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Measuring the Amplification Factor of Mechanical Power Amplifier for Varying Rope Materials

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Abstract: *Controlling a sizeable output load, a relatively modest amount of control force is required in various applications. A device such as a mechanical power amplifier, which often responds promptly, may produce the desired effects in this context. Power can be made instantly available from the continually rotating drums of the mechanical power amplifier, depending on the requirements. This paper aimed to evaluate the amplification factor of mechanical power amplifiers for diverse rope materials like leather, woven cotton, and steel rope. A capstan mechanical amplifier-rope was used for the experiment. The experimental analysis showed that the power amplification factor is 2.23 for leather contact, 1.867 for woven cotton contact, and 1.32 for steel contact of rope. The experimental results show that leather amplifiers shown more power than woven cotton and steel rope with an inclusion of a favourable amplification factor calculation, the results obtained are strikingly compatible with experimental data.*

Keywords: *Computation Factor, Mechanical Power Amplifier, Capstan, Rope Materials*

INTRODUCTION

A power amplifier is a specific kind of electrical amplifier designed to increase the power of a signal fed into it (Bienert *et al.*, 2022; Wang *et al.*, 2022; Choi, 2023; Jeonget al., 2023). The strength of the input signal is increased to a level capable of driving various output devices. Amplifiers can be divided into current, voltage, and power amplifiers based on the modifications they make to the incoming signal. This paper examines power amplifiers in a mechanical context. Electronic devices based on the Capstan concept are known as mechanical power amplifiers. These amplifiers are utilized to amplify the magnitude of an electrical signal.

The capstan is a simple mechanical amplifier that works by winding rope until the slack on the free end is taken up on motorized drum slides. In common parlance, the capstan is utilized if the user is tasked with lifting or pulling something that is beyond the scope of what they can accomplish with their capabilities. The amount of force needed on the free end and to hoist the load depends on the rope's twist count and coefficient of friction. The power amplifier can provide precise angular placement in addition to output in both directions by using bands attached to an input shaft and arm (Thokale, 2016). Capstan mechanical amplifier describes a mechanical device consisting of a drum and gear arrangement and a single electrical motor that operates on electrical energy. Typically, capstans are employed to help lift or pull heavy things using winches. A capstan had the ability to dynamically magnify the input by adjusting the input strain on the cord (Starkey & Williams, 2011). These devices vary the control force that amplified the power share partially supplied to the drum. Two rotating drums mounted back-to-back can supply the bi-directional power between input and output shafts (Gawande, 2018). It is designed to replace conventional electrical, hydraulic, and pneumatic transducers. As a result, it lessens the likelihood of cumulative inaccuracy resulting from using transducers. The Capstan principle relates the hold force to the load force when a flexible rope line is wound around a cylinder (Baser, & IlhanKankseven, 2010; Qi *et al.*, 2018; Li *et al.*, 2022; Schumann *et al.*, 2022). As force is applied in the direction of rotation, friction is developed between the rope and the drum. The generated friction will then act in the same direction as the pull, amplifying the user's force.

In a broad sense, the purpose of the capstan is to provide an adequate amount of friction force between the rope and the drum so that the rope can move at the same speed as the drum. Slippage of any kind is undesirable for most lifting and winching jobs. Because static friction is created when the rope rubs against the capstan in this manner, the usage of the capstan might be categorized as static. However, if the rope slides around the drum, there will be kinetic friction, and the system can be described as dynamic (Paynter, 2002). Literature has emphasized various modifications in the Capstan amplifiers. For example, Thomas *et al.,* (2012) investigated the characterization of a continuously variable liner force amplifier based on the theory of Capstans using an elastic cable that enables a control actuator to declutch by releasing tension. The results demonstrate that a system of distributed capstan amplifiers driven by a central torque source with cable engagement switched by lightweight, low-torque actuators has the potential to reduce the mass of distance actuators and enable more dynamic performance in robotic applications. To increase the extensometer's accuracy and resolution for strain monitoring of high-temperature components, Hu *et al.* (2012) developed a displacement amplifier for incorporating an amplifier into an extensometer. The results validate the amplification ratio equation and demonstrate that the extensometer rods can be used to apply the loading force generated by the flexure hinge's torque moment. Also, Hu *et al.* (2012) designed a method based on electrostatic sensing to continuously and non-contact monitor the crosswise vibration of power transmission belts. The results show that the belt vibrates at well-separated modal frequencies that increase with the axial speed. A closer distance between the electrode and the belt makes higher-order vibration modes identifiable but also leads to severe signal distortion that produces higher-order harmonics in the signal. In order to generate electricity from low-amplitude (1mm) and low- frequency (5Hz) vibrations in the presence of significant static displacements, Shahosseini &Najafi (2014) described the design, optimization, and test results of a mechanical amplifier coupled to an electromagnetic energy harvester. The results indicate that a complete electromagnetic energy harvester using this mechanical amplifier generates a high-power density of 170 W/cm3 and a 16x expansion in output power (30mW vs. 1.9mW without amplifier at 5Hz). The literature reviewed indicates that the capstan amplifier generally consists of a rope wound around the drum that potentiates the amplifications of any load attached to an output end of a rope by its interaction with the tension in the rope.

On the other hand, the probability of the rope becoming bound likewise rises with each extra turn applied to it. The increased strain in the cord during binding allows the rope to effectively attach to the drum, which results in the kinetic friction coefficient becoming more significant than the static friction coefficient. The response time of a mechanical power amplifier is relatively quick. Instantaneous access to power is provided by its drums, which are in state of continuous rotation. When utilized for position control applications, pneumatic, hydraulic, and electrical systems require transducers to transform signals from one energy form to another. This is the case even with constantly operating power sources. On the other hand, the mechanical power amplifier makes it possible to sense the controlled motion directly. This present paper examines a prototype of a power amplifier to evaluate its performance through amplification factor by design optimization for several turns of rope materials. The study's primary objective was to compute the amplification factor of the Capstan model mechanical power amplifier for various rope materials.

MATERIALS AND METHODS

2.1 Experimental Set-Up and Construction

Fig.1 shows the experimental setup for the capstan amplifier.

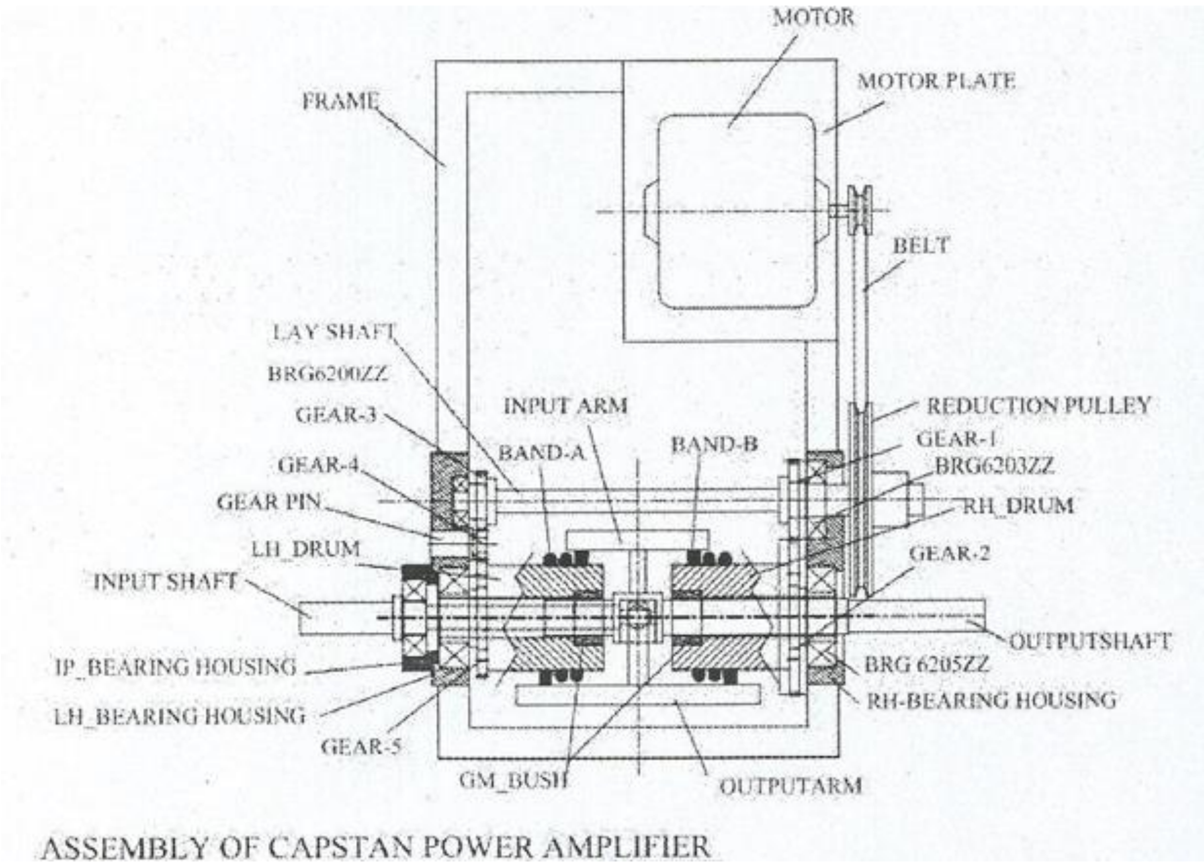

Fig.1 Experimental setup for capstan amplifier

The output overrun is stopped when the drum tightens the band B on this drum. The slip continues until the free end picks up the slack. The COF and the number of rotations affect the force needed at the free end to lift the load. The power amplifier precisely angles the connecting bands A and B to give an output in both directions. The input arm picks up the slack on band A and locks it to its drum when the input shaft is rotated clockwise (CW). As locked band A's load end is connected to the output arm, it sends the driven drum's CW motion to the output shaft. If a flexible line is looped around a cylinder, the holding and load forces are related by the belt friction or capstan equation (a bollard, a winch). A Capstan system depends on the holding force exerted on one side to carry a considerably bigger loading force on the other side. Bands A and B are connected to an input shaft and arm by the power amplifier, which outputs output directions and precise angular placement. The input shaft and arm by the power amplifier, which outputs output directions and precise angular placement. The input arm picks up the slack on band A and locks it to its drum when the input shaft is rotated clockwise. Locked band A transmits the clockwise rotation of the tail drum on which it is wound to the output shaft insofar as the load end of the band is attached to the output arm. As a result, band B becomes lazy and trips over its drum. Band A slips on its drum when the input shaft's clockwise rotation ends since the tension is no longer constrained. The output arm will pull on band B to tighten it on the counterclockwise revolving drum and halt the shaft I the output shaft tries to overflow. The motor drives Drum-B counter clockwise, which powers the input shaft in the opposite direction. The diameter of the drums, the number of wraps on the bands on each drum, and the coefficient of friction between the drum and band all affect how much torque is amplified. By using the aforementioned amplifier configuration, input power given to the input shaft is multiplied and delivered to the output shaft.

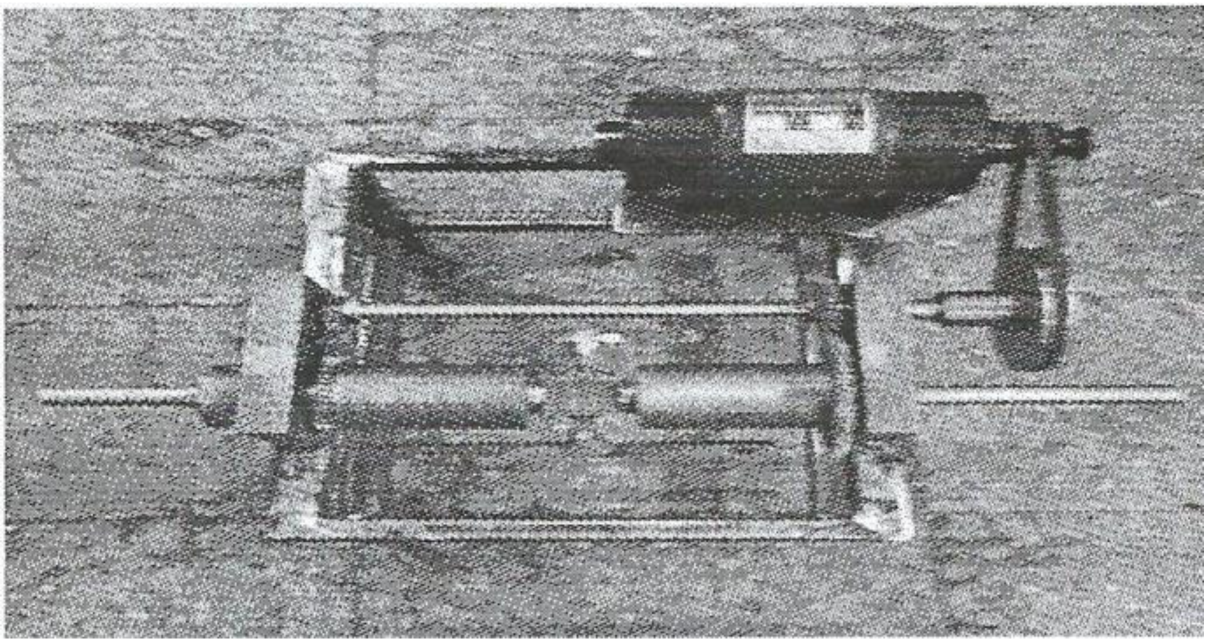

Fig. 2 The prototype of capstan mechanical power amplifier

Table-1 Capstan mechanical power amplifier components.

1	Electrical Motor	The electrical motor has a variable speed range of 0 to 9500 rpm and has 50-watt capacity. An electronic speed variator is used to control the speed. The motor's motor pulley provides the system's drive, and the reduction pulley is positioned on the layshaft.
2	Motor Selection	The power is transmitted to the input shaft of the amplifier using an open belt drive using two pulleys and a belt on a single-phase AC Motor with a 2 kg-cm Torque and 6000rpm speed with 50-watt input

		power. The motor pulley diameter (25mm), input shaft pulley diameter (100mm), input speed (2100rpm). Output speed at lay shaft (2100/4=525), rpm Power (2 x π x 2100 x .20/60 = 43.98 W)
3	Lay Shaft	Two ball bearings installed in a bearing housing support the layshaft, built of the material EN4, and have mechanical qualities. The layshaft carries the reduction pulley and a set of gears from the gear train at one end.
4	Gear Train Specification	Gear-1:1. 5 modules, 18 teeth, and a 5mm face width Gear – 2 1. 20 teeth, 5 modules, and a 5mm face width Gear-3:1. 5 modules, 40 teeth, and a 5mm face width Gear -4: 1.5 modules, 32 teeth, and a 5mm face width. Gear-5:1. 5 modules, 64 teeth, and a 5mm face width
5	LH and RH Drums	The output shaft is supported by a gunmetal busing attached to the left and right-hand drums, located in bearings 6006ZZ and 6005ZZ, respectively, in the bearing housing. The band is coiled around the drums and connected to the input and output arms at its two ends, respectively
6	Input and Output Arms	The input and output arms are connected to the input shaft and output shaft. The band wound on the drums is connected to these arms at their two ends
7	Input Shaft	The input shaft has a ball bearing 6203zz installed on one end that is retained in the input shaft housing, and the input arm is attached to the other ends.
8	Output Shaft	The output shaft is placed inside the load drums by gunmetal bush bearings. One end of the output shaft is hollow so the input shaft can pass through it.
9	Frame	The frame is the part of the power amplifier that holds it all together. The LH and RH bearing housings and the motor plate are welded to the frame.
10	Rope	The rope is made of cotton beads and has a diameter of 6mm. The left band is wound around the left drum, and the right band is wound around the right drum. Both the input and output arms are attached to the ends of these bands.

2.2 Test Trials and Measurement

To conduct the trial, a dyno-brake pulley cord, and weight pan are provided on the output shaft.
Input Data

1. Drive Motor < AC230 Volt – 0.5 Amp, 50 watt – 50 Hz, 200 to 9500rpm

(TEFC Commulator Motor)

2. Select the leather material for the rope and wound three numbers of the turn-around corresponding drums. Then, trials are conducted by the following procedure.

Procedure

The motor started by shifting the electronic speed variator knob to allow the mechanism to run & stabilize at a certain speed (e.g., 1300rpm). The weight in the weight pan was attached to the input arm bracket of the LH side input shaft, and 100gm weight was placed into the weight pan. The speed for this load was recorded using a tachnometer. Also, an additional 200gm weight was added to the weight pan. The electronic loading cell attached to the output arm bracket was mounted on the load pulley fixed on the RH side output for proper recording. The input and output torque were calculated using arm length = 100mm.

Thus, the observed recording was tabulated, and Torque versus speed characteristics and power versus speed characteristics were plotted. At the same time, the steps were repeated by varying rope materials such as woolen, cotton, and steel. Finally, the sample was calculated.

Table-2 shows sample calculations for observation

Input Torque	Weight in the pan (N) Input arm length (m) = 0.1 9.81 0.10 0.0981 N-m
Output	Electronic load cell analysis (N) x Length of output arm (m) = 0.170 x 9.81 x 0.1 = 0.1667 N-m
Power consumed across the output shaft	2π x N x T/60 = 2x3.143x2100x0.1667/60 = 36.656 Watt
Efficiency	Input/Output = 36.656/71.56 = 51.23%

2.3 The Mechanical Power Amplifier Working Principle

The capstan model, mainly composed of two counter-rotating drums and rope coiled around it, as shown in Fig. 3, serves as the foundation for the operation of a mechanical power amplifier.

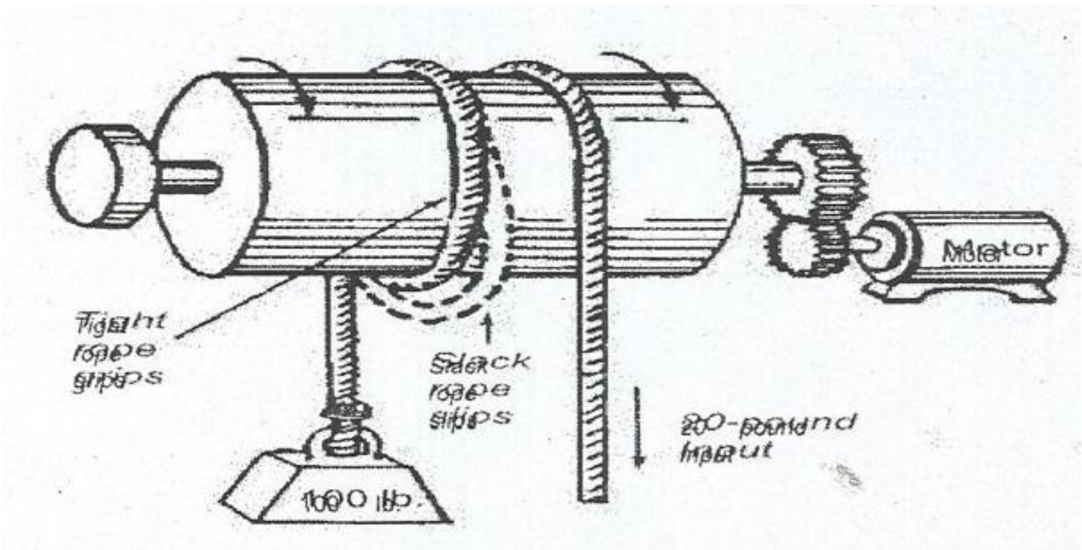

Fig. 3 Basic layout of mechanical power amplifier

Where T_{load} is the actual tension on the rope line, T_{hold} is the force that is subsequently applied on the opposite side of the capstan, is the coefficient of friction between the materials of the rope and capstan, and 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 (4). From Fig 3, it is seen that the gain in force propagates exponentially with the coefficient of friction, the number of turns, and the contact angle. Note that the cylinder radius does not influence the gain in force. Table 3 shows the factor e^{up} based on the number of turns and coefficient of friction.

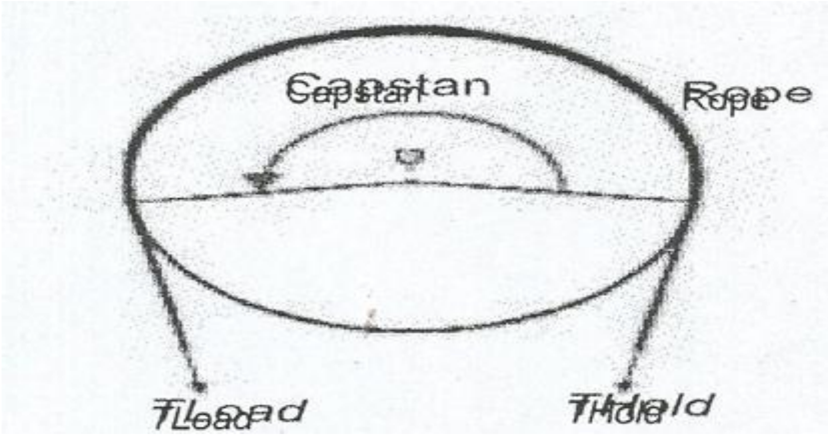

Fig. 4 Working principle of mechanical power amplifier

Table-3 explains why a sheet, a rope attached to a snail's loose side, rarely wound more than three times around a winch. The force gain would be excessive in addition to being counterproductive because there is a chance of a riding turn, which would cause the sheet to be foul, form a knot, and not run out when relaxed (by letting go of the hold end of the tail, in land-speak). To prevent the rope (anchor warp or sail sheet) from sliding down, it is traditional in ancient and modern worlds for anchor capstans and jib winches to have a somewhat flared-out base instead of being cylindrical. If the rope is tailed (the loose end is pulled clear) by hand or with a self-trailer, it can slowly climb upwards around the winch without much chance of a riding turn. Applying this theory can create a mechanical power amplifier that amplifies the modest control force generated by an input motor. The device's output can then be utilized to demonstrate the implementation of load position.

Table-3 Capstan principle

No of rotation	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	81612437503	
4	12	152	1881	23228	286751	3540026	43702631

RESULTS AND DISCUSSION

The weight pan's input weight was changed over several tests, ranging from 100g to 1kg; the electronic load cell's readings variations in the speed, input/output torque, power, and efficiency are documented. Table 6, summarizes the results from utilizing two numbers of turns and rope material as leather. The observations for steel and woven cotton are presented similarly in Tables 5 and 7. The relationship between speed, torque, power, and efficiency of the power amplifier assembly is displayed below. The findings are strikingly compatible with experimental measurements, including a successful computation of the amplification factor.

Table-4 Loading and unloading Data

Weight(gm)		Loading Speed	Unloading Weight (gm)	Speed (rpm)	Mean 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 for power amplification factor with steel rope

S/N	Input Load Consumption (gm) reading at output/input talk		Load Sell Power Amplification Factor reading at output shaft	Speed efficiency (rpm %)	Input Torque (Nm)	Output Torque	Output am amplified	Power consumption (watt)
1.	100	110	2100	0.0981	0.10791	23.718618	1.1	33.1439
2.	150	180	1960	0.14715	0.17658	36.2247984	1.2	45.17521
3.	200	233.3334	1750	0.1962	0.228900065	41.92686198	1.166667	48.7877
4.	250	378	1250	0.24525	0.2943	4928544	1.2	54.11748
5.	300	378	1250	0.2943	0.370818	48.515355	1.26	54.81697
6.	350	460.83345	1050	0.34335	0.452077614	49.68332983	1.316667	56.629
7.	500	614.2855	810	0.4905	0.602614076	51.08962132	1.228571	55.7840
8.	600	6979.5	650	0.5886	0.6842475	46.55163825	1.1625	51.6985
9.	700	882	535	0.6867	0.865242	48.45066786	1.26	54.7756
10.	800	1024	520	0.7848	1.004544	54.67398144	1.28	58.9705
11.	1000	129	380	0.981	1.26549	50.3327556	1.29	56.54245

Table-6 Observation for power amplifcation factor with leather rope

S/N	Input Load Consumption (gm) reading at output/input talk		Load Sell Power Amplification Factor reading at output shaft	Speed efficiency (rpm %)	Input Torque (Nm)	Output Torque	Output am amplified	Power Consumption (watt)
1.	100	170	2100	0.0981	0.16677	36.656046	1.7	51.22250825
2.	150	262.5	1960	0.14715	0.2575125	52.827831	1.75	65.88051963
3.	200	356	1750	0.1962	0.349236	63.968394	1.78	74.43612261
4.	250	450	1600	0.24525	0.44145	73.92816	1.8	81.17622256
5.	300	540	12500	2943	0.52974	69.30765	1.8	78.30996817
6.	350	647.5	810	0.34335	0.6351975	69.80820525	1.85	79.56786874
7.	500	940	650	0.4905	0.92214	78.1790292	1..88	85.36264583
8.	600	1230	535	0.5886	1.20664	82.091061	2.05	91.16729388
9.	700	1477	520	0.6867	1.448937	81.1364221	2.11	91.72749805
10.	800	1624	520	0.7848	1.593144	86.790951744	2.03	93.52360221
11.	1000	2230	380	0.981	2.18763	87.0093372	2.23	97.74392716

Table-7 Observation for power amplifcation with woven cotton rope

S/N	Input Load Consumption (gm) reading at output/input talk		Load Sell Power Amplification Factor reading at output shaft	Speed efficiency (rpm %)	Input Torque (Nm)	Output Torque	Output am amplified	Power Consumption (watt)
1.	100	150	2100	0.0981	0.14715	32.34357	1.1	45.1963081
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	0.3943	0.485595	63.5320125	1.6	71.78413748
6.	350	388	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	0.6886	1.012392	68.8765024	1.5625	76.49148315
9.	700	1239	535	0.6867	1.012392	68.8764024	1.48	76.49148315
10.	800	1472	520	0.7848	1.444032	78.59384832	1.39	84.7701616
11.	1000	1840	380	0.981	1.81485	72.182634	1.2	81.08801132

It can be noted from Fig. 5 that when the speed decreases, the torque recorded at the input shaft increases due to the increased input load. It is also noted that as the speed decreases, the measured troque at the output shaft increases. The relationship between troque and speed is inverse, although the amplification factor increases as speed drops. The maximum value of the amplification factor is 2.23 for leather rope, 1.867 for woven cotton, and 1.32 for steel at low speeds with correspondingly large troque values. Very little variety remains in the values of the amplification factor. Maximum output torque is attained at 380 revolutions per minute, equaling 2.18 Newton meters for leather, 1.266 Newton meters for steel rope, and 1.815 Newton meters for woven rope.

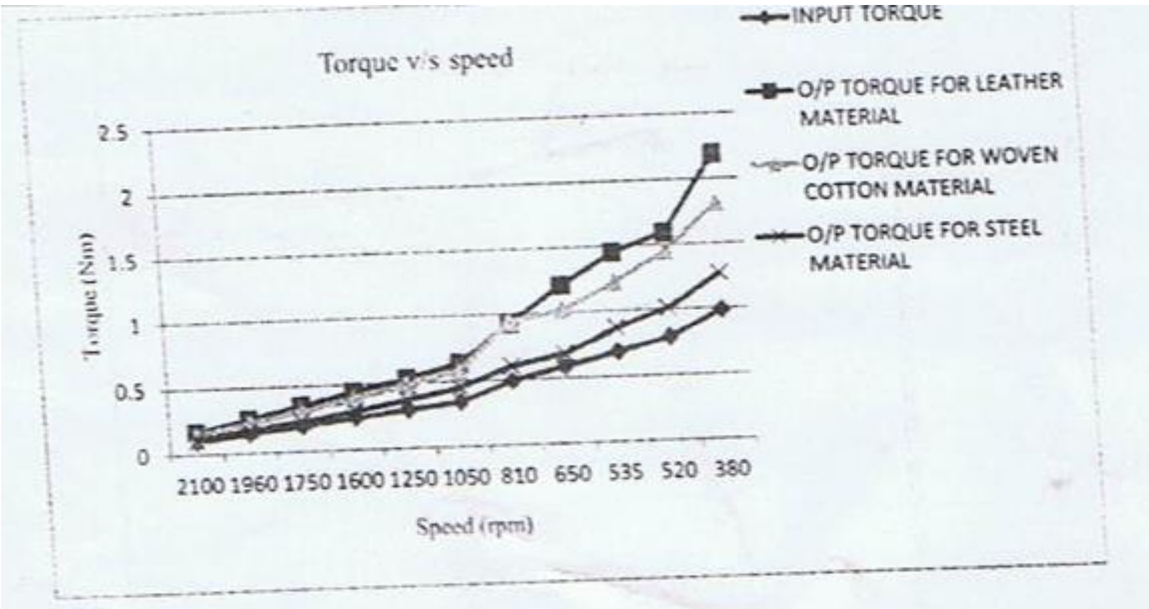

Fig. 5 Evaluation of torque against speed

As shown in Fig 6, system efficiency rises as speed falls. As a result, efficiency is poor, yet initial speed is high. The efficiency of several power transmission systems, such as the belt drive and gear system, declines as the system's load grows; as a result, power transmission systems, such as the belt drive and gear system, declines as the system's load grows; as result, the system's total efficiency drops after a certain threshold. At 230 rpm and 1000g input weight, leather rope materials achieve a maximum efficiency of 97.74 percent. Similar to this, woven cotton has a maximum efficiency of 84.87percent at 520 revolutions per minute and 800 grams. Steel rope material has 520 spins per minute and weight 800 grams.

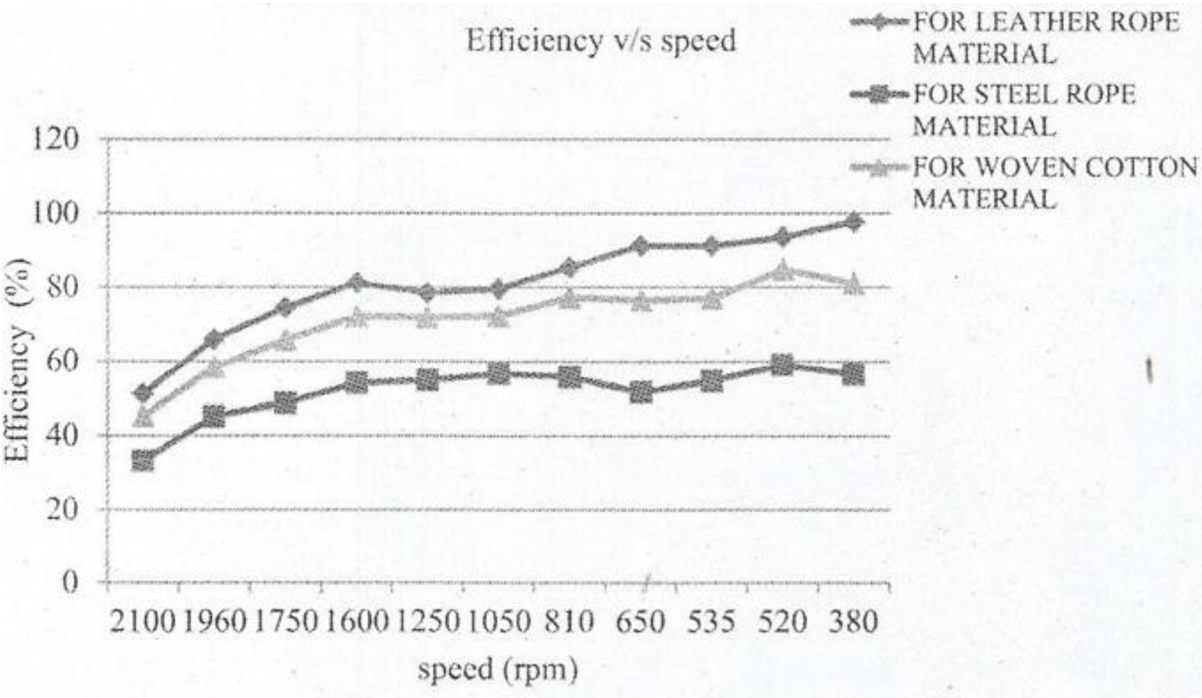

Fig. 6 Graph of efficiency against speed

As speed decreases, it can be seen from Fig 7 that power over the system's output shaft increases. As a result, at first, power is low, and speed is high. Power across the output shaft increases when load increases, speed across the shaft decreases, and vice versa. The maximum power at the output arm for leather rope is 87.008 watts, compared to 78.59 watts for woven cotton rope and 54.67 watts for steel. According to experimental studies, a mechanical power amplifiers performance can be improved by raising its amplification factor. The following variable affects the amplifying factor. It is based on the number of rope rotations and the angle at which the rope is wrapped around the capstan drum. The number of turns has an exponential relationship with the amplification factor. However, going beyond two or three spins will result in the rope rangled around the revolving drum, reducing the amount of kinetic energy the drum receives from the electric motor drive. It leads to decreased transmission power and efficiency, producing ludicrous outcomes. Given this, choosing the ideal number of turns, two or three will produce the appropriate outcomes. It also depends on the friction between the rope and the drum. Power amplification can be improved by choosing an elastic rope material with a high coefficient of friction. It is clear that among the other materials, such as woven cotton and steel, the leather –to-steel rope-drum pair has the highest coefficient of friction.

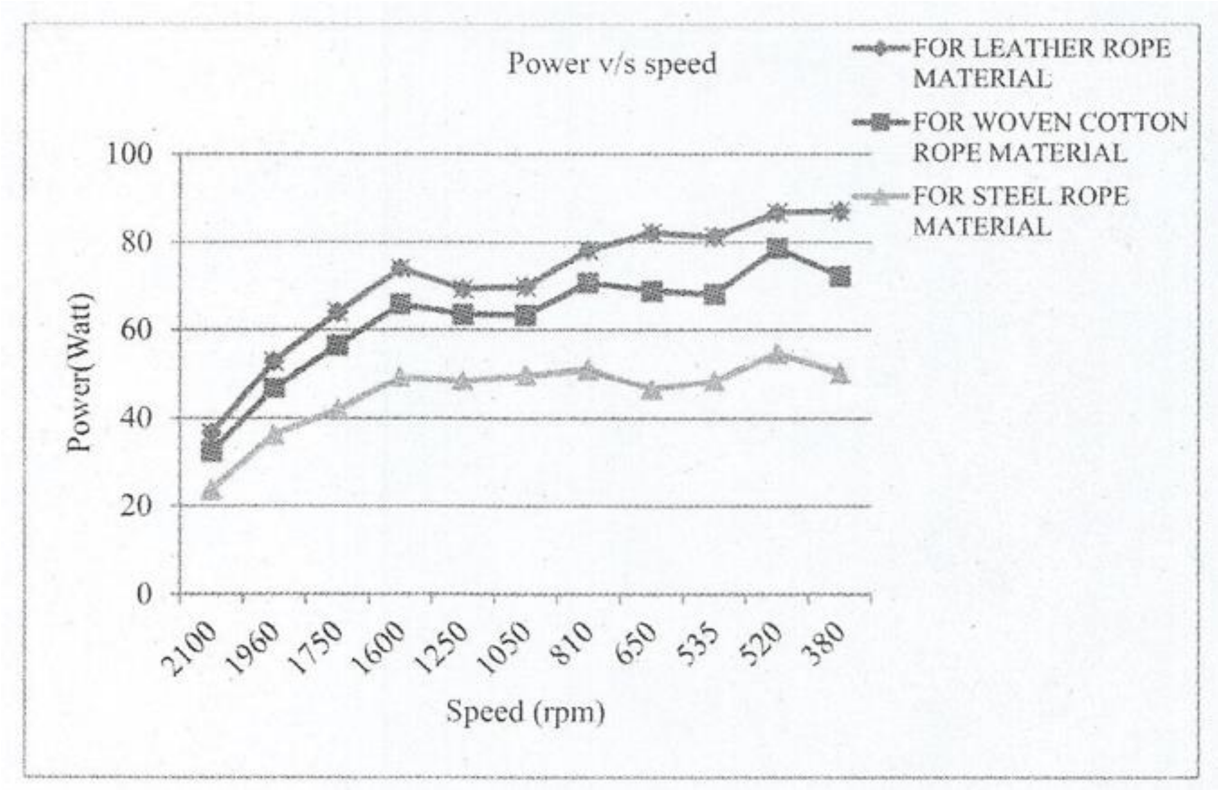

Fig. 7 Graph of power against speed

CONCLUSION

The primary purpose of this work was to calculate the amplification factor of mechanical power amplifiers for various rope materials such as leather, woven cotton, and steel rope, an intensive combination of analytical and experimental research was utilized to accomplish this goal. The experimental study verifies that maintaining an optimal number of turns equal to two results in a power amplification factor of 2.23 for leather contact, 1.867 or woven cotton contact, and 1.32 for steel contact of rope. This is the case when the optimal number of turns is maintained. It is clear from these results that the power amplification of leather is superior to that of woven cotton and steel. The results showed a remarkable consistency with the experimental measurements, including a positive estimate for the amplification factor.

CONFLICT OF INTEREST

There is no conflict of interest for this research work.

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