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Performance enhancement of mechanical power amplifier

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ABSTRACT

In many applications it is required to control a large output load using a relatively low control force. To satisfy such purposes, device like mechanical power amplifier can be used which generally gives very fast response. As per the requirement of the system, power can be instantaneously available from continuously rotating drums of mechanical power amplifier. This project will focus on the computation of amplification factor of mechanical power amplifier for different rope material like leather, woven cotton and steel rope. This study will be carried out for determination of optimum performance of mechanical power amplifier.

Keywords— **Mechanical Power Amplifier, Capstan Principle, Rope, Drum, Motor, Gear train, lay shaft.**

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I. INTRODUCTION

The Mechanical power amplifiers are those devices which are based on capstan principle. These devices vary the control force and amplify the part of power partially supplied to the drum. Two rotating drums mounted back to back can supply the bi-directional power between input and output shafts. It replaces conventional transducers which are used in the electrical, hydraulic, pneumatic systems. Thus it reduces the possibility of the cumulative error due to the use of transducers. The capstan principle also known as belt friction equation as well as Eytelwein's equation. It relates the hold-force to the load–force when flexible rope line is wound around a cylinder, in this case because of the interaction of frictional forces between rope & drum, tension in the rope, the resultant force acting on the rope line wrapped around a capstan drum may be different on its either side. Thus, a small holding force exerted on one side can carry a much large load on the other side. This paper focus on the study related to design and tests of the proposed prototype of power amplifier to evaluate its performance through amplification factor by design optimization for number of turns of rope, different material (Leather, woven cotton, steel) and proper sizing of its assembly.

II. LITERATURE REVIEW

[1] explains that the frictional force play an important role in rope rescue operation. Understanding of the various factors that affect rope friction is essential because friction in rope rescue can change exponentially with the rope geometry and the coefficient of friction. This paper highlights the frictional force in the rope which depends upon the load on the rope, the coefficient of friction and the angle that the rope turns through. The angle and coefficient of friction can cause an exponential change in rope tension. Thomas and Gimenez [2] given insight about the design and experimental characterization of a continuously variable linear force amplifier based on the theory of capstans. It uses an elastic cable, enabling a control actuator to not only continuously clutch output to a rotating drum but also passively declutch by releasing tension. These systems have the potential to increase the dynamic performance of a robotic system by reducing the overall

inertia of moving parts. Their design allows more number of turns and thus higher amplification ratios, without the binding of ropes around the drum with the use of elastic cable. It avoids binding due to elastic cable's high bending stiffness and casing has been used around the drum through which elastic cable follows helical wraps. It also shows elastic cable is preferable over regular cord as it reduce spring back effect. Morten, et al. [3] worked on a petroleum well intervention winch system. This system uses a bending flexible rope in the order to provide reduced size of the drum and all sheaves and wheels over which the rope passes. The system includes for all moving components confined in a high-pressure housing, and has a capstan drive, used for taking the load of the rope running with the tool string in the well. When the access to well is open, the invention allows for a slender and robust vertically extending unit for being mounted on a tool string gate chamber on a wellhead, the winch system for operating under well pressure.

Brandt [4] worked on an automated rail car gate operating system for capstan-operated rail-car gates sequentially locates and opens and closes gate operating capstans on the fly as the car move along across a cargo receiving pits that, in addition to automatically unloading stationary railcars. This results in exclusion of a separate indexing system. Worked performed by Schena and Cooper [5] relates to a compact design of capstan drive which includes a drum, a coupled hub, a passage extending through the drum and hub and a shaft extending through the drum and hub. The shaft engages the passage such that the shaft can transmit a torsional force to the drum and the hub which are free to move along the length of the shaft. This system controls the cable drive which the driver of servo mechanisms that is coupled to the robotically controlled working tool to drive and control the movement of the tool. As space in the surgical field where robotically controlled working tools are being used is to be optimum. It aims to minimize the angle in the cable at the take-off point of the capstan while at the same time providing a compact mechanism to drive and control movement of a robotically controlled working tool. Tjader [6] work relates to pulling equipment for use in trenchless pipe replacement. Trenchless pipe replacement technique is used to replace large diameter underground pipes used for water, sewage mail lines. This method includes inserting a flexible line through an existing pipe and attaching a bursting tool to a distal end of the flexible line. The method also includes a proximal end of the flexible line to a pulling device. Coupling to the pulling device includes routing the flexible line around the capstan and rotating the capstan to pull the bursting tool through existing pipe. For rotating capstan includes powering a harmonic drive gear reduction coupled to the drum. Jenkins [7] represents a case study on the development of a capstan drive with feedback control for use in optical fibre production. Uniformity of diameter of optical cable is critical concern for its effective operation and optimum cost control. This can be achieved by the design of an optical fibre draw capstan pulley. Key steps in the design and development of the capstan system includes the motor selection, design of capstan pulley and belt material. The system modelling of the process and selection of design parameters using multidisciplinary criteria was used to develop a machine that performed better than had the design been serially completed by each engineering discipline. Bingaman [8] developed an apparatus and method for controlling the speed of a tape drive having an ingoing capstan and an outgoing capstan with a magnetic head there between. These capstans are drive by DC servo motors. Two phase Lock loop servo-circuits to initiate the drive motors'. Lewis and Oaks [9] improve the performance of magnetic recording apparatus by the use of the dual capstan type. This dual capstan drive consists of a reversible drive motor which connected to the two capstans by a belt-coupling system. This will cause the lead capstan to be rotated at a slightly higher speed than the other capstan because of which a certain minimum tape tension across the transducer heads of the recording apparatus at all times.

After studying all above research papers, we have reached to the basis of concept that, capstan amplifier generally consists of rope wound around drum. It is desirable to have compact design with elastic rope which should not be rigid otherwise substantial portion of tension will be utilised to overcome the same. As a result, it can amplify the load connected to output end of rope by virtue of its interaction with the tension in the rope, coefficient of friction between the rope and drum and also number of turns of rope. While some of the parameter like drum diameter, input driving system consist of motor drive shall be optimize to control cost and make the more compact design. However, the likelihood of binding also increases with additional number of turn of rope. When binding occurs, the increased tension in the cord causes the rope to effectively adhere to the drum, thus changing the kinetic friction coefficient greater than static friction coefficient. Rope binding on the drum results in the loss of control over the tensile loading of the output rope.

Number of turns	Coefficient of friction (μ)						
	0.1	0.2	0.3	0.4	0.5	0.6	0.7
1	1.9	3.5	6.6	12	23	43	81
2	3.5	12	43	152	535	1881	6661
3	6.6	43	286	1881	12392	81612	437503
4	12	152	1881	23228	286751	3540026	43702631

III. WORKING PRINCIPLE FOR MECHANICAL POWER AMPLIFIER

The capstan principle is the basis for the mechanical power amplifier which primarily consists of two counter rotating drums and rope wound around it as shown in Fig.1.

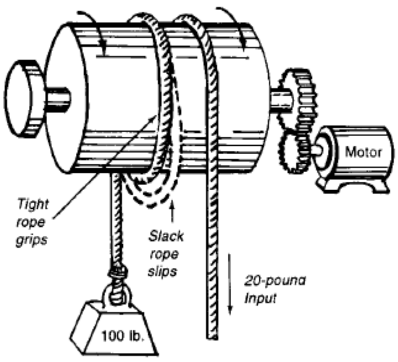


Fig. 1 Basic layout of mechanical power amplifier

The working principle for mechanical power amplifier is given by below capstan equation:

$T_{load} = T_{hold} e^{\mu\varphi}$ ----------------------------[1]

Where is the applied tension on the rope line, is the resultant force exerted at the other side of the capstan, is the coefficient of friction between the rope and capstan materials, is the total angle swept by all turns of the rope, measured in radians (i.e., with one full turn the angle), as shown in

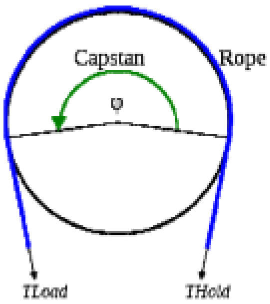


Fig.2

Fig. 2 Working principle of mechanical power amplifier

Following assumptions are made for the formula to be valid:

1.The rope is on the verge of full sliding, i.e. is the maximum load that one can hold. Smaller loads can be held as well, resulting in a smaller effective contact angle.

2.It is important that the Rope line is not rigid, otherwise significant force would be lost in the bending of the line tightly around the cylinder. For example, a Bowden cable is to some extent rigid and doesn't obey the principles of the Capstan equation.

3.The rope line is made of elastic material.

From the Eq.1, it is observed that the force gain grows exponentially with the coefficient of friction, the number of turns around the cylinder, and the angle of contact. Note that the radius of the cylinder has no influence on the force gain. The Table1 lists values of the factor based on the number of turns and coefficient of friction.

Table1- Theoretical Study of Capstan Principle

From the Table1 it is evident why one seldom sees a sheet (a rope to the loose side of a sail) wound more than three turns around a winch. The force gain would be extreme besides being counter-productive since there is risk of a riding turn, result being that the sheet will foul, form a knot and not run out when eased (by slacking grip on the tail (free end), or in land talk, one lets go of the hold end. It is both ancient and modern practice for anchor capstans and jib winches to be slightly flared out at the base, rather than cylindrical, to prevent the rope (anchor warp or sail sheet) from sliding down. The rope wound several times around the winch can slip upwards gradually, with little risk of a riding turn, provided it is tailed(loose end is pulled clear), by hand or a self-trailer.

Using the above principle, it is thus possible to develop a mechanical power amplifier, that will amplify the small control force applied by means of a input motor. The output of the device can then be used for demonstration of load positioning application.

IV. PROBLEM FORMULATION AND OBJECTIVE

After studying research papers, patents & Technical reports as mentioned in reference section, we have decided the basis of this research work that the mechanical power amplifier generally consists of rope wound around the drum shall have compact design with elastic rope which should not be rigid so that it can amplify the load connected to output end of rope by virtue of its interaction with the tension in the rope, coefficient of friction between rope & drum material, number of turn of rope. While some of parameter like drum diameter, input driving system consists of motor drive which should be optimize to control cost and make the compact design. It also eliminates the need of any other device such as transducer, pneumatic valve to change energy form required for controlled position and motion of heavy loads. The aim of this work is to design and test the proposed prototype of power amplifier to evaluate its performance used in aforesaid application through design optimization for number of turns of rope, material and proper sizing of its assembly.

In order to execute the above stated aim, following objectives were set in this work:

- Development of mathematical model for capstan drum.
- Design and development of power amplifier mechanism for kinematic linkage arrangement for input and output arms, location and specifications of gear train.
- Manufacturing and assembly of power amplifier.
- To perform test & trial on mechanical power amplifier with different rope materials to determine performance characteristics.

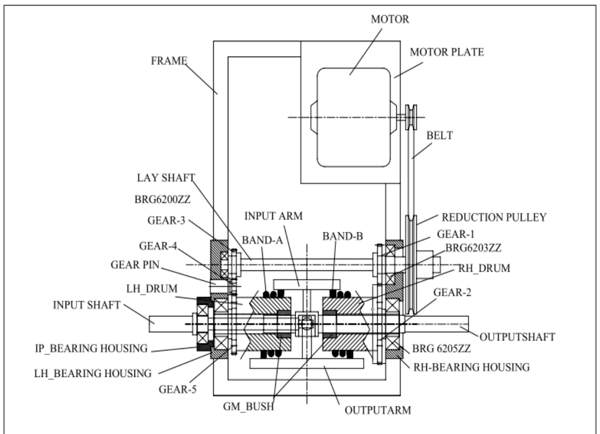
V. EXPERIMENTAL SET UP AND CONSTRUCTION

A capstan is a simple mechanical amplifier-rope wound on a motor-driven drum. The drums are continuously rotating but only transmit torque when the input shaft is rotated to tighten on drum A as shown in Fig.3

Fig.3 Experimental set-up for capstan power amplifier

Fig. 4 Fabricated assembly of mechanical power amplifier

Overrun of output is stopped by the drum, when it tightens the band B on this drum. Slip takes place until slack is taken up on the free end. The force needed on the free end to lift the load depends on the coefficient of friction and the number of turns of rope. By connecting bands A and B to an input shaft and arm, the power amplifier provides an output in both directions, plus accurate angular positioning.



ASSEMBLY OF CAPSTAN POWER AMPLIFIER

When the input shaft is turned clockwise, the input arm takes up the slack on band A, locking it to its drum. Because the load end of locked band A is connected to the output arm, it transmits the CW motion of the driven drum on which it is wound to the output shaft. The capstan equation or belt friction equation, also known as Eytelwein's formula relates the hold-force to the load-force if a flexible line is wound around a cylinder (a bollard, a winch) because of the interaction of frictional forces and tension, the tension on a line wrapped around a capstan may be different on either side of the capstan. A small holding force exerted on one side can carry a much larger loading force on the other side; this is the principle by which a capstan-type device operates. For instance in rock climbing with so-called top-roping, a lighter person can hold (belay) a heavier person due to this effect. By connecting bands A and B to an input shaft and arm, the power amplifier provides an output in both directions, plus accurate angular positioning. When the input shaft is turned clockwise, the input arm takes up the slack on band A, locking it to its drum. In as much as the load end of locked band A is connected to the output arm, it transmits the clockwise motion of the driven drum on which it is wound, to the output shaft. Band B therefore slacks off and slips on its drum. When the clockwise motion of the input shaft stops, tension on band A is released and it slips on its own drum. If the output shaft tries to overrun, the output arm will apply tension to band B, causing it to tighten on the counter clockwise rotating drum and stop the shaft. Motor delivers power to the input shaft in clockwise direction whereas drives drum-B in anticlockwise direction. The torque amplification depends upon the coefficient of friction between drum and band, diameter of the drums and the number of wraps on the bands on their respective drums. Input power delivered to the input shaft is multiplied using the above amplifier arrangement and

delivered to the output shaft.

The prototype of Capstan mechanical power amplifier consists of the following components:

1. *Electrical motor*: The electrical motor is a single phase AC motor of 50 watt capacity and 0 to 9500 rpm variable speed. The speed control is done by means of an electronic speed variator. The motor carries the motor pulley which connected to the reduction pulley mounted on the lay shaft which forms the drive for the system.

Motor Selection: The power is transmitted to the input shaft of the amplifier by means of an open belt drive using two pulleys and belt, the specifications of the drive are as follows,

i. Motor pulley diameter = 25 mm
ii. Input shaft pulley diameter = 100 mm
iii. Reduction ratio (i) = 4
iv. Input speed = 2100 rpm
v. Reduction ratio = 4
vi. Output speed at lay shaft = 2100/4 =525 rpm

Power = $2 \times \pi \times 2100 \times .20/60 = 43.98$ W.

Hence motor of 50 watt is selected with following details.

a. Motor type: single phase AC Motor .
b. Torque: 2 kgcm.
c. Speed: 6000 rpm.
d. Input power: 50 watt.

2. *Lay shaft*

The lay shaft is held between two ball bearings mounted in bearing housing. The lay shaft carries a set of gears from the gear train and the reduction pulley at one end.

Table 2 Mechanical properties of EN24 material

Designation	Ultimate Tensile Strength N/mm^2	Yield strength N/mm^2
EN 24 (40 N; $2c_r1$Mo 28)	720	600

3. *Gear train Specification*

The gear train comprises of five gears namely:

Gear-1: 1.5 module, 18 teeth, face width 5mm
Gear-2: 1.5 module, 20 teeth, face width 5mm
Gear-3: 1.5 module, 40 teeth, face width 5mm
Gear-4: 1.5 module, 32 teeth, face width 5mm
Gear-5: 1.5 module, 64 teeth, face width 5mm

4. *LH and RH Drums*

The left and right hand drums are mounted in bearings 6005ZZ respectively in the bearing housing and carry gun metal bushing that support the output shaft. The band is wound on the drums and it is further connected to input and out arms respectively at its two ends.

5. *Input and output Arms*

The input and out arms are connected to the input shaft and output shaft respectively. The bands wound on the drums are connected to these arms at their two ends.

6. *Input shaft*

The input shaft is mounted in ball bearing 6203zz held in the input shaft housing at one end where as the other end is connected to the input arm.

7. *Output shaft*

The output shaft held in gunmetal bush bearings mounted inside the load drums and it is made hollow at one end so that the input shaft passes through it.

8. *Frame*

The frame is the structural member that supports the entire power amplifier assembly, the LH & RH bearing housings, motor plate are welded to the frame.

9. *Rope*

The rope is a cotton beaded rope of 6 mm diameter with the left hand band wound on the left hand drum and the right hand band wound on the right hand drum. The ends of these bands are fixed to the input and output arms respectively.

Table 3- List of component

Sr. No.	Part Code	Description	Qty	Material
1.	pamp-1	motor	01	std
2.	pamp -2	belt	01	std
3.	pamp -3	reduction pulley	01	en9
4.	pamp -4	rh_ brg_housing	01	en9
5.	pamp -5	frame	01	ms
6.	pamp -6	motor plate	01	ms
7.	pamp -7	lay shaft	01	en24
8.	pamp -8	ip_shaft	01	en24
9.	pamp -9	op_shaft	01	en24
10.	pamp –10	lh_drum	01	en24
11.	pamp –11	rh_drum	01	en24
12.	pamp –12	input arm	01	en9
13.	pamp -13	output arm	01	en9
14.	pamp -14	gears	05	std
15.	pamp -15	band	01	std
16.	pamp -16	ip_brg housing	01	en9
17.	pamp-17	gear pin	01	en24
18.	pamp-19	brg 6203zz	02	std
19.	pamp-20	brg 6200zz	01	std

VI. TEST TRIALS AND MEASUREMENT

In order to conduct trial, an dyno-brake pulley cord, weight pan are provided on the output shaft.

Input Data:-

A) Drive Motor

AC230 Volt

0.5 Amp, 50 watt

50 Hz, 200 to 9500 rpm

TEFC COMMUTATOR MOTOR

B) Select the leather material for rope and wound three numbers of turn of it around corresponding drums. Then conduct trials by following procedure as;

Procedure:-

1. Start motor by turning electronic speed variator knob.
2. Let mechanism run & stabilize at certain speed (say 1300 rpm)
3. Place the weight in the weight pan attached to input arm bracket of LH side input shaft and add 100 gm weight into weight pan. Simultaneously note down the speed for this load by means of tachometer.
4. Keep adding another 100 gm weight into the weight pan & take reading.
5. Note down the reading on electronic loading cell which is attached to output arm bracket mounted on load pulley fixed on RH side output shaft.
6. Calculate the input torque and output torque by using arm length = 100 mm.
7. Tabulate the readings in the observation table.
8. Plot Torque versus speed characteristic, power versus speed characteristic.
9. Repeat above steps of trial by varying rope material as woven cotton and steel.
10. Sample Calculations

Here sample calculations for observation 1 as Table 6 are given as;

- Input Torque = Load in the weight pan (N) ×Length of input arm (m)

  = 0.1×9.81× 0.10 = 0.0981 N-m
- Output Torque = Electronic load cell reading (N) ×Length of output arm (m)

  = 0.170×9.81× 0.1 = 0.1667 N-m

- Power consumed across output shaft = 2×π×N×T/60

  = 2×3.143×2100× 0.1667 / 60

  = 36.656 Watt
- Efficiency = Input / output = 36.656/ 71.56 = 51.23 %

From observation Table 6 and its calculations, it is evident that maximum amplification factor for leather rope material is 2.23. In similar way, from observation Table 5 and its calculations, maximum amplification factor for steel rope material is 1.32 and from observation Table 7, that of woven cotton is 1.867

Table 4:- Loading and unloading data

Sr. No.	Loading		Unloading		Mean Speed (rpm)
	Weight (gm)	Speed rpm	Weight (gm)	Speed (rpm)	
1.	100	2100	100	2100	2100
2.	150	1960	150	1960	1960
3.	200	1750	200	1750	1750
4.	250	1600	250	1600	1600
5.	300	1250	300	1250	1250
6.	350	1050	350	1050	1050
7.	500	810	500	810	810
8.	600	650	600	650	650
9.	700	535	700	535	535
10	800	520	800	520	520

Table 5:- observation table for power amplification factor with material

Sr. No.	Load at input shaft (gm)	Load cell reading at output shaft (gm)	Speed (rpm)	Input torque (N-m)	Output Arm Amplified torque (N-m)	Power consumed across output shaft (watt)	Power amplification factor = (output torque / input torque)	Efficiency (%)
1	100	110	2100	0.0981	0.10791	23.718	1.1	33.1439
2	150	180	1960	0.14715	0.17658	36.224	1.2	45.17521
3	200	233.3334	1750	0.1962	0.2289	41.926	1.166667	48.7877
4	250	300	1600	0.24525	0.2943	49.2854	1.2	54.11748
5	300	378	1250	0.2943	0.370818	48.515	1.26	54.81697
6	350	460.83345	1050	0.34335	0.45207	49.683	1.316667	56.629
7	500	614.2855	810	0.4905	0.60261	51.0896	1.228571	55.7840
8	600	697.5	650	0.5886	0.68424	46.55	1.1625	51.6985
9	700	882	535	0.6867	0.8652	48.450	1.26	54.7756
10	800	1024	520	0.7848	1.0045	54.673	1.28	58.9705
11	1000	1290	380	0.981	1.265	50.332	1.29	56.5424

Table 7:- observation table for power amplification factor with woven cotton rope material

Sr. No.	Load at input shaft (gm)	Load cell reading at output shaft (gm)	Speed (rpm)	Input torque (N-m)	Output Arm Amplified torque (N-m)	Power consumed across output shaft (watt)	Power amplification factor = (output torque / input torque)	Efficiency (%)
1	100	150	2100	0.0981	0.14715	32.34357	1.1	45.19633081
2	150	232.5	1960	0.14715	0.2280825	46.7903646	1.3	58.35131739
3	200	314	1750	0.1962	0.308034	56.421561	1.433333	65.65433287
4	250	400	1600	0.24525	0.3924	65.71392	1.5	72.15664228
5	300	495	1250	0.2943	0.485595	63.5320125	1.6	71.78413748
6	350	588	1050	0.34335	0.576828	63.3933972	1.75	72.25622675
7	500	850	810	0.4905	0.83385	70.693803	1.857143	77.18962655
8	600	1032	650	0.5886	1.012392	68.8764024	1.5625	76.49158315
9	700	1239	535	0.6867	1.215459	68.06165247	1.48	76.94676376
10	800	1472	520	0.7848	1.444032	78.59384832	1.39	84.7701616
11	1000	1850	380	0.981	1.81485	72.182634	1.2	81.08801132

VII. RESULT AND DISCUSSION

To validate the experimental findings number of trials were conducted by varying input loads in weight pan from 100 gm to 1kg and corresponding readings of electronic load cell, variation in the speed, input torque, output torque, power and efficiency are noted. Results obtained by using rope material as leather material and by using two numbers of turns are tabulated in Table 6 similarly, Table 5 for steel material, table 7 for woven cotton material. From Table 4 and Table 6 relationship between speed, torque, power , efficiency of power amplifier assembly are plotted as shown in Fig. 5, Fig. 6 and Fig.7. The results were remarkably consistent with experimental measurements including favorable calculation of amplification factor.

From Figure 5, it is observed that as speed goes on decreasing torque measured at the input shaft goes on increasing due to increase in the applied input load. It is also observed that as speed goes on decreasing, torque measured at the output shaft goes on increasing. Torque varies in inverse proportion to the speed, though the amplification factor goes on increasing as speed decreases. Maximum value of amplification factor is equal to 2.34 at low speed values with corresponding high torque value. Still variation in the values of amplification factor remains is very less. Maximum output torque obtained at speed 380 rpm and is equal to 2.18 N-m.

From Fig.6, it is observed that as speed goes on decreasing, efficiency of the system goes on increasing. Hence initially speed is high, efficiency is less. As load on the system goes on increasing, efficiency of different power transmission system including belt drive and gear system goes on decreasing, hence overall efficiency of the system goes on decreasing after some threshold limit. The efficiency of 81.18 % is obtained at speed of 1600rpm and input load of 250 gm.

From Fig.7, it is observed that as speed goes on decreasing, power across output shaft of the system goes on increasing. Hence initially speed is high, power is less. As load across output shaft goes on increasing, speed goes on decreasing hence power across output shaft goes on increasing.

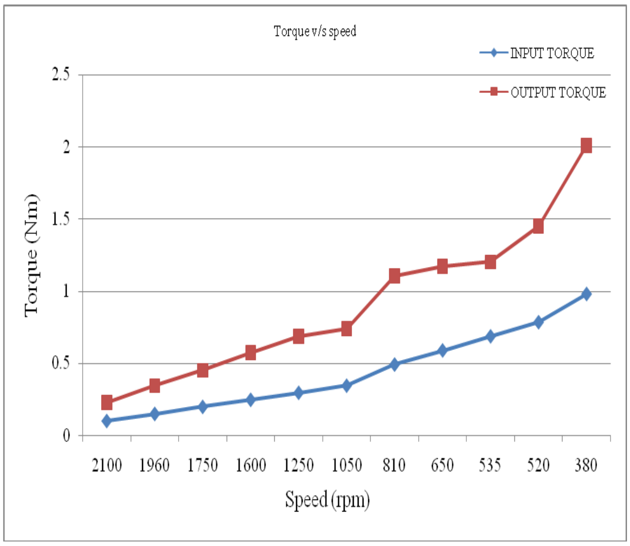


Fig.5 Torque versus speed

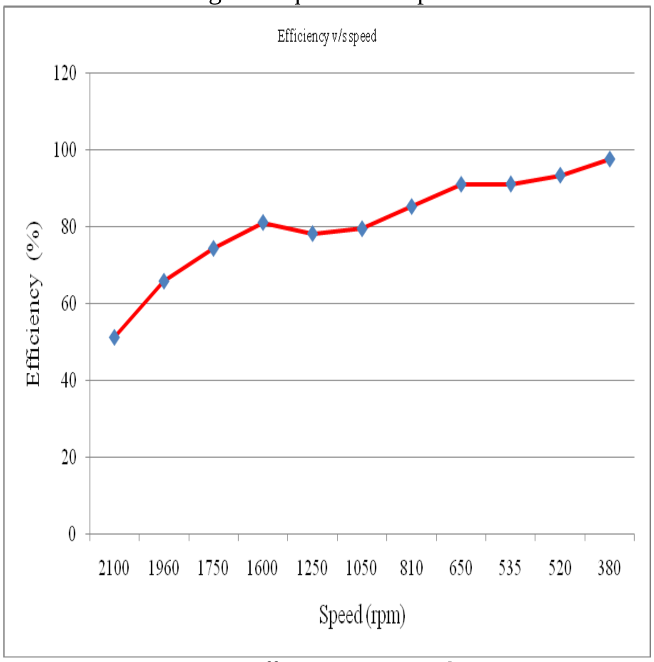


Fig 6 Efficiency versus speed

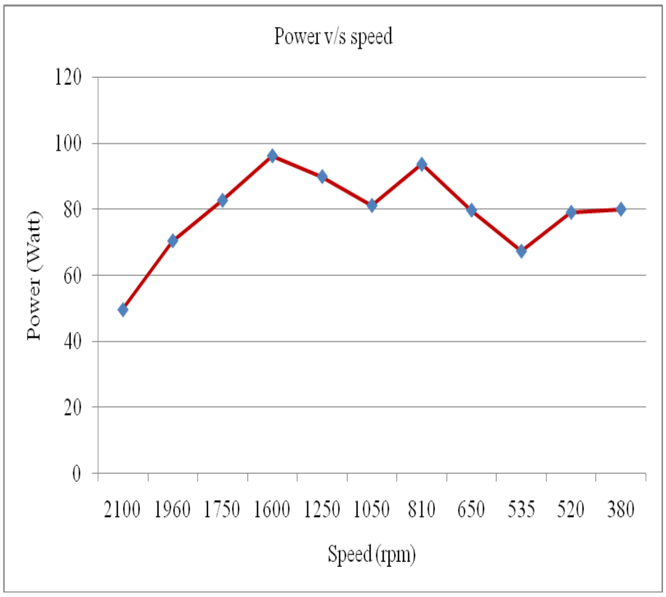


Fig. 7 Power versus speed

From experimental investigations it is seen that the performance of mechanical power amplifier can be enhanced by increasing its amplification factor.

Amplification factor depends upon following variables;

- It depends upon angle of wrap of rope wound around capstan drum .i.e. no of turns of rope. Amplification factor is exponentially proportional to number of turns. But if we increase no of turns beyond two or three, it will have binding of rope around drum which indeed decreases kinetic energy intake of rotating drum taken from electric motor drive. It results in loss of power and efficiency of transmission which gives absurd results. Taking this into account, selecting optimum number of turns i.e. two or three number of turns will give desired results.
- It also depends upon coefficient of friction between rope material and drum. By selecting proper elastic rope material having high coefficient of friction, power amplification factor can be enhanced.

It is evident that leather to steel rope-drum pair has the highest coefficient of friction (0.6) among the remaining materials i.e. woven

VIII. CONCLUSION

From the experimental analysis, it confirms fact that by keeping optimum number of turns equal to two, power amplification factor are found to be 2.23 for leather contact, 1.867 for woven cotton contact, 1.32 for steel contact of rope. It shows that power amplification is higher for leather as compare to woven cotton and steel. The results were remarkably consistent with experimental measurements including favorable calculation of amplification factor.

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