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Research Article

Design and Performance Evaluation of a Variable Speed Bucket Elevator

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ABSTRACT

The bucket elevator was designed and constructed at the Federal University of Technology Owerri, Imo state, Nigeria. A variable speed bucket elevator with dimensions of 0.3 m by 0.243 m and 0.47 m high with a base stand of 0.47 m high making the total height of 0.9 m was designed, evaluated and tested to determine the throughput capacity of the machine, which gave 0.176 tons h^{-1} at higher speed of 0.5 m s^{-1} with optimal efficiency at the centrifugal discharge force of 0.366 N when grain (cowpea) was elevated, and a throughput capacity of 0.109 tons h^{-1} at a slower speed of 0.4 m s^{-1} with optimal efficiency of 7.78% at the gravitational discharge force of 0.392 N when small lumpy material was elevated. 0.5 m s^{-1} and 0.4 m s^{-1} used for the experiment were obtained from the grooved step pulley with variable diameters, connected to a motor of 0.18 kW (1340 rpm) at the head, with a gear reducer of 189.7 rpm coupled to a vee belt. The result obtained during test running of the prototype model of the bucket elevator conveyor, shows that at variable speed, bucket elevator can convey different materials, which becomes an advantage instead of installing different conveyor while the same can perform the same function with a change in the pulley. This will become advantageous to low-income countries, where resources are meager to purchase different equipment whereas, a well-designed single elevator can perform variably and obtain same outcome.

Keywords: *Efficiency, Bucket elevator system, Progression, Variable speed, Nigeria*

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INTRODUCTION

Bucket elevators can be described as machines that permit the continuous transportation of granular materials to a specific location under a given condition. They consist of a variable number of buckets attached to a moving belt or chain that conveys the motion to the buckets, for a complete mechanical description (Perez-Aparicio *et al*., 2014). Similarly, Snehal *et al.* (2012) noted that bucket elevators are powered equipment for conveying bulk agricultural and industrial materials in a vertical path, consisting of an endless belt, or chain to which metallic buckets are fixed. In addition, Taher *et al.* (2014) stated that, bucket elevator and belt conveyor are the media of material transportation from one location to another in a commercial space.

However, it consists of buckets to contain the material, a belt or chain, either round link, roller or drive or belt tension, accessories for loading the buckets or picking up the materials for receiving the discharged material, for maintaining the belt and chain tensions for enclosing and protecting the elevator maybe vertical. Wolstencroft (2005) posited that during the design of bucket elevator for distribution, some facts were considered, such include, material conveyed and casing selection. Furthermore, He note that the material conveyed, and casing selection considerations include, high and low bulk densities, temperature, abrasiveness, corrosiveness, flow ability, moisture content, particle size and distribution. According to Maghirang *et al.* (2006) there are two main types of bucket elevators namely, gravity assisted and centrifugal discharged. Similarly, Gholami (2016) suggested that attention is to be paid to material change and discharge characteristics. In the same vein, Yashaswini *et al.* (2014) stated that the final selection of a bucket elevator should be made solely after careful consideration of all factors affecting the application. According to Gerber (2008), the bucket elevator with a variable speed mechanism for its operation, is built to handle high capacity up to 45,000 bushes per hour.

Furthermore, Dave (2008) stated that bucket elevators also apply variable speed drive systems of this kind for belt bucket elevator and chain drive systems. While Wolstencroft (2005) noted that, in designing a bucket elevator, the following points require consideration, material conveyed and casing selection. According to Sharma (2000) conveyors of various types and sizes are available in the production, mining and construction industries. He further stated that there are two types of conveyors: traction type and traction less type conveyors. Perez-Aparicio *et al.* (2014) noted that they comprise of a variable number of buckets attached to a moving belt or chain that transmits the motion to the buckets for a complete mechanical description. The current bucket elevator under use utilizes a single mechanism; the challenge becomes how we convey a sticky material and a dry granular material using the same elevator with rates of conveying different from others. Furthermore, Snehal *et al.* (2012) posits that current construction uses a rubber belt with plastic buckets. Pulleys several feet in diameter are used at the top and bottom. To this effect, a prototype model bucket elevator which utilizes different speed through the shafts with different pulley drive which operates at a variable speed using an electric gear motor was designed and evaluated to determine its flow rate and optimal conveying speed for some agricultural products.

MATERIALS and METHODS

The study was conducted at the Engineering workshop 3 of the Federal University of Technology Owerri, Imo State, Nigeria. The area experiences a mean daily minimum temperature range of 19-24°C and a maximum range of 28-35°C, average relative humidity of up to 80%, and a longer wet season which lasts from April-November (Ogbuagu and Okoli, 2013).

The materials and equipment used for the study include:

a. A gear motor of 0.18 kW power with 1340 rpm and gear speed of 81.6 rpm (calculated)
b. Metal sheets for the casing and buckets
c. Angle bar for the base stand and brazing
d. Two variable diameters pulley
e. Two rollers of 0.050 m diameters with a length of 0.183 m
f. Flat belt of 0.100 m wide
g. Four rubber cork for shock absorption at the pulleys and shaft contacts
h. Four industrial bearings with grease nipples
i. Seven buckets with 0.05 m spacing, 0.05 m depth, and 0.09 m length, project of 0.08 m
j. Rectangular inlet chute and discharge chute with 0.095 m wide and inclined at an angle of 45°
k. Two shafts of 0.260 m for the tail roller and 0.30 m for the head roller section.
l. Flat bar for the internal frame and brazing
m. Thirteen diameter nuts and bolts
n. Two drive vee-belts of different length
o. Four rings plate with 0.080 m diameters.

Description of the New Machine:

The bucket elevating conveyor is made up of steel metal pans, rubbers, irons and wood materials. The dimensions of the bucket elevator are 0.300 m length, 0.243 m and 0.900 m high, respectively. The height of the casing is 0.470 m, and the height of the base stand is 0.430 m, making its total height to be 0.900 m. The casing consists of different items such as pulleys, rollers, bearings belts, buckets, inspection doors, inlet and discharge chutes. The location of the electric motor is at the base stand of the bucket elevator, where the vee-belt is connected to the drive pulley of the bucket elevator. The casing size and clearance are fabricated in a standard of 0.470 m high with a makeup section of 0.430 m, which gives the overall height of the bucket elevator. The single casing section used was pressed, welded and bolted construction. The casing section was made to be removable for inspection or maintenance.

Design considerations and calculations

Three principal variables in the design of a bucket elevator were considered, and they are:

1. Bucket size and pitch (spacing)
2. Belt speed
3. Diameter of head and tail pulleys.

The buckets are mounted on the belt so that the back of the buckets can bend as the mounting bolts are partly pulled into the belt. With thin-walled narrow buckets made of sheet steel for this elevator. The back is flexible enough to follow the shape of the roller shell.

Bucket size= width × projection × depth (1)

$= 0.05 \text{ m} \times 0.08 \text{ m} \times 0.05 \text{ m}$

$= 0.0002 \text{ m}^3$

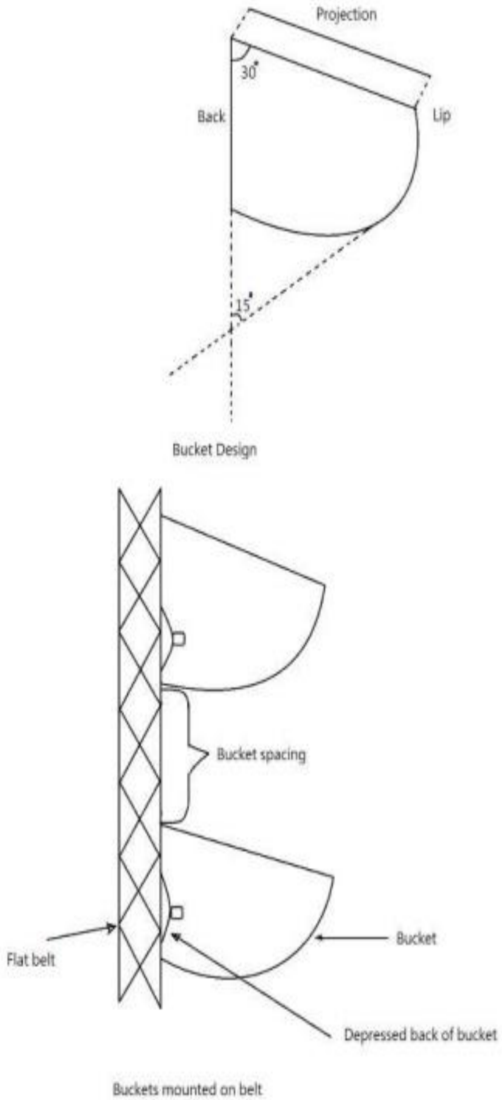

Figure 1. *Bucket design and bucket mounted on belt.*

The head section is a robust, pulley welded construction, with removable head section for easy access to the driving shaft pulleys. The shape of the head section is a function of bucket designed, pulley diameter and belt speed. This allows for free turning and less wearing. The angle of wrap and the friction between belt and the roller are important to know, a conventional bucket elevator has an angle of wrap of 180°.

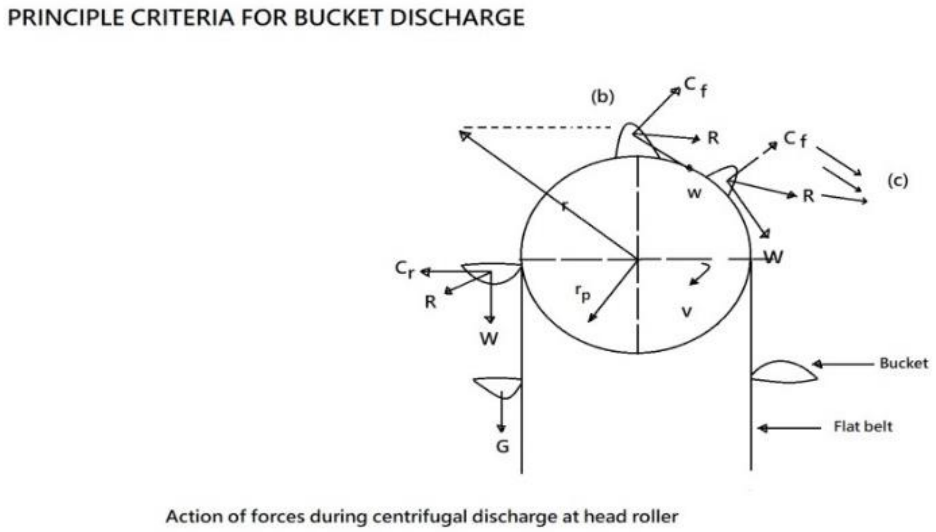

Figure 2*. Action of forces during centrifugal discharge at head roller.*

Where:
r_p= Pulley (roller) radius (m)
r= Radius from the center to the bucket edge= (0.135 m)
G= Weight of load carried (kg)
W= Mg= Gravitational force (N)
R= Resultant force (N)
C_f= Centrifugal force (N)
V= Belt speed (m s^{-1})
G= Acceleration due to gravity= 9.81 m s^{-2}
M= Mass of the product = 40 g
B= Angle of throw= 15°

The boot section of the bucket elevator is bolted and assembled to follow for proper maintenance and replacement of the pulley (roller), shaft, liner material and so on. The loading chute is located so that the pickup of the product by the buckets takes place above the center line of the return pulley. The return pulley provides the means for turning the belt and for the tensioning of the belt. The drive pulleys (head vee-pulley) of variable diameters are 30 mm and 50 mm. This variation allows for variable speeds (slow and high speeds) when connected to a motor with the help of different belt lengths. The internal rollers which carry the flat belt are made of wooden material suitable for the flat belt to rotate with less wearing.

Relationship Between Belt Speed, Pick Up and Bucket Discharge

When a product mass turns around a pulley, it is influenced by two forces.

1. Gravitational force, which is oriented downwards with magnitude W.

$$W = Mg \tag{2}$$

$= 40 \times 10^{-3} \times 9.81$

$= 0.392$ N

2. Centrifugal force, C_f whose, radial of the rotational center is oriented out wards, with magnitude (Sondalini, 2004).

$$C_f = \frac{W.V^2}{g \times r} \cos\beta = \frac{M.V^2}{r} \cos\beta \tag{3}$$

But, $V^2 = g \times r \times \cos\beta$ (4)

$= 9.81 \times 0.135 \cos(15°)$

$V^2 = 1.28 \text{ m s}^{-1}$

$C_f = \frac{40 \times 10^{-3} \times 1.28}{0.135} \cos 15°$

$= 0.366$ N

If W and C_f are equally large, then the resultant, R, will be oriented at right angles onto the front of the bucket. The product mass will be in equilibrium. The magnitude of R can be measured on a scale, and it will be $\sqrt{2} \times W$. Figure 2 illustrates that when W decreases, C_f increases, and the resultant R decreases. With the bucket position of Figure 2 in position 'b' the resultant R= 0, if both forces C_f and W are equal and opposite. With this condition of equilibrium

$$W = C_f \text{ that is } W = \frac{W.V^2}{g.r} = V^2 = g\,r \tag{5}$$

In this case, the product mass in the bucket is in a state of equilibrium, without the tendency to be thrown out, however, with the ability to flow freely if later the resultant of both forces increases downward. If W and C_f are equally large, there will be no spillage of the product in position 'b'. Similarly, in position 'c', the resultant 'R' works towards the mouth of the bucket and urges the product mass, which is no longer subjected to the counter pressure of the bucket lip to move towards the discharge chute. Hence, the resultant 'R' still increases, and the product is discharged. The through-off curve has a parabolic shape (trajectory).

In position 'b', we have belt speed,

$$V = \frac{2\pi r N}{60} \tag{6}$$

Where, N = Amount of rotations per minutes of the driving shaft

$$\frac{(2\pi r N)^2}{60} = g \times r \tag{7}$$

$$N = \frac{30}{\sqrt{r}} \text{ rpm} = \frac{30}{\sqrt{0.135}} = 81.65 \text{ rpm} \tag{8}$$

Belt speed $V = \frac{2 \times 3.142 \times 0.135 \times 81.65}{60} = 1.154 \text{ m s}^{-1}$

(Kurmi and Gupta, 2014).

Effect of Forces

i. Centrifugal forces effect of a higher belt speed. We first consider the driving shaft. In this case, the contents of the bucket in position 'a' in Figure 2 is subjected to a greater force C_f the direction of C_f shows that part of the product will be spilled over the bucket lip. The spilled product returns to the upgoing part of the elevator.

ii. Gravitational discharge effect of a slow belt speed. In the upper half of the pulley (roller) in Figure 2, a filled bucket in position 'a' will not spill because the resultant 'R' only slightly deviates from W in size and dissection.

Belt Speeds from the Variable Pulley Diameters

For pulley 'A' with diameter d= 30 m= 0.03 m,
R= d/2= 0.015 m

But $N_1 = \frac{30}{\sqrt{r1}} = \frac{30}{\sqrt{0.015}} = 244.9$ rpm

$N_2 = \frac{30}{\sqrt{r2}} = \frac{30}{\sqrt{0.025}} = 189.7$ rpm

Belt speed, $V_A = \frac{2\pi r N_1}{60} = \frac{2 \ x \ 3.142 \ x \ 0.015 \ x \ 244.9}{60} = 0.5 \text{ m s}^{-1}$

For pulley 'B' with diameter d= 50 mm= 0.05 m,
R= d/ 2= 0.025 m

Belt speed $V_B = \frac{2\pi r N2}{60} = \frac{2 \ x \ 3.142 \ x \ 0.025 \ x \ 189.7}{60} = 0.4 \text{ m s}^{-1}$

(Kurmi and Gupta, 2014)

The Handling Capacity (Throughput Capacity)

The shape of the bucket is influenced by load characteristics throughput capacity which is given as;

$$Q = \frac{3.6 \ GV}{t_b} \quad (9)$$

Where,

$$G = i_o e \psi \quad (10)$$

e= Bulk density of load (kg m^{-3})
ψ= Coefficient of filling= 0.7
i_o= Geometric volume of each bucket in m^3= 0.0002 m^3
t_b= Bucket spacing (pitch) in meter = 0.12 m

Bulk density of load,

$$e = \frac{mass}{volume} \quad (11)$$

$\frac{40 \ x \ 10^{-3}}{0.0002} = 200 \text{ k g m}^{-3}$

However, G= 0.0002 × 200 × 0.7
=0.028 kg ≈ 0.000028 tons

For gravitational discharge,
Throughput capacity for gravitational discharge,

$$Q_1 = \frac{3.6 \ GV_A}{t_b} \quad (12)$$

$= \frac{3.6 \ x \ 0.028 \ x \ 0.5}{0.12} = 0.109 \text{ tons h}^{-1}$

Similarly, throughput capacity for centrifugal discharge,

$$Q_2 = \frac{3.6\ GV_B}{t_b}$$

$$= \frac{3.6\ x\ 0.028\ x\ 0.4}{0.12} = 0.176 \text{ tons h}^{-1}$$

Belt selection: the following parameters were considered for the selection; the belt length in meters, the belt type (flat and vee-type) and the power transmitted.

Belt type

A conventional agricultural v-belt for drive and more woven flat bucket cannier were chosen.

The belt length is given as,

$$L_1 = \pi/2 + d_{p1} + h_c + h_s \quad (13a)$$

$$L_2 = \pi/2 + d_{p2} + h_c - h_m \quad (13b)$$

Where,

d_{p1}= Diameter of drive pulley 'A'= 0.03 m

d_{p2}= Diameter of drive pulley 'B'= 0.05 m

h_c=Height of bucket casing= 0.47 m

h_m= Height of motor from the base to the casing

L_1= Length of belt for pulley 'A'

L_2= Length of belt for pulley 'B'

Therefore, $L_1 = \frac{3.142}{2} + 0.03 + 0.47 + 0.22 = 2.286 - 1 = 1.29$ m

And $L_2 = \frac{3.142}{2} + 0.05 + 0.47 + 0.22 = 2.306 - 1 = 1.31$ m

Tension on the Belt

Power of motor = $(T_1 – C_f)\ (L_1/Q_1)\ V_A$, for belt on pulley 'A' (14a)

Power of motor = $(T_2 – C_f)\ (L_2/Q_2)\ V_B$, for belt on pulley 'B' (14b)

Where,

T_1= Belt tension on pulley 'A' in Newton

T_2= Belt tension on pulley 'B' in Newton

V_A= Speed of belt on pulley 'A' in m s^{-1}

V_B= Speed of belt on pulley 'B' in m s^{-1}

$(T_1 – C_f)\ (L_1/Q_1)V_A$= Motor power (0.18 kW)

$(T_1 – 0.366)\ (1.29/0.109)0.5 = 0.18$

T_1= 0.483 N

Similarly,

$(T_2 – C_f)\ (L_2/Q_2)V_B = motor\ power$

$(T_2 - 0.366)\ (1.31/0.176)0.21 = 0.18$

T_2= 0.482 N

Torque on the Shaft, Ts

$$T_s = \frac{1000\ x\ P}{2\pi\ x \frac{N}{60}} \quad (15)$$

Where P = motor power = 0.18 kW

$T_s = \frac{1000 \, x \, P \, x \, 60}{2\pi \, x \, N} = \frac{1000 \, x \, 0.18 \, x \, 60}{2 \, x \, 3.142 \, x \, 81.65}$

T_s= 21.05 N m

Belt Friction Resistance, F

$F = \mu \, Me \, g$ (16)

Where, μ= Coefficient of friction= 0.33

Me= Effective total mass of all moving parts = 200 g

g= Acceleration due to gravity = 9.81 m s^{-2}

F = 0.33×200×9.81

= 647.46 N

Experimental Procedure and Calculations

The elevator unit, the head section, the boot section, the base stand, the electric gear motor, inlet and outlet chutes were set up as shown in Figure 2.

For each inlet coefficient of filling 40 g of grain (cowpea) and oil bean seed were introduced into the bucket elevator at different time. As the material were being elevated, the belt speed, tension, height lifted, time of flight, torque, throughput capacity, optimal efficiency was determined and recorded.

Determining the Optimal Efficiency

$Optimal \ efficiency = \frac{power \ output}{power \ input} \times 100\%$ (17)

Where,

Power output= $\frac{QH}{3.67} \, in \ kilowatts$ (18)

Power input= Power from motor= 0.18 kW

For gravitational force,

Power output= $\frac{Q_1 H}{3.67} = \frac{0.109 \, x \, 0.47}{3.67}$ (19a)

= 0.014 kW

Optimal efficiency= $\frac{0.014}{0.18} \times 100\%$

= 7.78%

For centrifugal force,

Power output= $\frac{Q_2 H}{3.67} = \frac{0.176 \, x \, 0.47}{3.67}$ (19b)

= 0.0225kw

Optimal efficiency= $\frac{0.0225}{0.18} \times 100\%$

= 12.55%

Calculation of the Throw into Chute and Chute Size

The standard trajectory formula was used, $S = U \times t + 0.5 \times a \times t^2$ (20)

Where,

S= Displacement (m)

U= Initial velocity (m s^{-1})

a= Acceleration due to gravity, g = 9.81 m s^{-1}

t= Time (s)

The horizontal component at top dead center of the pulley was acceleration due to gravity in the horizontal direction is zero is given by:

$S_h = U \times t$ (m) (21)

The vertical component at top dead center was velocity in the vertical direction is zero is given by:

$S_v = 0.5 \times a \times t^2$ (22)

The calculation of the horizontal and vertical positions of the product for every 0.1 seconds of flight time was shown in table 2.

Chute Size

Area of the discharge chute= area of the inlet chute= 0.08×0.04= 0.003 m^2

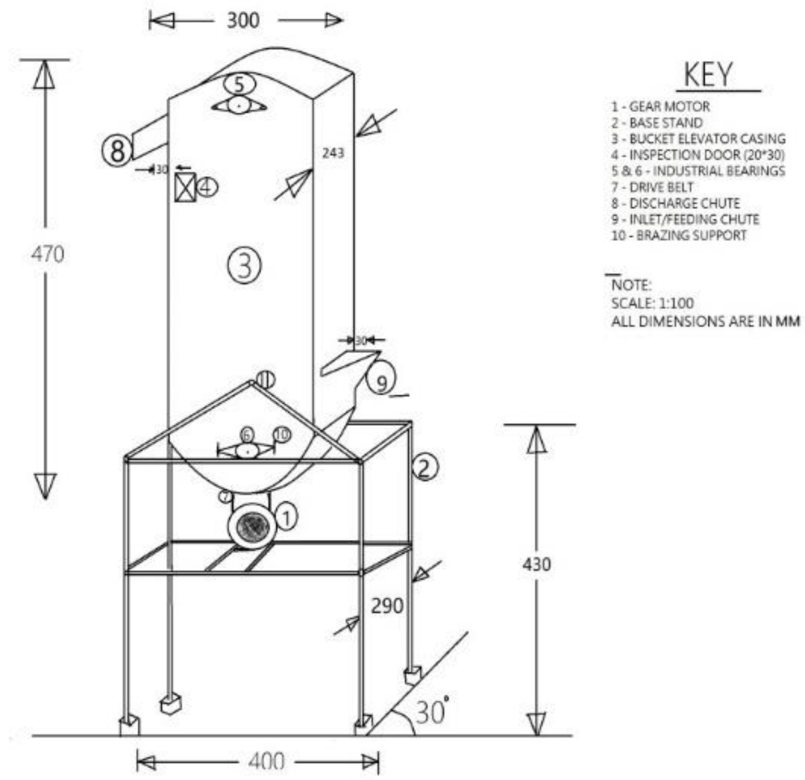

Figure 3. *Pictorial view a variable speed bucket elevator.*

RESULTS AND DISCUSSION

The various result obtained from the experimental determination of the variable speed bucket elevator are displaced in Table 1 and 2, while the relationships are represented graphically in Figure 3, 4, 5 and 6, respectively. The physical explanation for the variation of outcomes with the drawback parameter comes from the fabricated dynamism that is introduced by the fictional mechanisms (Bravo *et al.*, 2011).

Table 1. Variable speed performance.

Section	Material used	Belt Length (m)	Belt Speed (m s^{-1})	Shaft torque (N m)	Belt Tension (N)	Load Bulk Density (kg m^{-1})	Throughput Capacity (ton hr^{-1})	Optimal Efficiency (%)
High speed centrifugal Discharge force (0.366 N)	Grain (Beans/Cowpea)	1.290	0.500	21.050	0.484	200.000	0.176	12.550
Slow speed gravitational discharge force (0392 N)	Lumpy material (oil bean seeds)	1.310	0.400	21.050	0.482	200.000	0.109	7.780

Table 2. Throw into chute of horizontal and vertical position.

Time (sec)	Horizontal displacement (m)	Vertical displacement (m)
0.1	0.12	0.050
0.2	0.24	0.195
0.3	0.36	0.440
0.4	0.48	0.780
0.5	0.60	1.220

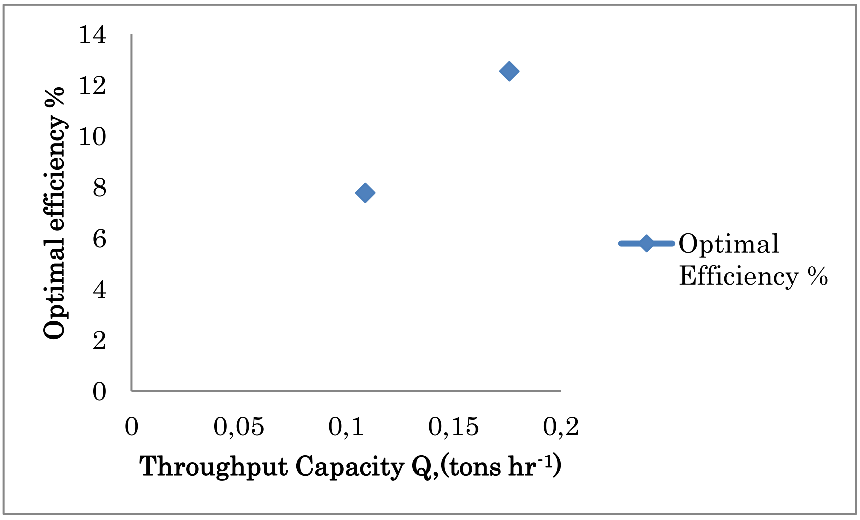

Figure 4. Optimal efficiency as a function of throughput capacity.

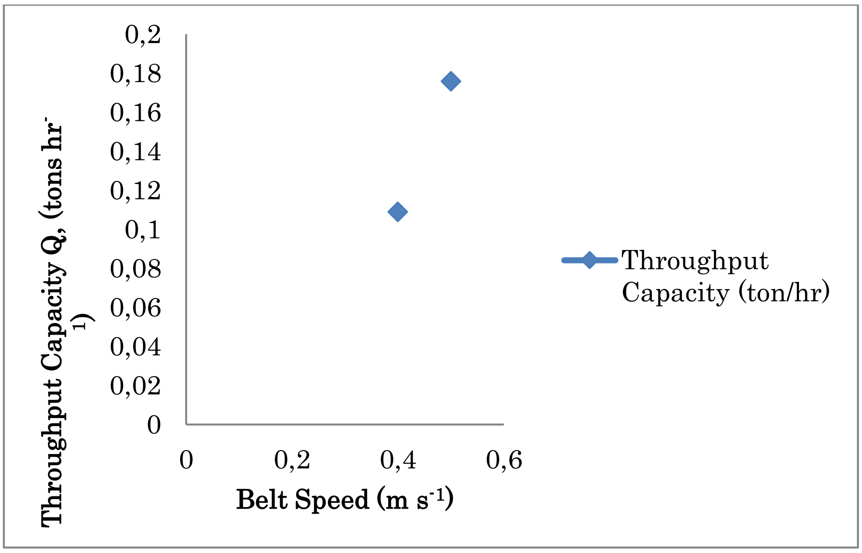

Figure 5. *Throughput capacity as a function of belt speed.*

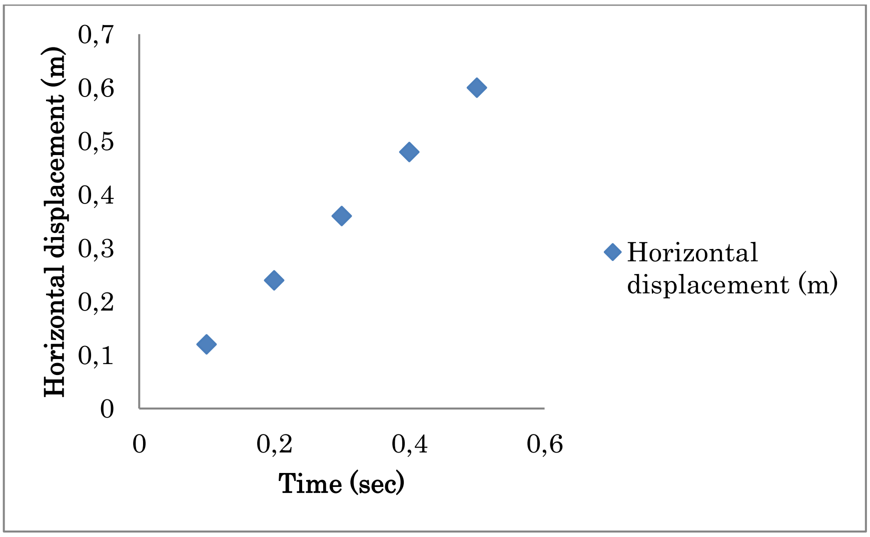

Figure 6. *Horizontal displacement as a function of time.*

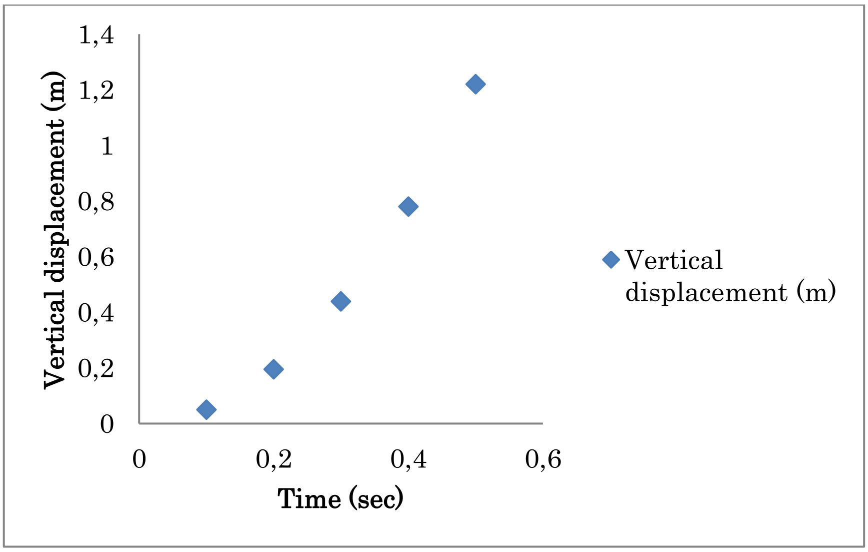

Figure 7. *Vertical displacement as a function of flight time.*

Figure 4 shows that the optimal efficiency of the machine increases linearly as its throughput capacity rises progressively. The fact that the optimal efficiency obtained from the experimental test carried out on the bucket elevator fabricated increases with throughput ca4pacity agrees with every other theoretical assumption available, although there is a discrepancy in the rate with which they vary. Hence, the relationship between throughput capacity and belt speed shown in Figure 4, conformed to the theoretical assumption made, which states that the throughput capacity of the machine increases as the speed of the belt increases, and that the variation of the drive pulley of the bucket elevator brought about this machine increase in the speed of belt. At higher speed, agricultural materials like grain (cowpea) were effectively elevated and discharged at the discharging chute, while at slow speed, a lumpy agricultural material like oil bean seeds were elevated and discharged, respectively. Figure 5 and 6 shows, the performance of the machine when the values of throw into chute were determined at its horizontal and vertical displacement of the elevated material. The result and the graphs showed that as the time of flight of the machine increased, the horizontal and vertical displacement of elevated products increased as they are thrown into the discharge chute. These show linearly and curve linearly lines of best fit of the machine's performance on the graphs.

CONCLUSION

A variable speed bucket elevator was designed and evaluated using a variable diameter pulley and two different agricultural materials to test the machine developed. The bucket elevator examined shows optimal efficiency of 12.55% with a throughput capacity of 0.176 ton h^{-1} obtained as a result of the high speed from the belt, which discharges grains centrifugally while 7.78% optimal efficiency that corresponds to the throughput capacity of 0.109 ton h^{-1} were obtained from the slow speed of the belt, which discharges lumpy materials like oil bean seeds gravitational as initially designed. The optimum output of the machine during operation were calculated to be 0.0225 N for the centrifugal force of 0.366 N and 0.014 kW for the gravitational force of discharge by 0.392 N, compared to the motor power of 0.18 kW as an input power.

The project work on the design and evaluation of a variable-speed bucket elevator is a profitable venture. It is both technically feasible and economically viable and should be considered for implementation in food processing industries and local farms. Additionally, it was worth recommending that agricultural and design engineers, to prevent and minimize costly expenses and waste of time, a variable speed elevator should be installed and used in food processing industries in place of different bucket elevators for other work purposes. There should be further research on the shape of buckets and motor sizes that are appropriate to convey and elevate different agricultural products to the area of processing or storage units like silos. In the same vein, a variable speed motor should be considered, if there will be any, which will be connected directly to the head pulley of the elevator, which will reduce much power loss due to the length of the drive belt and the weight of the moving parts.

DECLARATION OF COMPETING INTEREST

The authors hereby declare that there is no conflict-of-interest whtasoever.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Christopher Ikechi, OBINECHE: Conceptualization, writing original draft and methodology.
Bejoy Otuobi UNANKA: Data collection and editing
Nkechi Udochukwu, EZECHIKE: Formal analysis and review
Anthony Emeka AKUWUDIKE: Validation
Chinwendu Augustina OJIAKU: Visualization and editing.

ETHICS COMMITTEE DECISION

This article does not require any ethical committee decision.

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