Up-gradation and Re-modeling of Universal Vibration Tester

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Abstract- Every system tries to attain stability which includes both steady state and transient responses to the excitation induced. In any system some inherent vibrations are always present due to molecular excitation. This excitation may be internal and occurs due to unbalance in the system. Steady state response can be balanced while time taken to overcome transient vibrations is important for system stability. Forced vibration is a mode of vibration in which the system vibrates under the action of periodic excitations applied externally. The external excitation is in the form of motion and so produced by one dynamic system transferred to another. Few sources of excitation are resonance, loose or defective mating part, bent shaft; mass of rotating parts not distributed uniformly, variation in turning moment of the engine etc. Since, it is difficult to analyse system with various input signals, simple harmonic motion is assumed to be applied, for ease of analysis. The importance of this mode of vibration rises in the high speed engines and machines when mounted on foundations and supports, causing excessive amplitudes because of unbalanced forces setting-up during their working, leading to a serious damage of the machine.

Responses to harmonic and other periodic excitation can be modelled and studied using Universal Vibration Tester. In this paper, these real time situations are to be studied and analysed to avoid damages/failures of the system during working or operating conditions.

I. INTRODUCTION

The subject of mechanical vibrations is primarily concerned with the study of repeated, or nearly repeated, motion of mechanical systems. As engineers, especially design engineers are interested in avoiding excessive vibration in a structure, machine or vehicle, or wish to induce certain types of vibrations in a very precise manner.

The response and durability of an engineering system to short duration, high intensity, loading is a function of the vibration characteristics of the system. In many cases vibration effects are experienced in our everyday lives. These include vibrations felt while travelling in an automobile, or while riding a bicycle, vibration of an airplane wing while flying etc. But vibrations also play vital role in some of the applications like conversation over telephone or while listening to music coming from stereo speakers etc. Even the ability to speak stems from the vibrations of vocal chords.

Due to faulty design and limitations during manufacturing there will be unbalance in system which causes excessive and unpleasant stresses due to vibration. In locomotives, improper design and load/material distribution leads to excessive vibrations which results in lower efficiency, sometimes accidents or heavy loss. Many buildings, structures and even bridges fall because of vibrations.

Due to molecular motions, all bodies try to vibrate from their mean positions. When no external force acts on the system after giving it an initial displacement, the body vibrates. These vibrations are called free vibrations and their frequency as natural frequency. In practical applications, consisting of multi degree of freedom systems, if the frequency of excitation coincides with one of the natural frequencies of the system, the condition of resonance is reached, and dangerously large oscillations may occur which may result in the mechanical failure of the system. Excessive vibrations are always harmful to the system. Thus keeping in view of these devastating effects, the study of vibration is essential for a design engineer to minimize the vibrational effects of mechanical components by designing and developing them suitably.[1][2]

The Universal Vibration Tester present in our laboratory is remodeled so as to conduct different experiment related to vibrations and the mechanical elements required to conduct these experiments are designed and fabricated, explained in further chapters.[4]

II. UNIVERSAL VIBRATION TESTER

Universal vibration tester enables to perform a comprehensive range of vibration experiments with the minimum amount of assembly time and the maximum adaptability. Some of the major experiment includes pendulum experiments, mass-spring system, free and forced vibrations, damped torsional oscillations, torsional oscillations. The experiments lead through the basics of vibration theory.[6]The Universal Vibration Tester is an experimental setup helps in determining, different aspects of vibrations and oscillations in mechanical systems. These include pendulums, mass-springs systems and shafts and beams. The following apparatus shown in figure is remodelled and used to carry out the experiments

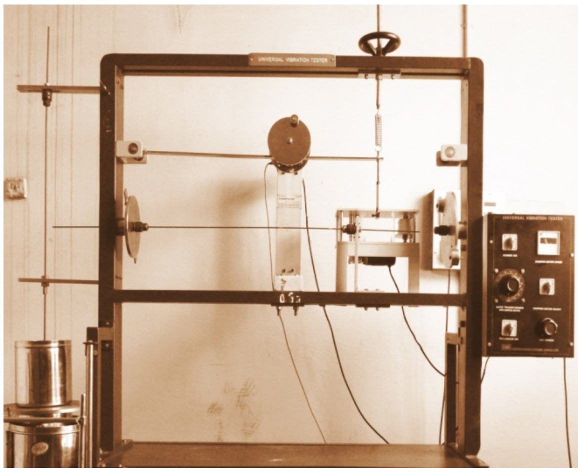


Figure 2.1: Universal Vibration Apparatus. [6]

The apparatus shown in figure consists of a heavy and sturdy steel frame with a useful cupboard to store our optional tools and machinery. The top of the cupboard is a useful work area. The upper part of the frame is the 'window', where most of the other (optional) experiments fit. Some experiments fit to the side of the frame.

III. DESIGN AND FABRICATION

3.1 Design and fabrication of stepped shaft and suitable love-joy coupling:

3.1.1. Problem associated with existing apparatus

When the motor rotates, the discs also rotates at a same speed ω in rpm, a harmonic excitation is established on the beam. A motor is connected to exciter using a rubber tube clamped at both ends. The transmission of power was found to be ineffective.

3.1.2. Modifications for the apparatus

Some new ideas to replace flexible rubber tube are as follows. A rigid coupling can be used, as there is no misalignment between two shafts. For the effective transmission of power, muff coupling alone cannot be used to connect these shafts because the distance between the two shafts is high. To fill up this distance, a stepped shaft is designed.

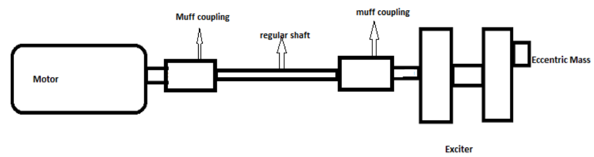


Figure 3.1: Line diagram showing connection using Muff coupling

It can be cited in the above figure 3.2, the rigid muff coupling doesn't provide flexibility for easy removal and attachment and hence a Love-joy coupling was selected.

A Love-joy Coupling has following advantages:

- Torsionally rigid without any backlash
- High power density
- No wearing parts, high resistance to harsh environmental conditions.

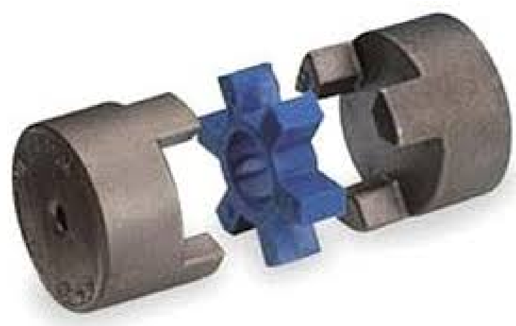


Figure 3.2: Love-joy coupling [8]

In the design, the Love-joy coupling is connecting the motor shaft and the stepped shaft that is designed. The other end of shaft is connected to exciter. The exciter shaft goes inside the stepped shaft which is bored at stepped end. Thus the two required shafts were coupled together effectively.

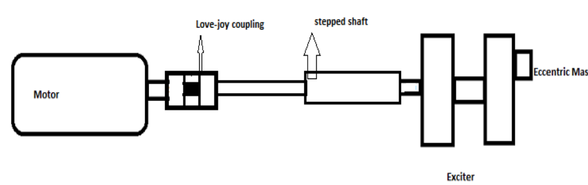


Figure 3.3: Line diagram showing connection of motor and exciter using Love-joy coupling and stepped shaft

3.1.3. Design of Shaft

The diameter of the shaft was selected depending on torque transmitting capacity.

Calculations:

Power of the motor (P) = 180 W
Speed (N) = 1800 rpm

Therefore,

Torque $T = \frac{9.55*10^6*P(KW)}{N}$ N-mm.

$T = \frac{9.55*10^6*.18}{1800}$ = 955 N-mm.

Shear stress induced $\tau = \frac{16*T*K_t}{\pi*d^3}$-----------(1)

For Safe Design,
Mild steel, τ = 90 MPa, K_t=1.2 (from Design Data Hand book, Using MSST)
T = 955 N-mm.

By substituting above values in equation (1), we get
Diameter of the shaft 'd' = 4.01 mm.
The adopted diameter 'd' = 11 mm.

As it can be seen, high FOS is used to avoid failure of the machine.[5]

For safe design, the motor shaft is of Φ 11mm with a key way of width 4mm. One end of the shaft is so designed that it couples with motor shaft (using Love-joy coupling). Therefore, one end is of Φ 11mm with a key way of width 4mm and depth 2mm. The exciter shaft is of Φ 8.1mm. The other end of the shaft is stepped and drilled. The outer diameter of stepped shaft is Φ 21mm. and bore diameter is Φ 8.2mm. The exciter shaft can go inside the bore which is tightened using grub screws. To connect motor shaft with exciter shaft a stepper shaft is designed and fabricated.

3.1.4. Fabrications of Shaft and Love-joy coupling

The shaft was fabricated to required dimensions. The various operations carried on the solid shaft are as follows:

- Turning
- Facing
- Milling
- Drilling
- Tapping

The Love-joy coupling was selected from market but some modifications were made as per requirements for our test grid. Lovejoy coupling is drilled to required diameter (Φ 11.2 mm). A key way is provided along with a tapped hole.

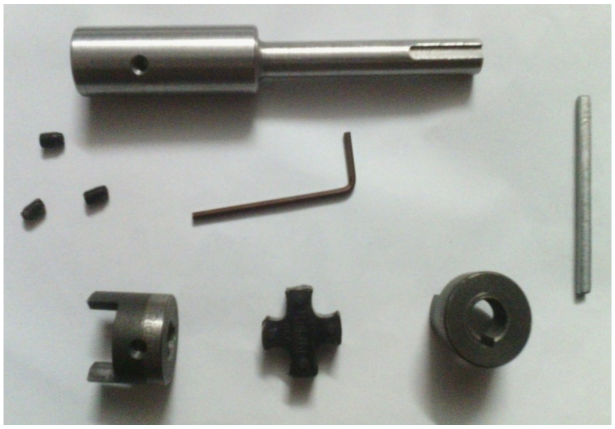


Figure 3.4: Fabricated parts after designing for the test grid

3.2. Sensor to detect the speed of the exciter disc:

3.2.1. Problem associated with setup:

To conduct the Forced vibration experiment the speed of the exciter motor is required. In the present experimental setup there is no means to determine the speed of the exciter disc.

3.2.2. Alternative approaches:

The disc speed can be determined by using various sensors such as proximity sensor, tachometer etc. In this experimental setup, the speed of the exciter motor was determined using a proximity sensor.

3.2.3. Proximity sensor

A proximity sensor is a sensor able to detect the presence of nearby objects without any physical contact. A proximity sensor emits an electromagnetic field or a beam of electromagnetic radiation (infrared, for instance), and looks for changes in the field or return signal. Different proximity sensors are available of which a capacitive or photoelectric sensor is suitable for a non-metallic target.

Figure 3.5: Proximity sensor. [8]

The capacitive proximity sensor as shown in figure is perfectly aligned with the non-metallic target (rubber) on the love-joy coupling. The speed (in rpm) of the exciter motor is indicated on the digital screen.

3.3. Design and Fabrication of L-shaped plotter:

The vibrations of the beam are transferred from beam to the recorder unit. Ametallic bar having provision for holding pencil can be used.

Straight bar was bend at right angles. One end of the bar was threaded and the other end was welded with pencil holding cylindrical ring.

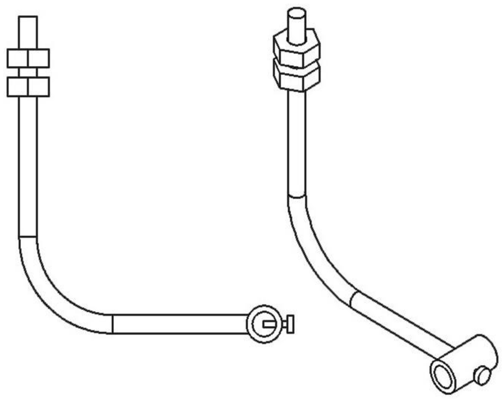


Figure 3.6: Design concept of L-shaped pencil holder

3.3.1 Problem associated:

The L – shaped bar was found to be ineffective to transfer the vibrations from beam to recorder unit.

The L – shaped bar used to vibrate transversely as well as longitudinally. The bar should transmit only transverse vibration and not longitudinal vibration due to recorder/plotter limitations. Thus, the L-shaped bar was discarded.

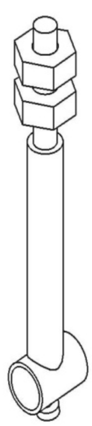


Figure 3.7: Straight shaped pen holder
This mode of transferring vibrations from beam to recorder unit was found to be effective.

Figure 3.8: Installed straight pencil holder with spring.

3.3.2. Design and Fabrication of straight pencil holder

To overcome the problem associated with L-shaped bar, a straight bar with provision for holding pencil was designed and fabricated. The figure shows the design of straight bar in CATIA.

3.4. Selection of Helical spring

The forced vibration experimental setup consists of rectangular beam supported at one end pivoted in a fixed housing. The outer end of the beam is to be supported by a helical spring bolted to the bracket fixed to the top member of the frame.

A helical spring of suitable stiffness was selected and bought. This helical spring is responsible for keeping the beam in horizontal position as in figure 3.12.

3.5. Mechanism to raise/lower the drum:

In this experiment, damped torsional vibrations are analyzed. The effect of damping can be studied by varying the depth of immersion of the flywheel inside the water. The depth of immersion is varied by raising the drum containing water. A screw jack is used to raise/lower the container.

A screw jack is used to lift weights. A screw jack is operated by turning a lead screw. The advantage of screw jack is that they are self-locking.

3.6. Design and fabrication of wooden block

3.6.1. Problem associated

The screw jack and container cannot be fixed directly. The holes drilled on the screw jack do not coincide with those on container. An intermediate plate or block can be used to fix screw jack and container.

3.6.2. Modification

Some ideas to fix screw jack and container
A metal plate can be used as an intermediate medium. A metal plate is strong enough to carry the load. A metal plate has few disadvantages such as:

- Since the container contains water, leakage of water may cause corrosion of the metal plate.
- Metal plate adds extra weight on the screw jack.
- Fabrication is costly.

A wooden block can be used instead of metal plate. The wooden block has higher compressive strength with less weight. Fabrication of wooden block is easy and cheaper.

3.6.3. Design of wooden block

A wooden block was designed in CATIA. The Figure 3.13 shows the designed wooden block. A window is provided within the wooden block to accommodate nut and bolts.

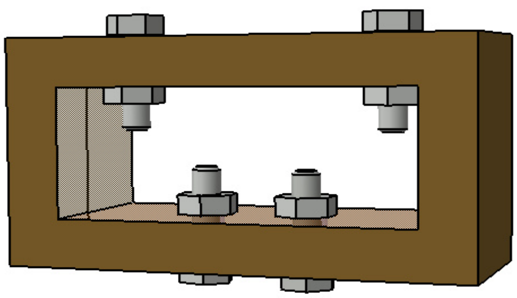


Figure 3.9: Wooden Block

The installed rectangular wooden block with the screw jack and container is shown in figure 3.14.

Figure 3.10: Screw jack with rectangular wooden block

3.7. Selection of shaft

In torsional oscillation of single rotor system, the chuck can hold a shaft up to 7mm. A suitable brass shaft of diameter 5mm was selected and bought. The torsional oscillations in single rotor system were studied using this shaft.

IV. CONDUCTION OF EXPERIMENTS

4.1. Description of Forced Vibration Tester

The apparatus shown in Figure 4.1consists of a rectangular beam, supported at one end by in a fixed housing. The other end of the beam is supported by a helical spring of known stiffness bolted to the bracket fixed to the top member of the frame. This bracket enables fine adjustments of the spring, thus raising and lowering the end of the beam. The Exciter Motor and Speed Control rigidly bolt to the beam. Two out-of-balance discs provide the forcing motion. The forcing frequency adjusts by means of the speed control unit.

The chart recorder fits to the right-hand vertical member of the frame and provides the means of obtaining a trace of the vibration. The recorder unit consists of a slowly rotating drum driven by a synchronous motor, operated from auxiliary supply on the Exciter Motor and Speed Control unit. A roll of recording paper is adjacent to the drum and is wound round the drum so that the paper is driven at a constant speed. A pencil fits to the free end of the pencil-holder; pencil just touches the paper. By switching on the motor, we can obtain a trace showing the oscillations of the end of the beam. Extra damping is introduced into the system by fitting the dashpot assembly.[6]

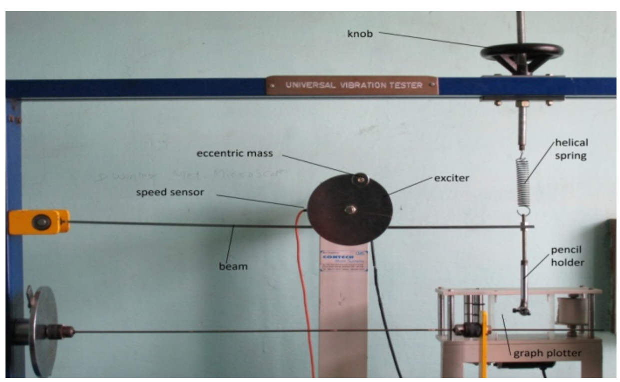


Figure 4.1: Forced Vibration experimental setup.

Observations:

1. Mass of the beam, M_b = 1.012 kg
2. Length of the beam, L = 0.9 m
3. Width of the beam, w = 25 mm.

4. Thickness of the beam, t = 5.5 mm.
5. Mass of the motor, M = 4.887 kg.
6. Distance of motor from pivot point, a = 0.45 m.
7. Eccentric masses, m = 0.055 kg
8. Eccentricity, e = 0.104 mm.
9. Stiffness of the spring, K = 450 N/m
10. Distance of spring from the pivot = 0.87 m

Procedure:

- While the motor is turned off, give the beam a small vertical displacement, and then release it to oscillate freely for ten oscillations. Record the elapsed time *T*.
- Switch on the speed control unit so the resulting forced vibration causes the beam to oscillate.
- Increase the speed of the motor slowly and notice the response of the system, and at the same time; try to identify the point at which resonance takes place. Record the speed of the motor at that state N_r.
- Bring the pencil in contact with the paper. Turn the motor of the drum on, and after ten seconds stop it and remove the chart for using it in the calculations.

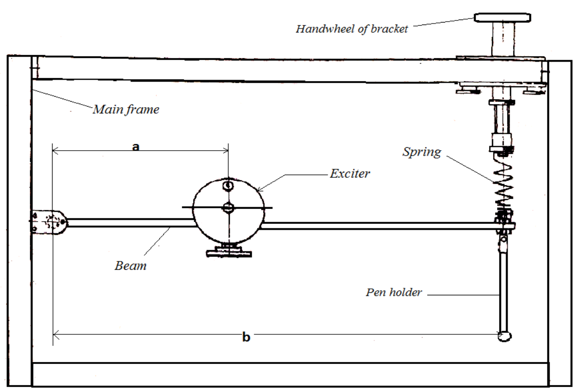


Figure 4.2: Schematic diagram of forced vibration experimental setup.

Calculations:

Free Vibrations

1. The natural frequency (theoretical) = $\omega_n = \sqrt{\frac{Kb^2}{I}}$

Where, $I = \left(Ma^2 + M_b \frac{L^2}{3}\right)$

$$I = \left(4.887 * 0.45^2 + 1.012 * \frac{0.9^2}{3}\right)$$

I =1.262 kg-m^2

$\omega_{n\ theoretical} = \sqrt{\frac{450*0.87^2}{1.262}}$

$\omega_{n\ theoretical}$= 16.42 rad/sec

Table 4.1 Natural frequency (experimental) ω_{nexp}

Sl No.	No. of Oscillations, n	Time for 'n' Oscillations, T sec	$\omega=\frac{2\pi N}{T}$ rad/sec
1	10	4.4	14.27
2	10	4.5	13.96
3	10	4.3	14.67

Forced Vibrations

1. Angular velocity of the disc, $\omega = \frac{2\pi N}{60}$ rad/sec

Where, N is in rpm

$\omega = \frac{2\pi \times 230}{60}$

ω = 24.085 rad/sec

2. Amplitude $X = \frac{mea\omega^2}{Kb^2 - I_A\omega^2}$

$= \frac{0.104*0.055*0.45*24.0855^2}{450*0.87^2 - 1.262*24.085^2}$

X= 4.386mm

3. Vertical displacement of the beam, $Y = LX = \frac{mea\omega^2}{Kb^2 - I_A\omega^2}$

Y = 0.9*4.386

= 3.94mm

Result:

1. Experimental natural frequency, ω_{exp}= 14.30 rad/sec.
2. Theoretical natural frequency, ω_{the} = 16.42 rad/sec.
3. Theoretical amplitude = 4.386 mm
4. Vertical Displacement of the beam = 3.94 mm

Conclusion:

Due to the external excitation the vibrations were continuous and did not decay with respect to time. The experimental and theoretical natural frequencies were compared. The theoretical amplitude could not be compared with the experimental value due to improper trace of vibration on the graph plotter. At higher speeds of the exciter the system was unstable.

4.2 Description of damped torsional vibration

The apparatus shown in figure 4.3, consists of a vertical shaft gripped at its upper end by a chuck attached to a bracket and by a similar chuck attached to a heavy rotor at its lower end. The rotor suspends over a cylindrical container containing damping liquid. The container can be raised or lowered by means of screw jack on its underside, allowing the contact area between the damping fluid in the container and the portion of the rotor to vary. This effectively varies the damping torque on the rotor when the latter oscillates. Record damped oscillation traces on paper wrapped round the drum mounted above the flywheel. It also consists of a pen-holder and pen, which adjust to make proper contact with the paper; the unit undergoes a controlled descent over the length of the drum by means of an oil dashpot clamped to the main frame.[6]

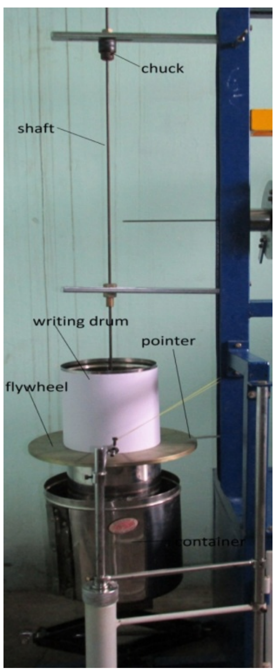


Figure 4.3: Damped Torsional vibration experiment setup

Procedure of Experiment:

1. With no liquid in the container allow the flywheel to oscillate and measure the time for 10 oscillations.
2. Put liquid(water) in the drum and note the depth of immersion.
3. Put the sketching pen in the bracket.
4. Allow the flywheel to vibrate.
5. Allow the pen to descend and see that it is in contact with the paper.
6. Measure the time for some oscillations by means of stop watch.
7. Determine amplitude (X_n) at any position and amplitude(X) after Y cycles.
8. Repeat the procedure for different depth of immersion.

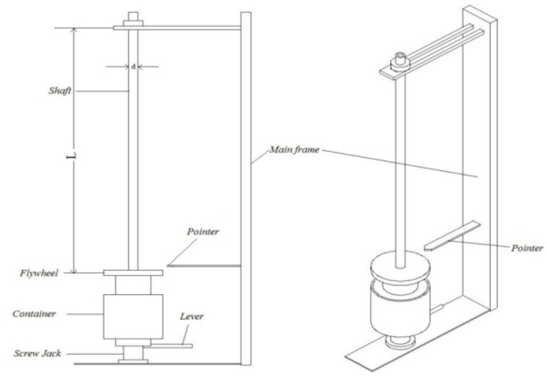


Figure 4.4: Schematic diagram of Damped torsional oscillations.

Observations:

1. Material of the shaft: Brass
2. Diameter of shaft (d) = 5.5 mm
3. Length of shaft (L) = 0.9m
4. Modulus of rigidity (G) = 40 GPa.

Table 4.2: Natural frequency of the shaft.

No. of N	Time, T in secs	$\omega_n=2\pi N/T$
10	11.27	5.575

Table 4.3: Amplitude at various depth of immersion

SL NO.	Depth of immersion (mm)	X_n cm	X cm
1	0	4.2	1.2
2	10	3.9	1.0
3	20	3.7	0.8
4	30	3.5	0.7
5	40	3.3	0.7

Calculations:

1. Natural frequency ω_n

$\omega_n = \frac{2\pi N}{T}$ *rads/sec*

$\omega_n = \frac{2\,\pi\,X\,10}{11.27}$

$\omega_n = 5.575$ *rad/sec*

2. Stiffnes of the shaft

$K_t = \frac{G * I_p}{L}$

$K_t = \frac{4\,X\,10^{10}\,X\,8.98\,X\,10^{-11}}{0.9}$ *N-m/rad*

= *3.99N-m/rad*

where $I_p = \frac{\pi d^4}{32} = \frac{\pi\,5.5^4}{32} = 8.98\ X\ 10^{-11}\ mm^4$

3. Damping ratio is given by

$\delta = \frac{1}{n} ln \frac{X_n}{X}$

$= \frac{1}{5} ln \frac{3.9}{1}$

= .272

4.Damping co-efficient ξ,

$\xi = \frac{\delta}{\sqrt{4\pi^2 + \delta^2}}$

$\xi = \frac{.272}{\sqrt{4\pi^2 + .272^2}}$

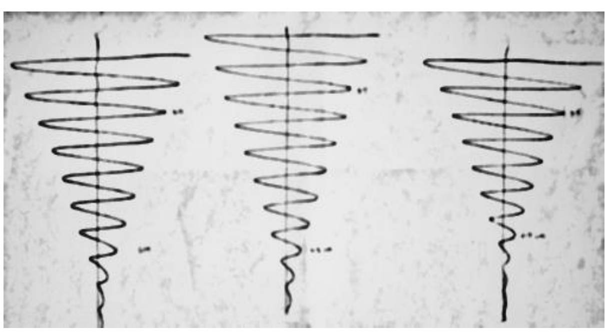
= 0.0432 *N-s/m*

5. Moment of Interia

$= \frac{K_t}{\omega_n^2}$

$= \frac{3.99}{5.575^2}$

= 0.128 *kg-m²*



Graph 4.1: Trace obtained from damped torsional vibrations.

Result:

1. Torsional stiffness of the shaft= 3.99 *N-m/rad*
2. Moment of Interia = 0.128 $kg\text{-}m^2$

Table 4.4: Result Table

SL No.	Depth of Immersion Mm	Damping ratio, δ	Co-efficient of damping, ξ
1	0	0.25	0.0397
2	10	0.272	0.0432
3	20	0.306	0.0486
4	30	0.322	0.0512
5	40	0.310	0.0490

Conclusion

As the depth of immersion was increased the amplitude of vibrations were decreased due to damping. The accurate results were obtained by keeping the angle of rotation of the flywheel same of every depth of immersion.

4.3 Description of Torsional oscillations of Single Rotor System

The apparatus shown in Figure 4.5 consist of cylindrical shaped rotor which provides required inertia. The diameter of the rotor is 260mm and weighs 2.87kgs. The rotor mounts on a short axle, which fits in the vertical members of the portal frame, and secures by a knurled knob. The rotor is fitted with a chuck designed to accept shafts of different diameter. An identical chuck rigidly clamps the shaft, which is an integral part of a bracket. This is at the same height as the flywheel chuck and adjustable, relative to the base of the portal frame.[6]

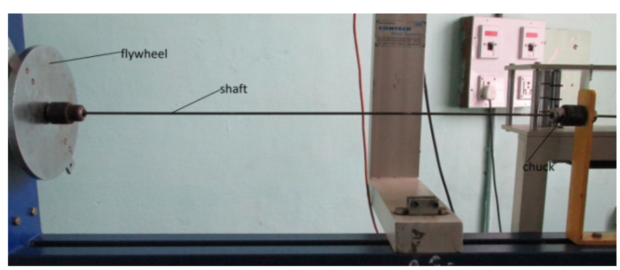


Figure 4.5: Experimental setup of Single Rotor system.

Observations:

1. Material = Brass
2. Shaft diameter, d = 4.5 mm.

3. Diameter of disc, D = 260 mm.
4. Weight of the disc, W = 2.87 kg.
5. Modulus of rigidity for shaft, G = 40 GPa.

Procedure:

1. Fix the brackets at convenient position along the lower beam.
2. Grip one end of the shaft at the bracket by chuck.
3. Fix the rotor on the other end of the shaft.
4. Twist the rotor through some angle and release.
5. Note down the time required for 5 to 10 oscillations.
6. Repeat the procedure for different length of the shaft.

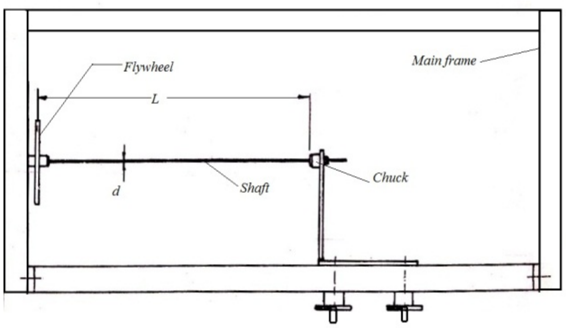


Figure 4.6: Schematic diagram of Single rotor system

Table 4.5: Observation table for single rotor system.

Length of the Shaft, L cm	Number of oscillations, n	Time for n oscillations, t, sec	Periodic time, T_{exp}= t/n sec	Frequency f = $1/T_{exp}$ Hz
70	5	3.77	0.754	1.32
75	5	3.75	0.75	1.33
80	5	3.72	0.744	1.34
85	5	3.65	0.73	1.36
90	5	3.55	0.71	1.40

Calculations:

For Trial 1

1. Polar moment of inertia of shaft (J) = $\pi * d^4 / 32 m^4$= $\pi*(0.0045^4 / 32)$=$4.025*10^{-11} m4$

2. Moment of inertia of disc, I = $(W)*(D^2/8) kg\text{-}m^2$ = $(2.87)*(.26^2/8)$ = 0.0242 $kg\text{-}m^2$

3. Torsional stiffness (Kt)= $\frac{J*G}{L}$ *N-m/ rad*
= $(4.025*10^{-11} *4 * 10^{10}) / 0.7$
= 2.3 *N-m/ rad*

4. Periodic time, T (theoretically)

$$T_{theo} = 2\pi\sqrt{\frac{I}{K_t}} \text{ sec}$$

$$=2\pi\sqrt{\frac{0.0242}{2.3}}$$

= 0.645 sec

5. Periodic time, T (expt) = t/n = 3.77 / 5
= 0.754 sec

6. Frequency, f (expt) = 1 / T_{exp} Hz
= 1/0.754
= 1.32 Hz

7. Frequency, f (theo) = $\frac{1}{2\pi}\sqrt{\frac{K_t}{I}}$ Hz

$$= \frac{1}{2\pi}\sqrt{\frac{2.3}{0.0242}}$$

=1.551Hz

Table 4.6: Result table

SL NO.	Periodic time T (expt) in Sec	Frequency, f(expt) Hz	Periodic time T (theo) in Sec	Frequency f (theo) Hz
1	0.754	1.32	0.645	1.551
2	0.75	1.33	0.668	1.497
3	0.745	1.34	0.689	1.450
4	0.73	1.36	0.710	1.408
5	0.71	1.40	0.730	1.370

Result:

1. The natural frequency of undamped free torsional vibration (theo) = 1.551 Hz
2. The natural frequency of undamped free torsional vibration (expt) = 1.32 Hz

Conclusion:

The experimental results show that the natural frequency of the shaft depends on its cross section and the material. The natural frequency is a material property and does not change with change in length of the shaft.

V. CONCLUSION

The main intention of this project is to upgrade and remodel Universal vibration tester present in our Design Laboratory which was out of order and had many problems associated with it.

After initial investigation, the various problems associated with the experimental setup were found. Out of many experiments that can be conducted, three experiments were selected.

1. Forced Vibration Tester.
2. Damped Torsional Vibrations.
3. Torsional Oscillations of Single Rotor Shaft.

We have designed and fabricated different machine elements which were necessary to rectify the problem associated for conduction of these three selected experiments. These elements were installed to carry out the experiments successfully.

Now, this experimental setup can be used to conduct those three experiments which give accurate results in comparison with theoretical values as discussed earlier.

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