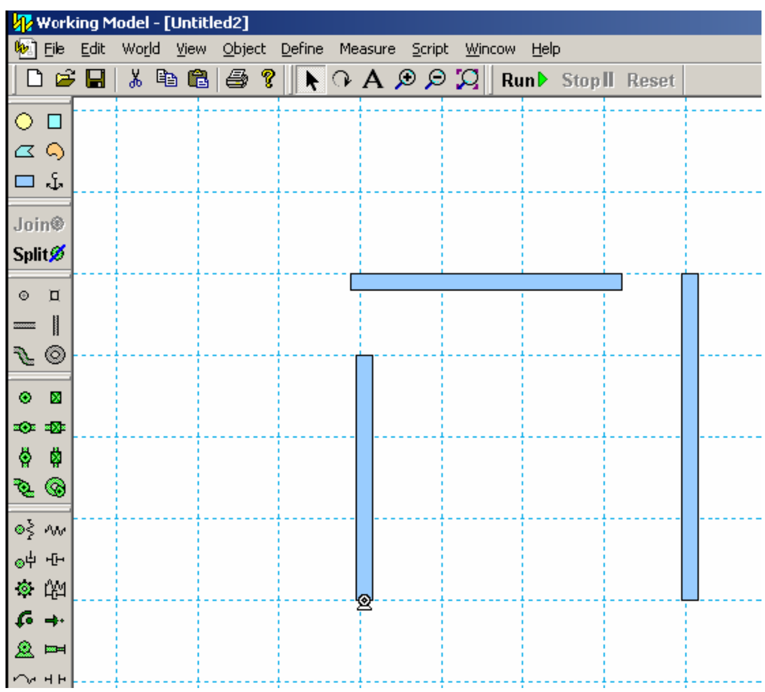
Make the length as (3 – 3.32 - 4)

6. Use the rotate tool and the select tool to arrange the rectangles:
Make sure that the spacing is 4 units as shown below:



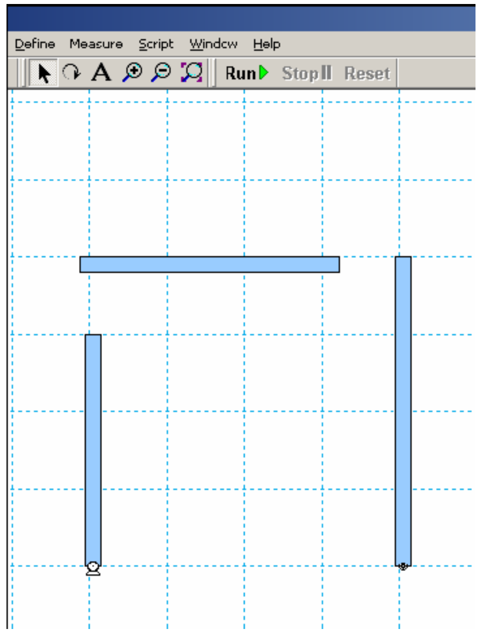
7. Put a motor at the lower end of the left link:
- First select the motor. - Then click at the desired point.



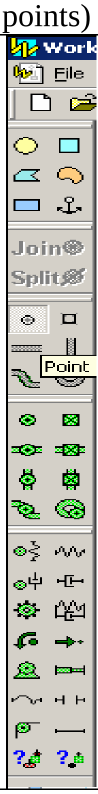
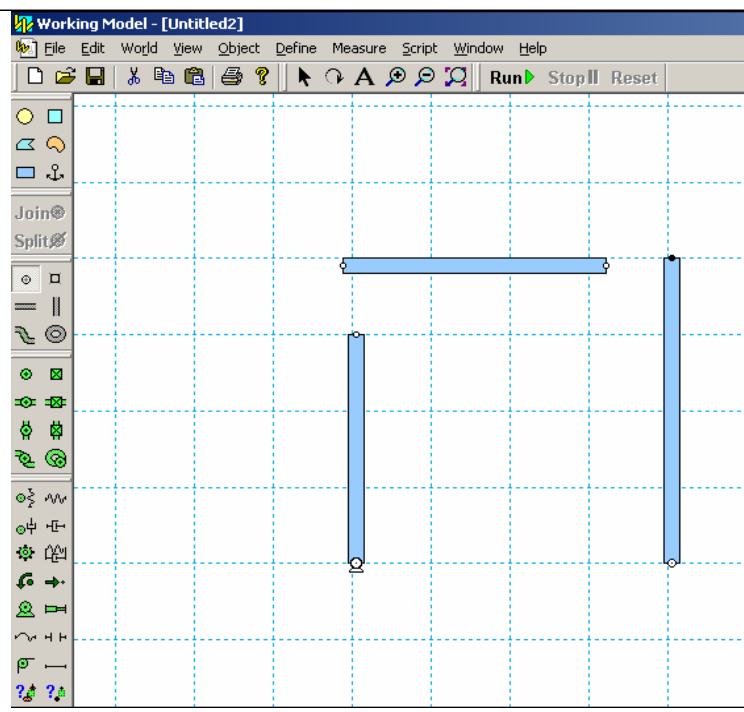


8. Put a pin joint at the lower end of the right link:

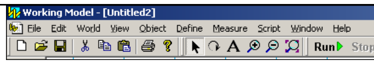
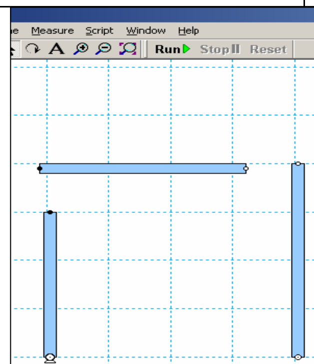
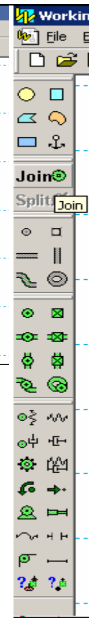
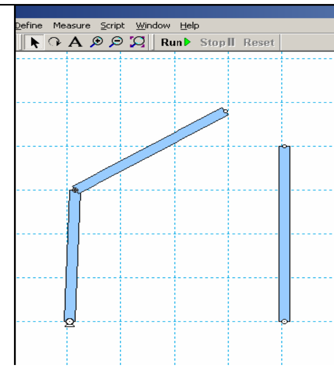
- First select the pin joint. - Then click at the desired point.



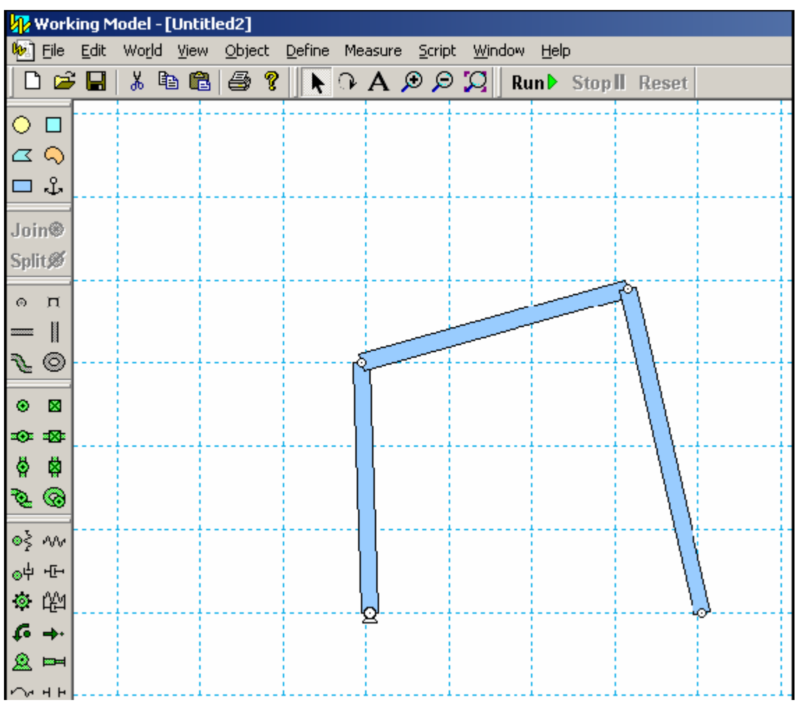
9. Put a point element at the remaining ends:

<table>
<tr><td>- First <u>double click</u> (this enable you to assign multiple points) on the point element.</td><td>It should look like below:</td></tr>
<tr><td>
</td><td>
</td></tr>
</table>

10. Join the links by selecting two points, then selecting Join:

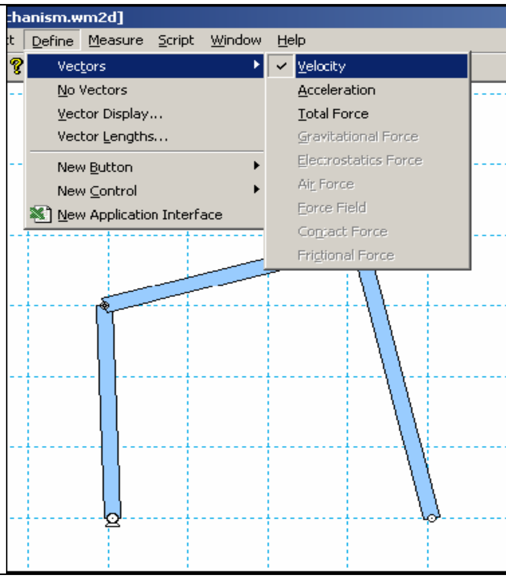
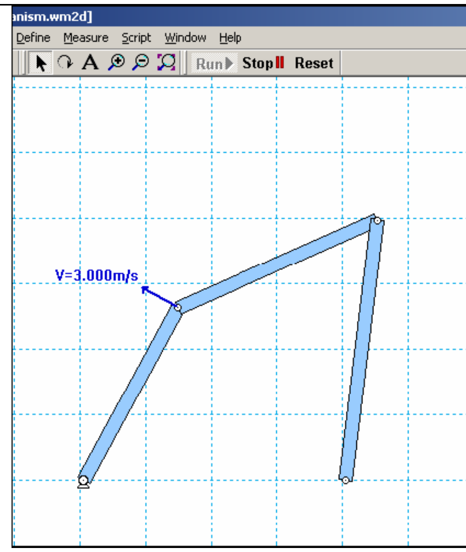
Click the arrow select tool:	Select first point – press SHIFT and click the other point	Press Join	They should look like below
			

11. Repeat the same for the remaining two points. Your model should look like below:



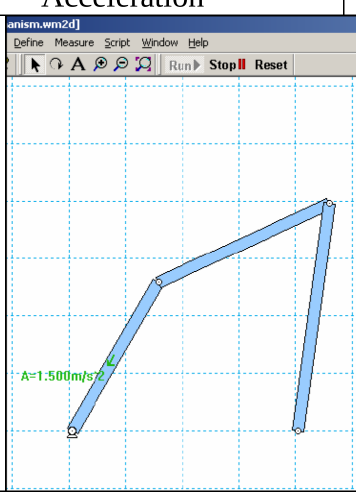
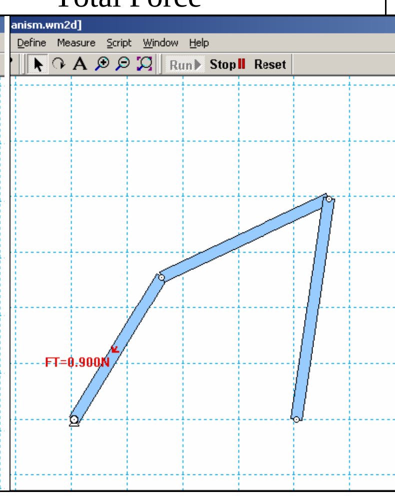
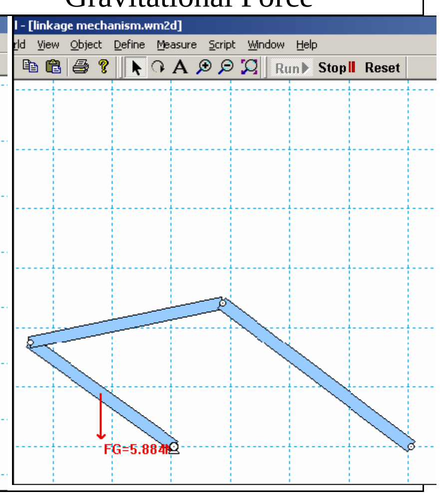
12. Click RUN () and watch it rotating.

13. Now we want to capture the velocity of the joint between the left link, and the middle one:

<table>
<tr><td>- Select it, and click on Define – Vectors- Velocity</td><td>Click Run, and watch the velocity change</td></tr>
<tr><td>
</td><td>
</td></tr>
</table>

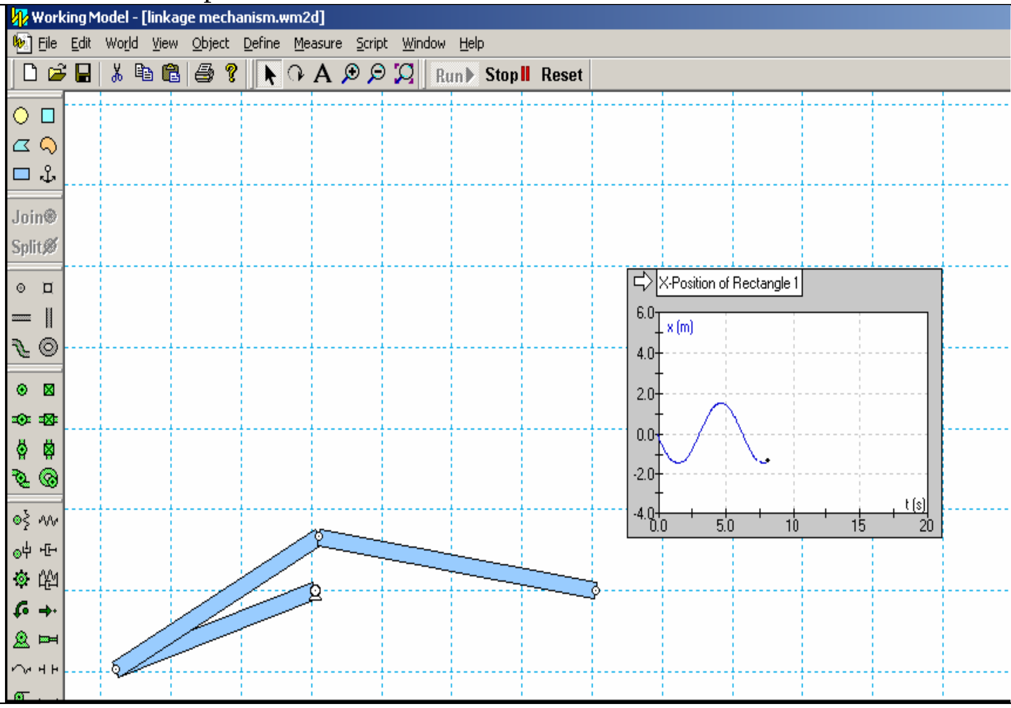
Note that by clicking on the link itself, and defining the velocity, the program calculates the velocity of the C.G. of the link.

14. Now you are ready to try different measurements:

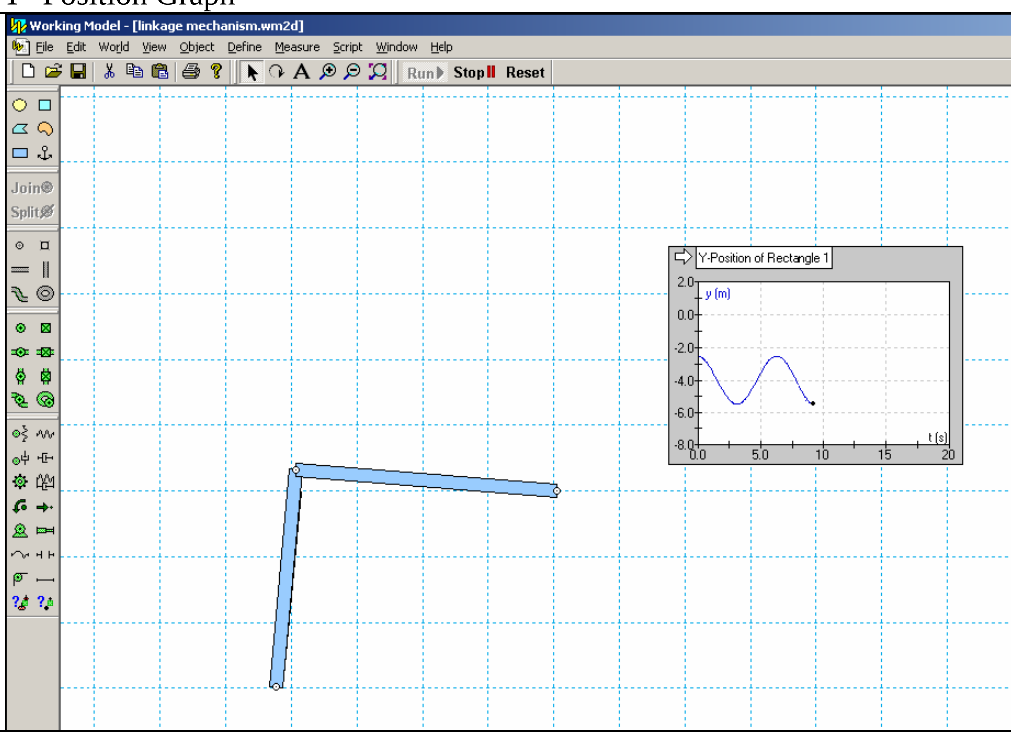
<table>
<tr><td>Acceleration</td><td>Total Force</td><td>Gravitational Force</td></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
</table>

15. Select a link and use the measure tool:

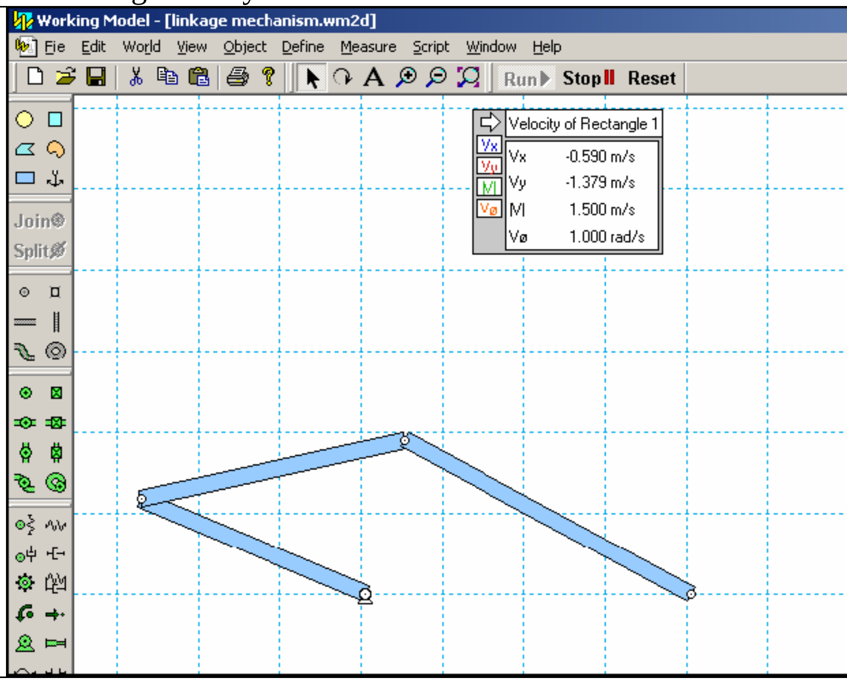
X- Position Graph



Y- Position Graph



Measuring velocity values



16. Now try to change the length of any of the links, and RUN the model, and observe for any change if any, and explain.

17. Change the mass of any of the links, and observe for any change in velocity, and force? And Why if there is any?

18. Now double click on the motor (resetting the mass for any link that has been changed), and notice that the value for velocity is 1 rad/sec. Change this to make it the same value for acceleration, and torque. Write what you observe, and try to explain.

19. Now increase the mass for one link (e.g. left one) gradual, and see how this will affect the motion for a fixed value for torque, velocity, or acceleration of the motor?

20. Now, replace the middle link with two links connected with total length as the middle one, run, observe, and explain.

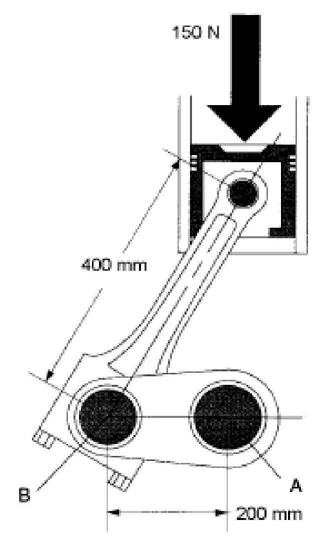
21. Based on (20) search for what is the equation, relation, or rule that governs the mechanism motion.

EXPERIMENT 10

NUMERICAL DYNAMIC SIMULATION: FLYWHEEL

Problem Definition:

In the two cycle piston engine shown, explosive gases are ignited in the combustion chamber above the piston. The explosions apply a force of 150 N for the duration of every downward stroke. The engine is equipped with a speed limiting device (rev limiter) which prevents the rotational speed from exceeding a set value (red-line). The masses of the piston and connecting rod are 0.75 kg and 1.5 kg, respectively. The mass of the crankshaft-flywheel assembly is 30 kg. Given that the red-line of the engine is 35 rad/sec (340 rpm). Assume the crankshaft-flywheel assembly can be modeled as a circular disk.



Objective:

Determine the forces at the crankshaft bearing (point A) and connection rod (point B) bearing.

Solution:

1. INTRODUCTION

Engines that exceed the manufacturer's maximum speed (over-revving) may be subject to excessive wear and possible failure. To prevent over revving, internal combustion engines are often fitted with a device known as a rev-limiter. When an engine exceeds its red-line, rev-limiters interrupt the ignition system, slowing the engine down. Once the speed drops below the maximum, the ignition system is switched back on. In this exercise you will model an internal combustion engine equipped with a rev-limiter. The engine has three bodies: the piston, the connecting rod and the crankshaft. The piston will be modeled by a square body. The connecting rod will be modeled by a rectangular body. The crankshaft will be modeled as a circular body. The bodies will be drawn, sized and joined to each other and the background. The piston's cylinder walls will be modeled with a keyed slot joint. The force of combustion will be modeled by a force attached to the top of the piston. The resulting forces at the bearings will be measured.

2. SETTING UP THE WORKSPACE

For this exercise, three changes in the workspace will be made. First, for clarity, the x-y axes will be displayed. The unit of distance will also be changed from meters (default) to millimeters.

- If the x-y axes are not currently displayed, choose Workspace from the View menu and choose X,Y Axes from the Workspace submenu. *The x-y axes provide a reference frame for building a simulation.*
- Choose Numbers and Units… from the View menu. *The Numbers and Units dialog appears.*
- Click the More Choices button. *The dialog box expands.*
- Click and hold in the Distance field (Figure 1). *The pop-up menu appears.*
- Choose millimeters from the Distance pop-up menu.

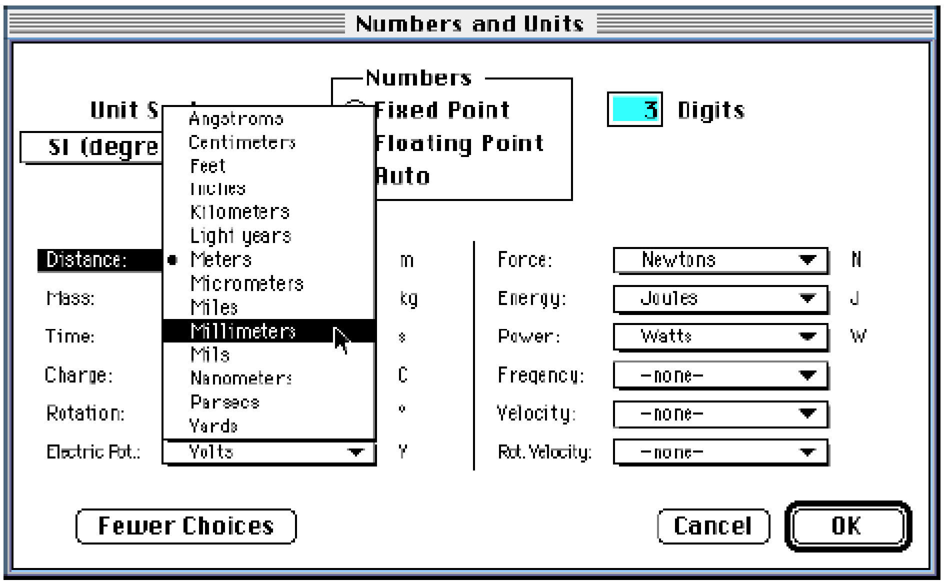


Figure 1 Choosing millimeters as the unit of distance from the Numbers and Units dialog
The unit of distance changes to millimeters.

- Click in the Rotation field and choose Radians from the pop-up menu.
- Click OK.

3. CREATING THE COMPONENTS

This exercise has three objects: a 1.5 kg connecting rod, a 0.75 kg piston, and a 30 kg crankshaft (see Figure 2 below). The connecting rod will be modeled by a thin rectangle 400 mm in length. Its width will be thin, 150 mm, so it closely resembles the actual connecting rod. The crankshaft, as stated in the exercise, is modeled as a circular disk with a 200 mm radius and a mass of 30 kg. A 200 mm square object will represent the piston. The objects will be created, sized and initialized in the following steps.

Creating the Crankshaft

The crankshaft is represented by a circle with a radius of 200 mm and mass of 30 kg. These parameters will be set using the Geometry and Properties utility windows.

I. To draw the crankshaft:

• Click the Circle tool in the Toolbar.
• Click once on the background. Move the mouse to expand the circle and click again to complete sketching.

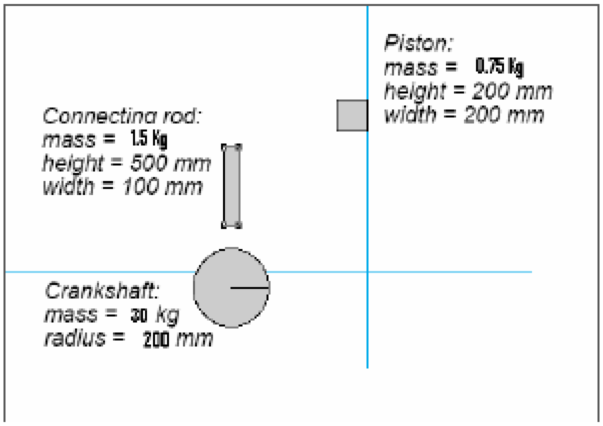


Figure 2. The Bodies that will be created

II. To set the mass of the crankshaft:

- Choose Properties from the Window menu.
- Click the mass field and enter the value 30.

III. To set the size of the crankshaft:

- Select the crankshaft if it not already selected.
- Click the Radius field (labeled “r”) of the Coordinates bar and enter the value 200 (Figure 3).

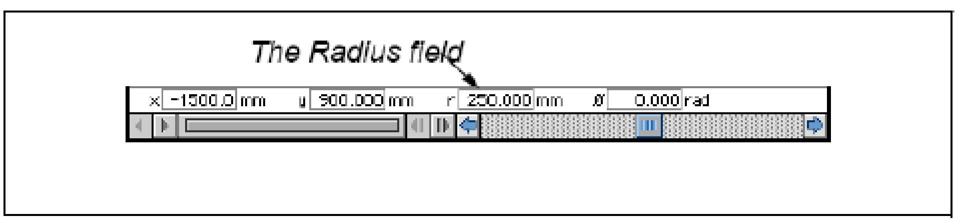


Figure 3. Coordinates bar for a circle

IV. Zooming In:

The circle will appear small after sizing. To make the rectangle easier to manipulate and appear larger, the workspace will be magnified using the Zoom tool. To zoom in:

- Click the Zoom In tool in the Toolbar.
- Click near the circle. The objects in the window are magnified by a factor of two with each click of the mouse. To zoom out while the Zoom In tool is selected, hold down

the Shift key (the magnifying glass pointer changes to "-") and click. Your screen should be similar to Figure 4 below.

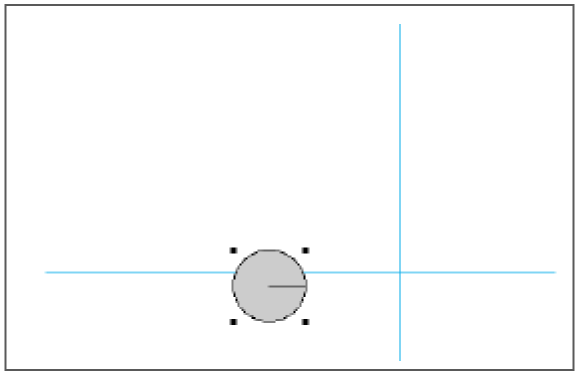


Figure 4 The workspace after zooming in

- Click the Arrow tool in the Toolbar or press the spacebar to deselect the Zoom In tool.

Creating the Piston

For this exercise, the piston will be modeled as a 200 mm square with the mass of .75 kg. The Square tool will be used to draw the piston, and the Properties window will be used to set its mass.

I. To draw the piston:

- Choose the Square tool in the Toolbar. On systems, the Square tool is "hidden" in the Rectangle/Square pop-up palette by default. Click and hold on the Rectangle tool to bring the pop-up palette in view (Figure 5 below).
- Click once on the background, drag to the right, and click again to complete sketching. A square appears on the screen. To set the size of the piston:
- Click in the Height or Width field of the Coordinates bar and enter 200. Either field changes both the height and the width of the object so that it remains square.

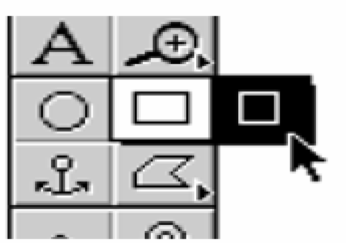


Figure 5 Rectangle/Square pop-up palette

II. To set the piston's mass:

- Select the piston if it not already selected.
- Choose Properties from the Window menu.

• Click in the mass field and enter the value 0.75.

Creating the Connecting Rod

In this exercise, the connecting rod is represented by a rectangle drawn with the Rectangle tool and sized using the Geometry window. To approximate an actual connecting rod, the rectangle will be given a mass of 2 kg, a height of 500 mm, and a width of 100 mm.

To draw the connecting rod:

I. Choose the Rectangle tool in the Toolbar. (On systems, the Square tool used above may have replaced the Rectangle tool in the Toolbar. If so, the Rectangle tool may be selected from the hidden pop-up palette by clicking and holding on the Square tool in the Toolbar).

II. Click once on the background, drag to the right, and click again to complete sketching. A rectangle appears on the screen. To set the mass of the connecting rod:
- Select the new rectangle if it not already selected.
- Choose Properties from the Window menu.
- Click in the Mass field and enter the value 2.

To set the size of the rod:

1. Click the Height field of the Coordinates bar and enter the value 500.
2. Click the Width field of the Coordinates bar and enter the value 100. Your screen should resemble Figure 6.

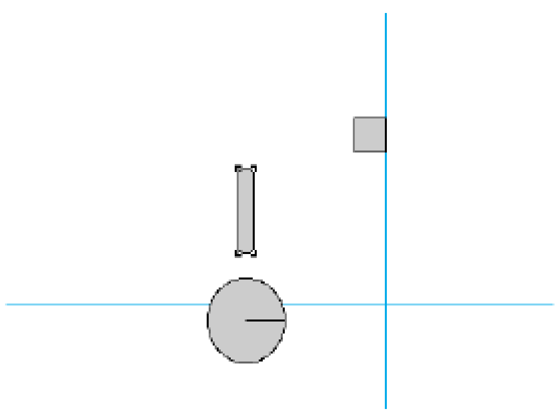


Figure 6 The piston, crankshaft and connecting rod

Creating the Points for Joining

The objects in this exercise are connected to each other and to the background (see Figure 7 below). The connections will be modeled by creating points and joining them. These points will be created with the Point tool and accurately positioned using the Properties window.

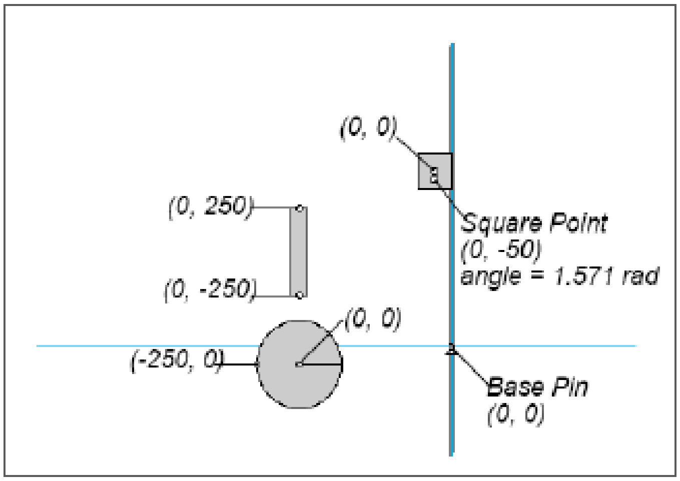


Figure 7 The points which will be created and their coordinates

Creating Points on the Connecting Rod

- Double-click the Point tool in the Toolbar. Double-clicking selects a tool for successive operations. On systems, the difference between single and double-clicking is indicated in the Toolbar by shading: a doubleclicked item is dark grey, while a single-clicked item is light grey.
- Place the mouse pointer over the connecting rod rectangle. Find the snap point at the top end of the connecting rod. An X symbol appears at snap points. Find the snap point located at the midpoint of the top side of the connecting rod.
- To attach a point element, click when the snap point located at the top end is visible. Observe that the point element is attached to the top end of the rod.
- In the same fashion, attach another point element to the bottom end of the connecting rod. Your screen should resemble Figure 8.

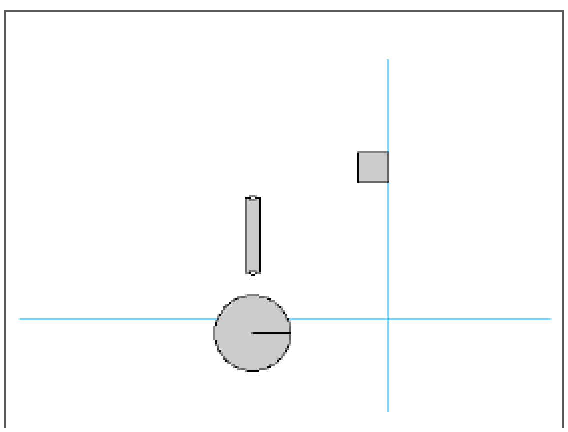


Figure 8 Connecting rod points in position

Attaching Points to the Crankshaft

The crankshaft needs two points: a center point representing the main bearing and an outer point representing the connecting rod bearing. These points will be accurately positioned at the center and at 200 mm from the center of the circle. To create and position the crankshaft points:

- Make sure the Point tool is still selected. Place the mouse pointer over the crankshaft. Find the snap point at the center of the circle.
- Click when the snap point at the center is visible. A point element is attached to the center of the circle.
- Place the mouse pointer near the left quadrant of the circle. Find the snap point at the left quadrant (Figure 9). As the mouse pointer nears the left quadrant of the circle, the snap point appears.
- Click when the snap point at the left quadrant is visible. Another point element is attached to the left quadrant of the circle.

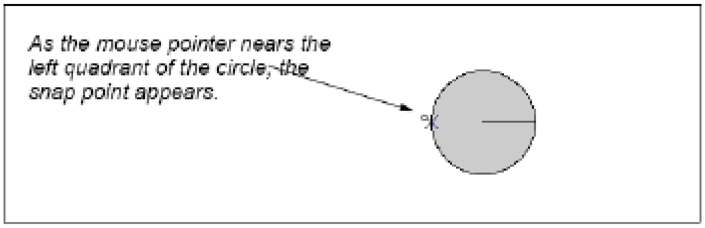


Figure 9 Snap point at the left quadrant of the circle

Attaching Points to the Piston

Two points need to be attached to the piston: a square point and a point. The square point will be joined to the slot on the background to create a keyed slot joint. The point will be joined to another point on the connecting rod to form a pin joint. The square point will be positioned on the piston at the coordinates of (0, -50). The square point will be rotated 90°, so that when joined to the slot, the piston will not rotate. This is because vertical slots are defined as being rotated 90°; horizontal slots are defined as having 0° rotation. When a square point is joined to a slot, the rotations of the two objects are aligned.

I. The point will be positioned at (0, 0). To create the points:

- Click the Square Point tool. The cursor turns into a square point.
- Click anywhere on the piston. Since the square point will be precisely position using the Coordinates bar below, it is not necessary to find a snap point.
- Click in the X field of the Coordinates bar and enter 0. If you attached the square point on a snap point, the x-field of the Coordinates bar may contain a formula expression (such as body[3] width or (0.0)). Simply overwrite the entire expression and enter 0.
- Press the tab key to move to the Y field of the Coordinates bar, and enter -50. Again, simply overwrite the y-field with the value -50.
- Choose the Properties in the Window menu. The Properties window appears.
- In the angle field of the Properties window (marked by ø), enter the value 1.571. The value of 1.571 radians is equivalent to 90°. The value will be displayed in a

rounded form, but internally the correct value will be used. The point's y-position is set to -50 so it will not interfere with the connecting rod joint.

II. To create the point:

- Click the Point tool.
- Place the pointer near the center of the square and find the snap point.
- Click when the snap point at the center is visible. The point is created at the center of the piston.

Attaching a Point to the Background

A point representing the main bearing of the crankshaft must be placed on the background. The point can be placed anywhere on the background; for clarity, it will be placed at the origin (0, 0). To create and position the point:

- Click the Point tool.
- Place the mouse pointer near the origin. Find the snap point that appears at the origin. Make sure that nobody is obstructing the origin. The snap point does not appear if the origin is covered by a body.
- Click when the snap point at the origin is visible. Verify the position of the point by noting the (x, y) position in the Coordinates bar; it should be (0, 0). We now name this point element so that it becomes easier to select later.
- Choose Appearance from the Window menu. The Appearance window appears.
- In the name field (where it says Point), type Base Pin. Since we will not be needing the Appearance window for the rest of the exercise, close the window by: (Windows) clicking the box marked "X" at the top-right corner of the window, or () clicking the box at the top-left corner of the window.

Attaching a Slot to the Background

The cylinder walls of the engine will be modeled with a keyed slot joint. The joint will be made by joining the square point on the piston to a slot attached to the background. The slot can be located anywhere on the background as long as it is located on the crankshaft's centerline (the yaxis for this model).

To create and position the slot on the background:

- Choose the Vertical Slot tool in the Toolbar. On systems, the Vertical Slot tool may be "hidden" in the Slot pop-up palette. Click and hold on the Slot tool in the Toolbar to bring the pop-up palette in view.
- Place the pointer near the point element attached to the origin. Find the snap point.
- Click when the snap point is visible. A vertical slot appears.

Creating Joints

In this exercise there are four joints (see Figure 10). The joints will connect: the piston to the slot, the piston to the connecting rod, the connecting rod to the crankshaft, and the crankshaft to the main bearing.

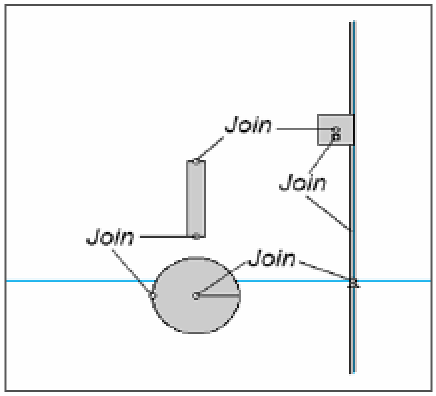


Figure 10 The points which will be joined

The following steps will demonstrate how to make these joints.

I. Joining the Piston to the Slot

In this example, the piston slides in a cylinder. The cylinder will be modeled as a keyed slot joint. The joint is created by joining the square point on the piston to the slot. To create the keyed slot joint:

- Select the square point on the piston, and while holding down the Shift key, select the slot. The word "Join" of the Join button in the Toolbar changes from gray to black indicating the two points can be joined.
- Click the Join button in the Toolbar. The piston moves to the slot (see Figure 11). Joining the Crankshaft to the Point on the Background The crankshaft main bearing is modeled as a pin joint. The pin joint will be created by joining the point at the center of the circle to the point at the origin.

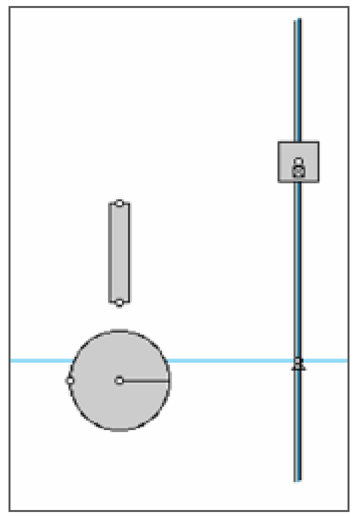


Figure 11 Piston joined to the slot

II. To join the crankshaft to the origin:

- Choose Properties in the Window menu.
- From the selection pop-up menu located at the top of the Properties window, choose Base Pin (Figure 12). The Base Pin is now selected.
- Hold the Shift key down and select the center point on the crankshaft circle.
- Click the Join button. The crankshaft circle moves to the origin.
- To see how the circle representing the crankshaft is constrained, bring the mouse pointer over the circle, hold down the mouse button, and drag the circle. The circle can rotate but is fixed to the Base Pin.

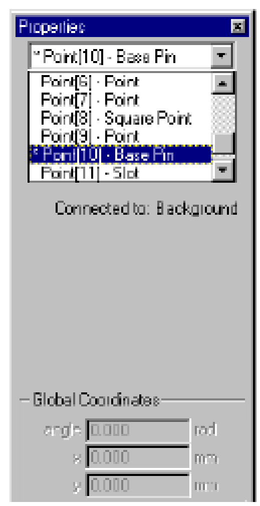


Figure 12 Selecting an object in the Properties window

III. Joining the Components

- The piston, connecting rod and crankshaft will now be joined together (see Figure 13). The following steps describe how to join them.

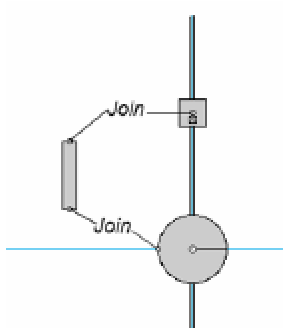


Figure 13 Joining the components

IV. To join the piston to the connecting rod:

- Select the (round) point on the piston and, while holding the Shift key down, select the top point on the connecting rod.
- Click the Join button. The two objects will come together.

V. To join the connecting rod to the crankshaft:

- Select the bottom point on the connecting rod and, while holding the Shift key down, select the remaining (left) point on the crankshaft.
- Click the Join button. Your screen should resemble Figure 14.

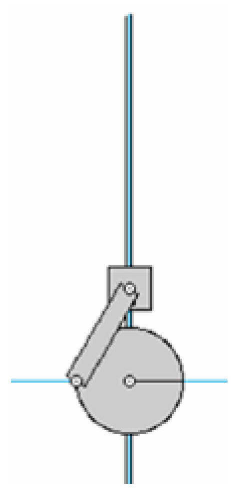


Figure 14 the completed engine

Editing the collision property of a pair of bodies

The Smart Editor keeps joints together during editing. To see this, try dragging the connecting rod. The connecting rod will stay joined while it is dragged and the crankshaft and piston will move accordingly. When you are done dragging the rod, move it back to the approximate position shown in the problem description on the first page of this exercise.

Preventing a Collision

In Working Model, objects which are directly connected to each other never collide. Notice that the piston and crankshaft may overlap when they are dragged during editing. Since the two objects are not directly connected, they will collide when you run the simulation. To prevent the collision, the Do Not Collide command will be used.

To prevent a collision:

- Select the piston and, while holding the Shift key down, select the crankshaft.

- Click and hold on the Object menu title in the menu bar (Figure 15). Notice that there is a checkmark beside "Collide", indicating that the pair of selected objects will collide when you run the simulation.
- Choose Do Not Collide in the Object menu.

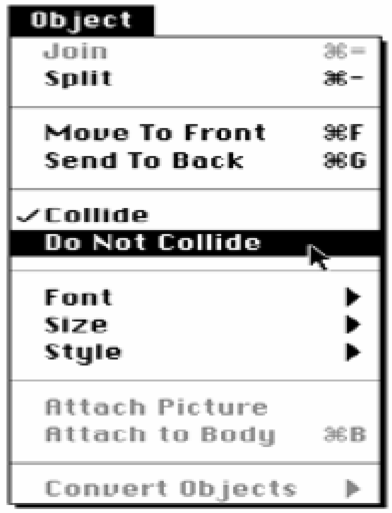


Figure 15 Editing the collision property of a pair of bodies

Creating the Force

A 100 N force is applied at the top of the piston in the negative y-direction (down). The force is only active while the piston is traveling with a negative y velocity. The force will be drawn using the Force tool and its magnitude and location will be set using the Properties window.

Drawing the Force

The force will be drawn in the downward direction using the Force tool.

To draw the force:

- Click the Force tool in the Toolbar.
- Place the pointer near the midpoint of the top end of the piston. Find the snap point.
- Click when the snap point is visible, drag the mouse upward, and click again to create the force. A force attached to the piston appears (Figure 16). Do not be concerned with the exact direction or magnitude of the force for now.

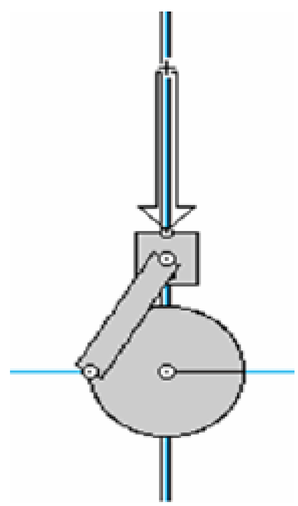


Figure 16 Creating a Force

Sizing the Force

The force's magnitude and direction will be set using the Coordinates bar. To size the force:

- Click the force vector to select the force.
- Click the Fy field of the Coordinates bar and type -100.
- Click the Fx field of the Coordinates bar and type 0. The force vector changes in length to reflect its new magnitude.

Timing the Force

The ignition timing of the engine must be simulated. The problem states that the force is active only on the downward stroke (i.e., when the piston has a negative velocity). The rev-limiter cuts off combustion when the rotational velocity is greater than 35 radians/second. To simulate these conditions, the “and (a,b)” function will be incorporated with the following formulas.

To determine when the piston has a negative velocity use the following formula:

body[c].v.y < 0

where c is the piston's object id number. To determine the piston’s id number, place the cursor over the piston and read the Status bar.

To determine when the engine’s speed is greater than 35 rad/s, use the following formula:

body[d].v.r < 35

where d is the crankshaft's object id number. Use the Status bar as above to determine the crankshaft’s id number.

The complete equation is:

and (body[c].v.y < 0, body[d].v.r < 35)

The complete equation will be placed in the Active When field in the force’s Properties window. Gravity will provide the initial downward velocity to start the engine.

To set the timing of the force:

- Select the force.
- Choose Properties from the Window menu.
- Click in the Active When field at the bottom of the Properties window. On Windows systems, you must first un-check the Always button before clicking in the Active When field.
- Type the following formula (see Figure 17):and(body [c].v.y <0,body[d].v.r< 35) where c and d are the object id numbers of the piston and crankshaft respectively.
- The force’s rev-limiter equation is designed for counter-clockwise (positive) engine rotation. It is important that the engine be “started” in a position similar to the figure on the first page of this section. If you want a rev-limiter which works in both directions try incorporating the abs() function into the formula.
- You can increase the width of the “Active when” field to view the entire equation by resizing the Properties window.

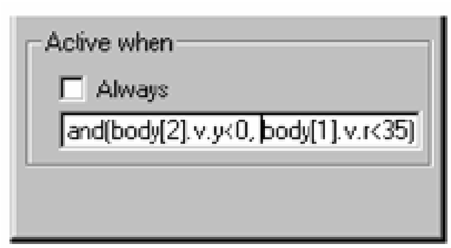


Figure 17 Active When field is in the property window for a Force

The simulation is ready to run.

- Click the Run button in the Toolbar. The engine runs. A warning may appear if you run the engine long enough; you can ignore the warning for now.
- When you are ready to continue, click the Reset button in the Toolbar.

Measuring Properties from the Simulation

A graph in conjunction with a digital meter is a nice way to illustrate the rotational speed of the engine's crankshaft. Two digital meters will be used to display the forces on the bearings. Follow the steps below to create these output devices.

Displaying a Graph

The angular velocity of the crankshaft will be displayed by a graph. To create the graph:

- Select the crankshaft circle. *Four squares "handles" will appear around the circle indicating that the circle is selected.*
- Choose Velocity from the Measure menu and Rotation Graph from the Velocity submenu. *A meter resembling Figure 18 appears.*

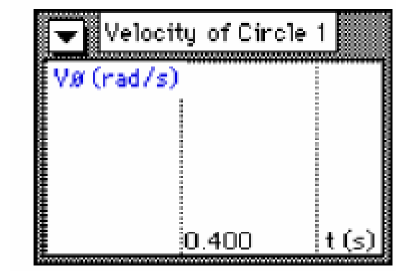


Figure 18 A Velocity Graph

Displaying Digital Force Meters

To display the digital force meters:

- Select the crankshaft-main bearing joint (see Figure 19).
- Choose Force from the Measure menu. *A digital meter appears.*
- Repeat for the connecting rod-crankshaft joint (see Figure 19).

A second digital meter appears. You may need to move the meters.

To move the meters:

- Select a meter.
- Drag it to any position you wish.

Your window should resemble Figure 20.

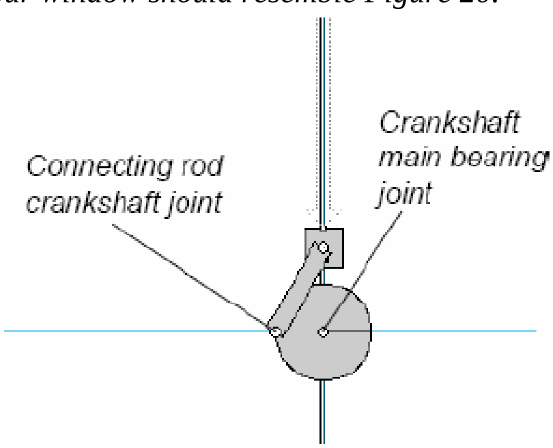


Figure 19 The Force to be measured

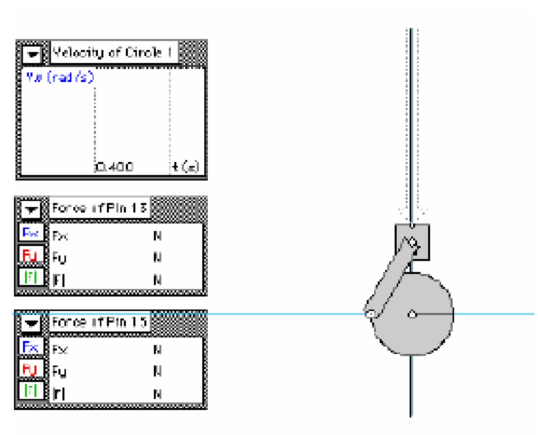


Figure 20 The completed workspace

Running the Simulation

Run the simulation. Notice that the angular velocity increases until it reaches 30 rad/s. This is so because we have turned off the force above 30 rad/s, just as a rev limiter t urns off the ignition of an engine above a certain speed.

Modifying the Graph Display
You may notice that the axis labels occlude the numeric labels along the tick marks of the plot. You can modify the display options using the Appearance window. For example, to turn off axis labels so that the numeric labels clearly appear:

- Select the velocity meter on the screen.
- Choose Appearance in the Window menu.*Alternatively, you could press Control+J (on Windows systems) or Command+J (on MacOS systems) to open the window.*
- Turn off the options titled "Labels" and "Units" (Figure 21) *You may wish to try modifying other options and observe the effects on the graph meter.*

  If you wish to show the meter coordinate axes, click the check box labeled Axes.

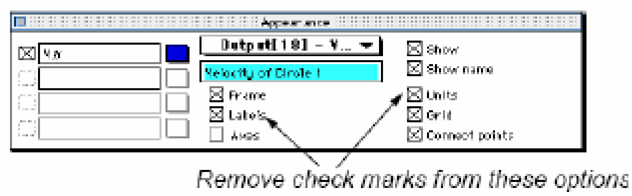


Figure 21 Appearance window for a meter

MODIFYING THE SIMULATION
Try modifying the masses of the crankshaft and connecting rod and notice how quickly red-line is reached. Also try changing the length of the connecting rod by repositioning one of the joints.

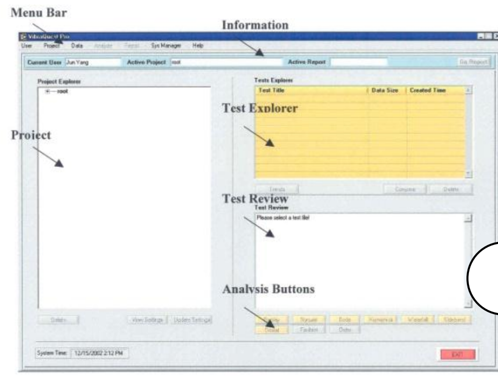
Appendix

A. Running the VibroQuest Software

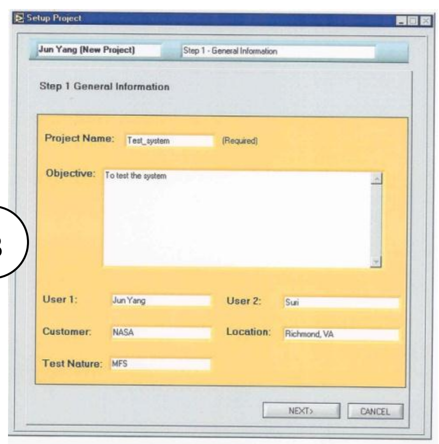
1. Run the VibroQuest:

2. New Project (under root)

1



2



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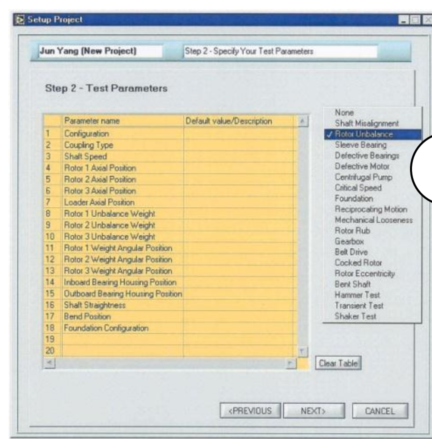
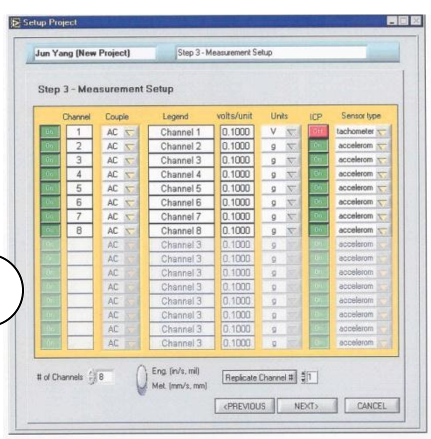


4

3. Fill up the window, click “Next”.

4. Select “None”, click “Next”.



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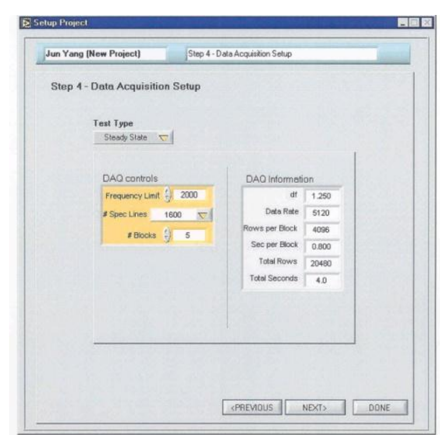
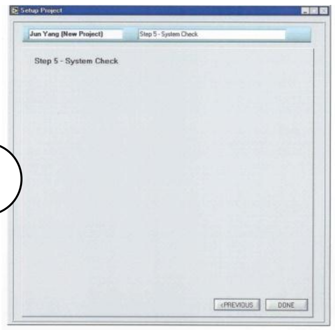


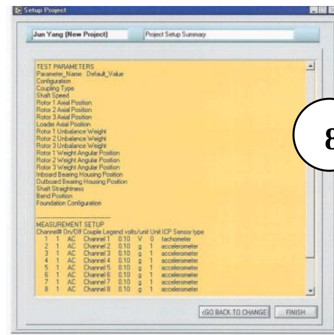
6

5. Review the table, (do not change the default), click “Next”.

6. Click “Next”.

7





8

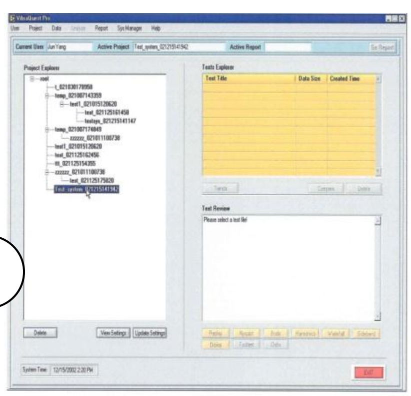
7. Click “Done”.

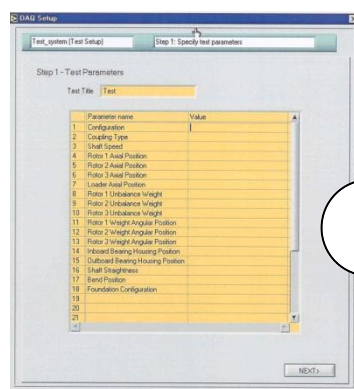
8. Click (review the information provided, if they are not ok go back to modify them), “Finish”.

B. Run the machine according to the procedure

9. Select “Data” from the toll bar on the computer.

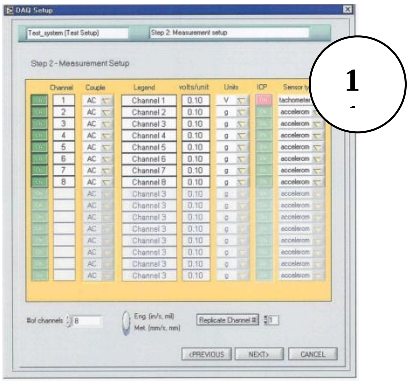
9

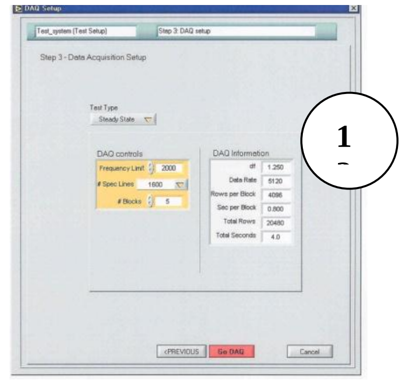




1

10. Name the “Test Title” in the window. Insert the parameters used in the test and click “Next”.

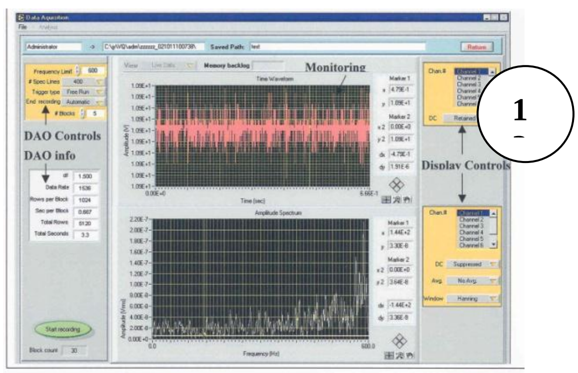




11. Review the information provided in the window and click “Next”.

12. Chose 2000 for <u>Frequency limit</u>, 1600 for <u>Space line</u>. Leave the rest information as defaulted and “**GO DAQ**”

13. “**START RECORDING**”



14. When the recording is finished save the file under the root of Data of the file which you are to compare with

15. Now select the project name from the left window, all the relevant tests will appear at the right window.

16. Hold down the shift key and select two tests that you are going to compare.

17. Click on Compare to observe the difference between the unbalanced systems with base system.