ANCIENT MOTORS FOR SIEGE TOWERS

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ABSTRACT In the paper are proposed some mechanical systems, all certainly used in the Classic Age, that could be easily adopted to power the siege towers, devices invented by Greek engineers and called Helepolis. These ancient motors are made up by capstans, tread wheels like those used for Greek-Roman cranes and counterweight motors, all installed into the helepolis.

The proposed motors are also analyzed from a mechanical point of view in order to examine, at least theoretically, their effectiveness in such applications.

1. INTRODUCTION

Among the siege devices and engines that were used in ancient times the siege towers or helepolis are particularly interesting. The term "helepolis" (ἑλέπολις ≈ "taker of cities") probably comes from the ancient greek words elein (ελειν from the verb αιρεω = to take, to conquer) and polis (πολις=city). These machines were widely described from ancient times by many authors, see. e.g. Diodorus Siculus (I century B.C.) [1], Publius Flavius Vegetius Renatus (IV-V century A.D.) [2], Julius Caesar [3] and others and were commonly used till the Middle Age. The first documented use dates back to the siege of Rhodes (305 B.C.) when the machines built by Demetrius I of Macedon (337–283 B.C.), called Poliorchetes were used: incidentally, the word "poliorchetes" (πολιορκητης) can be etymologically translated as "besieger or town conqueror".

For the reconstructions of the helepolis, we started from several classics; among them it seems interesting to report a piece from the "Epitoma Rei Militari" (Liber IV, par. XVII), written by Publius Flavius Vegetius

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Renatus among the end of the IV century and the first half of the V century A.D. in which these machines are well described. Generally the siege towers were mainly made by wood and higher than the walls of the besieged town; an average high of about 30 m can hence be considered, but much higher towers were also described. The base was rectangular or square with sides length equal to about 1/5–1/3 of the tower height; the structure was generally tapered at the upper part. Inside the tower some stairs permitted to reach the intermediate floors and the loft. The front side and perhaps also the lateral ones were covered by metallic plates (Diodorus Siculus) to protect the tower from the projectiles thrown by the defenders; the "armour" was completed by a curtain of not tanned and wet leathers held loosen that defended the tower from the incendiary projectiles. Under the machine some wheels were installed.

As for the helepolis moving, probably the ground was prepared by putting on it a track made by wooden boards.

Several authors also think that the helepolis were pushed or pulled by oxen or by a system of ropes and pulleys, the latter were installed on poles that were ram down at the base of the town's walls. We think that any system that pulled the tower (ropes, oxen etc.) was extremely vulnerable to the defenders' fire and hence very few effective. With regards to this aspect we can remember a piece by the Byzantine historian Procopius of Caesarea (about 500–565 A.D.) that tells about the unsuccessful siege of Rome from the Goths: Vitige, the king of the Goths (Wittigeis, ? – 540 A.D.) used wooden siege towers that were pulled by oxen; the defenders, however, easily killed the oxen making of no use the towers. Moreover is also difficult to think that so wide and heavy machines could be moved by pushing them from their back.

We think that external systems to move the towers could be used probably in the Middle Ages, but in the Classic Age more advanced systems were used. In fact, in the Classic Age, many knowledge about the Mechanics (and not only) were much more advanced than those of the Middle Ages. To this end, we can consider a piece from the De Bello Gallico (liber II, par. XXX and XXXI [3]), in which Caesar describes the siege at a town of the Gauls Atuatuci. From this piece, we understand that the Gauls were surprised when they saw very big machines that moved without any external source. Hence, it seems to us reasonable that the old helepolis were moved by "motors" fitted inside themselves.

In the following paragraphs some possible mechanical systems for the ancient helepolis propulsion are presented.

2. POSSIBLE INTERNAL "MOTORS" FOR THE HELEPOLIS

In this paragraph we propose some mechanical systems that were commonly used in the Classic Age or were perfectly compatible with the knowledge of the Mechanics of that age.

In any case we suppose that the torque (from the motor) was applied to the wheel by a rope that was rolled on a drum connected to the wheel axle and was pulled by one of the devices described later. This system was certainly used in many lifting devices in those ages and is schematically shown in figure 1.

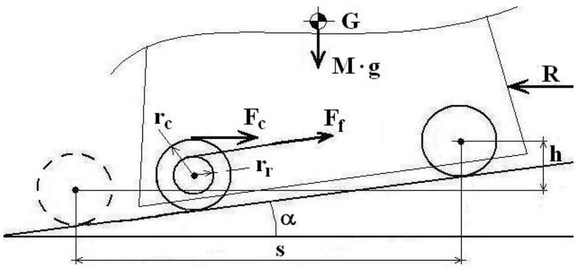

Fig. 1. Scheme of the device to apply the motor torque to the wheels axle.

2.1. The Force Required for the Traction

In order to evaluate the force required for the traction of an helepolis, we considered a machine of average dimensions having the following technical characteristics:

Helepolis height from the ground: 30 m;
Full helepolis' mass: 40000 kg,
Radius of the wheel rim: $r_c = 1.5$ m:
Radius of the drum connected to the wheel axle on which is rolled the rope: $r_r = 0.8$ m;
Slope: 2%;
Coefficient of friction between helepolis and ground: f = 0.02.

As for the data reported above, it must be pointed the followings:

- The slope value was fixed to represent an almost level ground with some local bottomlands;
- As for the coefficient of friction, it was considered wooden wheels on hard ground; it is evident that, if we had considered a track made by wooden boards, the friction would be rather lower.

With the above reported data it is easy to compute the force required to move the helepolis; it is given by the friction force and by the force required to climb the height difference.

$$R = M \times g \times (f + h/s) = 40000 \times 9.81 \times (0.02 + 0.02) \tilde{\ } 16000 \text{ N} \quad (1)$$

This force, naturally, is the force that must be exerted on the wheel rim to move the helepolis at constant speed; hence, on the drum it is necessary to exert a force:

$$F_c = R \times r_c / r_r = 16000 \times 1.5/0.8 = 30000 \text{ N} \quad (2)$$

A good rope made by hemp having 48 mm diameter made nowadays has a tensile strength higher than 150000 N (British Standard), that is to say 5 times higher. Obviously an high safety factor must be considered because it must be taken onto account both the rope wear and that 2000 years ago the ropes were not manufactured as well as now. The latter aspect plays a less important role than it could be thought: the British Standards of the middle of the XX century for naval ropes, cited before, give the same tensile strength for ropes made by stationary stranding-machine and for ropes made on the rope work train; the latter manufacturing technique is very similar to the one used from the age of Egyptians for medium and large ropes.

So, it seems reasonable to assume that, on the drum, a rope having 50 mm diameter was rolled. The force required to unroll the rope on a pulley can be computed by means of the following empirical equation [4]:

$$F_{av} = 0.02\, F\, d^2/D \quad (3)$$

If a rope diameter d = 50mm and a drum diameter $D = 2\, r_r = 1600$ mm are considered, by using the units of eq. (3), we obtain:

$$F_{av} = 0.02 \times 30000 \times (502/1600) = 937{,}5 \text{ N} \quad (4)$$

That can be neglected since, for our purposes, the computing can be rather rough. Hence, it will be assumed that the force that must be exerted on the drum is the one given by eq. (2).

In the following paragraphs the possible mechanical systems to exert this traction on the rope rolled on the drum will be presented.

2.2. Capstan Motor

The capstan is such a simple and well-known machine that it is not necessary to report any historical reference for it. The working principle is shown in figure 2. In the figure are indicated:

F^1 the force exerted on each of the capstan bars;
F_c the traction on the rope;
F_2 the force exerted on the other rope's end, essentially in order to obtain the necessary friction between the rope and the capstan;
b_1 the distance from the capstan axis where the force F_1 is exerted;
b_2 the radius of the rolled rope on the capstan.

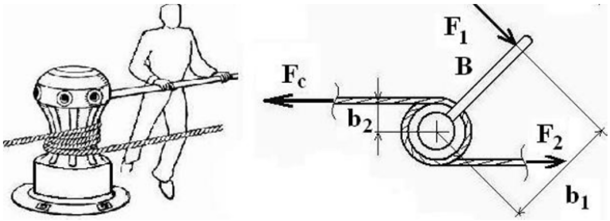

Fig. 2. Scheme of the capstan.

If we assume $b_1 = 1.5$ m, $b_2 = 0.3$ m and if we neglect the force F_2, the force that is necessary to apply to the bars in order to obtain the force F_c given from eq. (2) is:

$$F_1 = F_c \times r_2/r_1 = 30000 \times 0.3/1.5 = 6000\ \text{N}$$

If we assume that a man can exert on the bar a continuous force of 200 N average, we obtain that almost 30 men were necessary; this means that, for instance, we must suppose the presence of 2 capstan with 8 bars each and 2 men on each bar, that is to say 32 men. Since in the analysis we did not consider neither the force to unroll the rope nor the friction on the winch drum, the average force exerted by each one of the 32 men should be higher; this was possible but it seems not so easy.

In figure 3 is reported an our possible pictorial reconstruction of the propulsion system by capstans.

2.3. Tread Wheel

The tread wheel (or tread mill) is a device used since the Greek-Roman era to power lifting machines such as cranes etc. and is very similar (but obviously much bigger) to a squirrel cage. In figure 4 are reported a drawing from a bas-relief found at Capua (Italy) showing a crane of Hellenistic age, powered by a tread wheel, and the working principle of the latter.

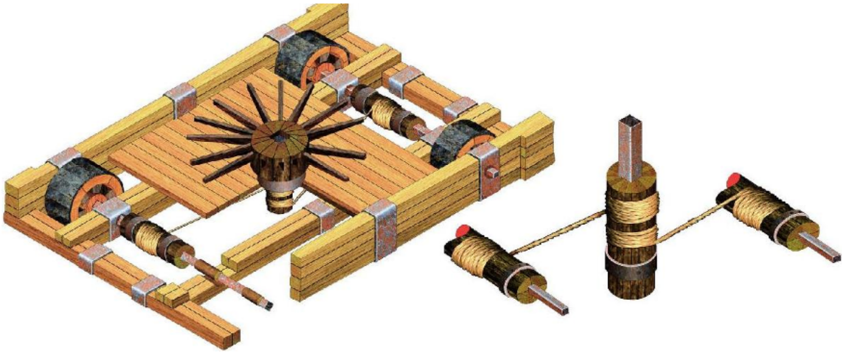

Fig. 3. Authors' pictorial reconstruction of the propulsion by capstans.

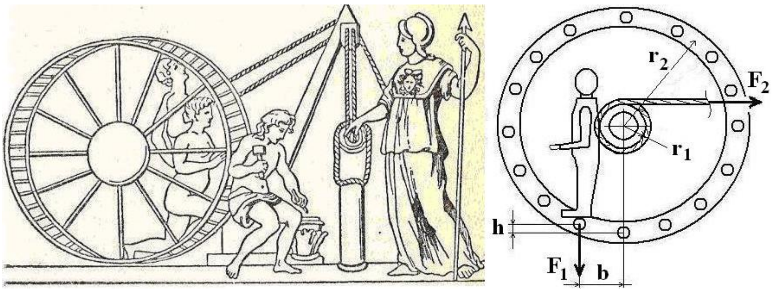

Fig. 4. Tread wheel.

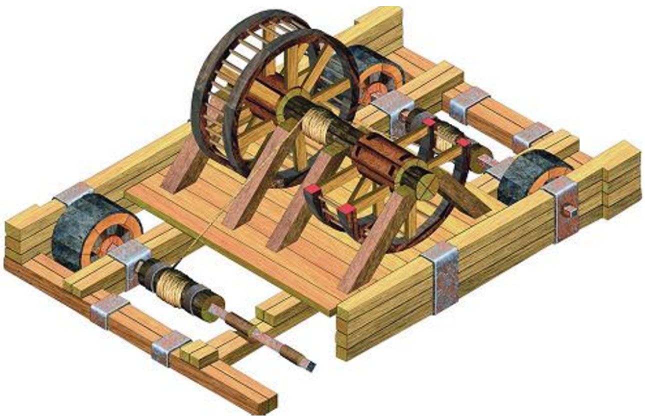

Fig. 5. Pictorial reconstruction of tread wheels for Helèpolis' propulsion.

In order to compute, roughly, the traction force on the rope that is possible to exert, let us assume the following data:

Mass of a man (in those ages): m = 65 kg, hence: $F_1 \approx 650$ N;
Mean radius of the rolling of the rope: $r_1 = 0.3$ m;
Mean radius of the tread wheel: $r_2 = 3$ m;
Mean level at which a man acts from the bottom: h = 0.5 m.
From figure 4 it is:

$$b = \sqrt{r_2^2 - (r_2 - h)^2} = 1.66\,\mathrm{m}$$

Hence:

$$F_2 = F_1\, b/r_1 \approx 3600\,\mathrm{N}$$

Obviously F_2 represents the force exerted on the rope by each of the men in the wheel. Hence, in order to obtain the traction computed by eq. (2), 30000/3600 ≈ 8 men were necessary. So, it is possible to suppose the presence of 2 tread wheels, each one with 4 men, disposed as in our pictorial reconstruction reported in figure 5. This reconstruction seems more realistic than the previous one.

2.4. Counterweight Motor

The counterweight motor, as will be illustrated, seems to be the more effective motor, from many points of view, for the helepolis' propulsion.

2.4.1. Historical references

The use of counterweight motors is documented in the Roman age for several applications like to move the curtains in the theatres [5]. It is also well-known that Heron of Alexandria, in the I century A.D., used counter-weight motors to move figurines representing animals in a sort of theatre in which the actors were automata moved by counterweight motors and a device that permitted, among other things, to program the law of motion of the automaton itself [5-8]. To this end it could be interesting to report the following piece from the Heron's treatise Perì Automatopoietiches (Περι αυτοματοποιητικης = about automatics) [9, 11] in which figurines mechanically moved in an automata's theatre are described:

> ς΄δύνανται δὲ καὶ ἕτεραι κινήσεις ὑπὸ τὸν πίνακα γίγνεσθαι, οἷον πῦρ ἀνάπτεσθαι ἢ ζώιδια ἐπιφαίνεσθαι πρότερον μὴ φαινόμενα καὶ πάλιν ἀφανίζεσθαι. καὶ ἁπλῶς, ὡς ἄν τις ἕληται δυνατόν ἐστι κινεῖν μηδενὸς προσιόντος τοῖς ζωιδίοις.

Also other movements under the platform (of the theatre) can be present, like to light a fire or figurines representing animals that before were not visible suddenly appear and then disappear again. And simply, like one could touch them, it is possible that they move without anyone approaches to the figurines representing animals.

In this one and in other pieces are described automata that move without any action from outside.

The treatise by Heron was translated during the Renaissance from Berardino Baldi, abbot of Guastalla, (Urbino, 1553–1617) [6]; in this work are described, among others, some examples of mobile automata, moved by a counterweight motor. In figure 6 are reported drawings from Baldi's work; on the left the working principle of the counterweight motor is evident since the counterweight, the rope linked to the latter and rolled on the wheels axle are clearly observable. In the figure it is possible to observe also the third wheel that is idle and the counterweight that is located in a tank filled with millet or mustard seeds in order to regulate the counterweight motion.

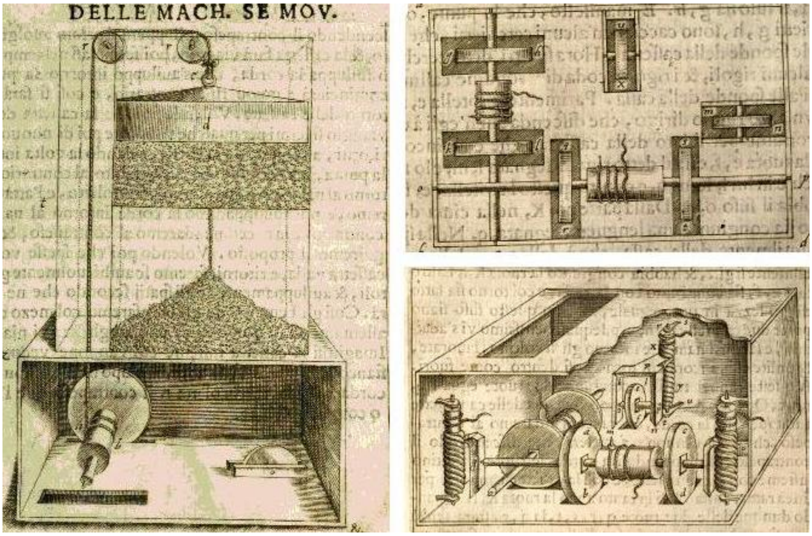

Fig. 6. Counterweight motor and mechanism to change direction [6].

Also very interesting are the systems, invented by Heron and described by Baldi, to change the cart's direction. In figure 6, on the right, are reported two Baldi's drawings in which is shown a first system used to change the cart's direction: in the drawing above it can be observed that two driving axles are used, each one is perpendicular to the other one; in the same way, also the axes of the idle wheels are perpendicular.

During the running, two driving wheels and an idle wheel lean on the ground while the other wheels (which axes are orthogonal to the first ones) are lifted up. By means of screw jacks, shown in the lower drawing in figure 8, that are also operated by ropes, it is possible to take down the wheels which axis is orthogonal to the ones' that lean on the ground. After this manoeuvre the chart will lean on these latter wheels and will move in a direction that is orthogonal to the previous one. To this end it is interesting to observe that the castle (or rook or tower) of the chessboard (that probably symbolize a siege tower) move on the chessboard just in the same way; it is well-known that the chess is a very ancient game that is described in Indian writings of the first centuries A.D.

Another system to change direction seems even more interesting because it uses the programmability of motion concept; this system also is attributed to Heron and is described by Baldi. In figure 7, on the left, a drawing from the work by Baldi is reported. The axle of the driving wheels is divided in two axle shafts that are independent one from the other; on each one of the latter a rope is rolled. If the rope is rolled on one of the axle shaft in a different way from the other axle shaft, when the counterweight goes down pulling the rope, one of the two driving wheels will rotate in different way from the other one. Moreover, it is also possible that, during the counter-weight's run, one of the wheel stops while the other rotates; this is obtained by wrapping a piece of the rope in an hank like shown in figure 7, on the right.

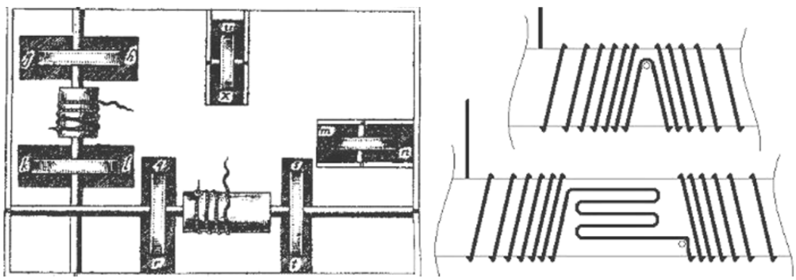

Fig. 7. Traction with independent axle shafts (left); scheme of rope rolling to program the motion (right).

During the time in which the hank unleashes that axle shaft is stopped. It is also possible to obtain that one of the axle shafts rotates in the opposite sense respect the other one; this is simply obtained by rolling the rope on one axle in the opposite sense respect the other one. Finally even a programming of the motion can be obtained by putting some knobs on the axle shaft like shown in figure 7; by means of these knobs it is possible to modify the rolling of the rope, as described before, in order to obtain different laws of motion for each wheel.

Some scholars (see e.g. [8,10]) have built, quite recently, models of charts moved by counterweight motors based on the works by Heron; they demonstrated, practically, the possibility of programming the motion.

2.4.2. The proposed reconstruction

In figure 8 is reported a scheme of our reconstruction.

In order to verify, conceptually, the possibility that a counterweigh motor could move an helepolis, we assumed the following data:

Counterweight mass = 1000 kg;
Radius of the helepolis' wheels: $r_c = 1.5$ m;
Radius of the drum that is the axle shaft: $r_r = 0.8$ m;
Block and tackle with 5 pulleys (Pentaspaston, described by Vitruvius in I century B.C.);
With the data above, it is easy to compute that if the counterweight goes down 20 m, the helepolis will go ahead: $20/5 \cdot 1.5/0.8 = 7.5$ m.

This amount seems reasonable with respect to the speed of a siege machine.

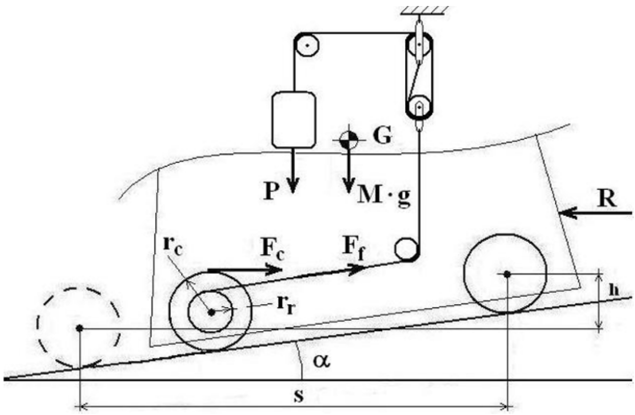

Fig. 8. Scheme of the helepolis' counterweight.

It can also be supposed that the force F_c that must be exerted on the wheels ring to move the helepolis at a constant speed is the one computed by eq. (1) and that the force F_f that must be exerted on the drum is that given by eq. (2).

Since the Block and tackle has 5 pulleys, and also two more pulleys are present as transfer case, if we suppose that manufacturing of pulleys and shaft was not very accurate, we can compute [12] an efficiency η≈0,7.

So, the counterweight that exerts a force of about 10000 N, through the block and tackle will pull the rope rolled on the drum with a force:

$$F = 1000 \cdot 9.807 \cdot 5 \cdot 0{,}7 = 34335 \text{ N} > F_f$$

Therefore, conceptually, such a motor could be able to move an helepolis which mass is 40000 kg.

It must be also observed that a counterweight, which mass is 1000 kg, can be easily made by a tank having a capacity of 1 m^3, filled with water; the tank could be unloaded when it reached the lower end of its run, then brought empty at the top and there filled by water with a chain of buckets. In addition, at those ages, suitable reciprocating water pumps were available (see e.g. [5]). The presence of water on the helepolis was documented in a piece (XX, 851) by Diodorus Siculus.

The study of the helepolis' movement with a counterweight motor can be carried on by means of a simulation software; in figure 9 is reported the simulation model and the results of a dynamical 2-dimensional simulation made by Working Model 2D ™.

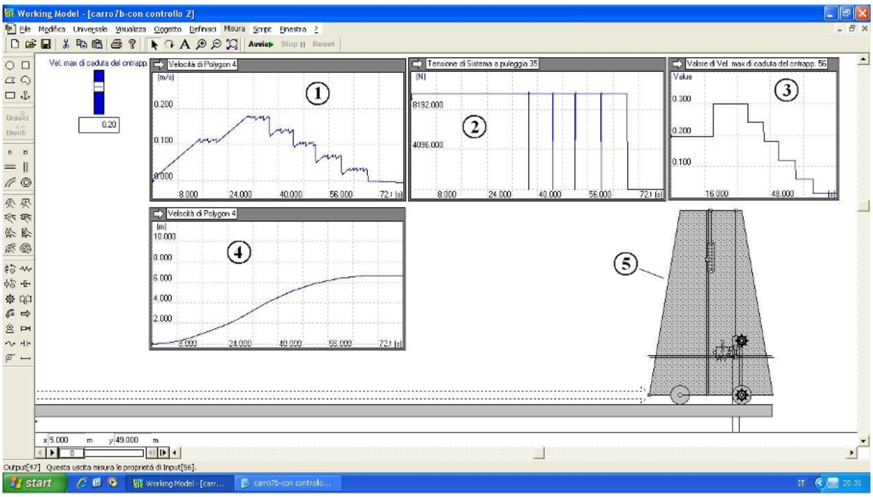

Fig. 9. Helepolis' with counterweight motor WM2D model.

In the figure are reported: the velocity of the helepolis 1, the stress on the pulley system 2, the velocity of the counterweigh 3, the displacement of the helepolis 4 and the model of the helepolis 5.

As for the modelling, the following can be observed:

1) The tower was modelled with a polygonal rigid body; the counterweight (1000 kg mass), running downwards, lifts a body (having negligible mass) that is pressed against a cylinder which diameter is 1.6 m. The spring that presses the body on the cylinder is pre-charged and, in parallel, a damper was added to avoid that the body could bounce on the cylinder. The latter is moved, hence, by friction. The cylinder moves the wheel of the chart through a transmission having a gear ratio 0.2, in order to simulate the 5 pulleys block and tackle (pentaspaston).

2) Naturally, the counterweight motion would be an uniformly accelerated motion. In order to adjust the counterweight motion a force proportional to the counterweight speed F=k·v was added. Since the weight is 9077 N, the constant k is simply: k=F/v=9807/v; so, if a speed of 0.2 m/s is required, it will be k=49035Ns/m;

3) The force against the motion (due to friction between wheels and ground and to a 2% ground slope) were considered by applying a resistance force R = 16000N (proportional to the tower's weight) at the tower's base. This force acts only if the towers goes forwards and is null if the tower stops.

The scheme of the applied forces is reported in figure 8. These represent, from top left clockwise, the helepolis' speed, the strain of the block and tackle rope, the counterweight speed and the helepolis' displacement. It must be observed that, in the presented simulation, we supposed that the counterweight motion was controlled. In the small counterweight motors (small self-propelled automata and similar devices) this control was obtained by putting the counterweight itself in a cylinder filled with millet or mustard seed and by regulating the seed's flow by a valve, as described by Heron and reported by Baldi. Such a device, although theoretically possible, was not suitable for an helepolis but we can imagine that a brake could be installed on one of the mechanism's ropes. In the reported simulation's results we supposed that the counterweight maximum speed was set at 0.2 m/s at the run's beginning, then was increased to 0.3 m/s and finally was decreased at 0.06 m/s till the stop. In figure 9 the instants of time when the manoeuvres to adjust the speed are made are clearly visible because in those instants the strain of the block and tackle rope becomes zero for a very short time.

3. CONCLUSIONS

Some possible reconstructions of motors that could have been used for the helepolis' motion were examined. Among these, the one that seems more suitable and effective is the counterweight motor.

We must admit that, while from the historical sources it clearly comes that the helepolis were self-propelled by internal motors (in which certainly mechanical devices were present), the “proofs” that counterweight motors were adopted for the helepolis are mostly circumstantial. It is sure, in fact, that such motors were adopted, rather widely, in ancient times to move self-propelled automata and charts; nevertheless as far as their use in the helepolis is concerned, we did not found, still, a deciding proof.

Nevertheless it seems quite certain that the siege towers were self propelled; as for this aspect is concerned, it is also interesting to report the following piece from Julius Caesar (the De Bello Gallico, liber II, par. XXX and XXXI [3]), in which describes the siege at a town of the Atuatuci Gauls:

> XXX – …Ubi vineis actis aggere exstructo turrim procul constitui viderunt, primum inridere ex muro atque increpitare vocibus, quod tanta machinatio a tanto spatio instrueretur: quibusnam manibus aut quibus viribus praesertim homines tantulae staturae - nam plerumque omnibus Gallis prae magnitudine corporum suorum brevitas nostra contemptui est - tanti oneris turrim in muro posse conlocare confiderent?
>
> XXXI – Ubi vero moveri et adpropinquare moenibus viderunt, nova atque inusitata specie commoti legatos ad Caesarem de pace miserunt, qui ad hunc modum locuti: <u>non se existimare Romanos sine ope divina bellum gerere, qui tantae altitudinis machinationes tanta celeritate promovere et ex propinquitate pugnare possent</u>, se suaque omnia eorum potestati permittere dixerunt.

> XXX – … As soon as (the Gauls) saw that, having we pushed on the vinea (mobile roofs) and built an embankment, we started to built a tower, at first they derided and insulted us because a so big device was built so far (the walls): on what hands and on what force could ever the Romans rely, small as they were, in order to bring near the walls a so heavy tower? All the Gauls, in fact, scorn our height if compared with their large bodies.
>
> XXXI – As they saw that the tower was moved and was approaching their walls, frightened by the unusual sight, (the Gauls) sent ambassadors to Caesar to negotiate the peace; <u>they said that they think the Roman make war with the help of the goods since they can move such big machines so fast</u>, (hence) the put themselves and all their wealth under the power of Caesar.

This study, anyway, demonstrates that the use of counterweight motors for the propulsion of the helepolis was certainly possible and probably the most effective.

Finally this also is an example that shows how, in order to correctly understand the past, it is necessary a wider cooperation between scholars having humanistic knowledge and scholars having technical knowledge.

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