Historical and Technological Study of the 26 and 30 Mechanisms of "The Book of Secrets" by Ibn Khalaf al-Muradi

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Abstract. In the present chapter, a historical study and technological analysis of some mechanisms or mechanical devices of the Middle Ages, around 1100 year, will be carried out. In that time, it was very usual to see devices working moved by water, in most cases by animal power, made of affordable materials such as wood and built by hand. The 26 and 30 mechanisms of "The Book of Secrets", a manuscript written by the Andalusian engineer named Ibn Khalaf al-Muradi, will be specifically analyzed. They show a mechanism to raise water from a well by means of a bucket in a repetitive way, operated by animal power and a water clock. A description of the components of the mechanisms, their operation and their most significant characteristics will be made. Next, a virtual reconstruction of the mechanisms will be presented, using geometrical modeling software such as Catia V5, which facilitates the virtual reconstruction of these devices. Finally, a virtual animation can be generated to appreciate the operation mode, as well as to carry out mechanical analysis.

Keywords: History of Machines and Mechanisms · Geometric modeling

1 Introduction

With the fall of the Roman Empire (476 AD), the period called Antiquity ended and the Middle Ages began until the discovery of America (1492 AD) in which the Renaissance began. That era was characterized by continuous wars throughout the European geography. They were appearing different peoples (Goths, Celts, Franks, Muslims…) which posed a very unstable situation, in which the study of technology did not take place. Perhaps the most interesting developments in engineering and technology in the Middle Ages are those that occur in the Islamic world, but did not become very well-known because the knowledge was passing from teachers to apprentices without being reflected in written documents, and of the few manuscripts that came to be written, a minimum part have survived due to their loss and deterioration.

The Muslim population was concentrated mainly near the rivers, where they used their waters for the irrigation of agriculture and other domestic chores. For the use of

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water from the rivers, they devised numerous devices for their elevation and manipulation. Many of these machines and devices such as the shaduf, the noria and the diversion dam are included in the Islamic illustrations of the time.

Caliph Al-Ma'mun in the ninth century founded in Baghdad the "House of Wisdom" dedicated to study and translation. Among other works, they translated works by Hero, Archimedes or Euclid. In it, many important personalities of the time were formed, such as the Banu Musa brothers (Mohammed Jafar ibn Musa, Ahmad ibn Musa, and al-Hasan ibn Musa). The three Banu Musa brothers write their "Treatise on ingenious devices" considered to be the first book in the Islamic world on the subject. It describes a lot of mechanisms, some very advanced, many of which are known for the translations of the works of Hero and Philon. In the manuscript, many improvements of old machines are reflected as well as new machines in which its inventiveness stands out. It is characterized by the description of the machines, drawings, purpose and operation of the mechanism. The studies developed in the book of the Banu Musa brothers were adopted by later Arab engineers, who transmit all this wisdom during the conquest of Spain, where the Arabs found Al-Andalus and from there to the rest of Europe.

In the thirteenth century, Al-Jazari, considered to be the most important mechanical engineer of his time, writes the book: "Treaty of knowledge about mechanisms", which stands out for a greater detail of the explanations and drawings of the mechanisms and that had great influence both in the Islamic world and in European mechanical engineering. Its classification of technology is curious: the "quality", with more sophisticated machines and instruments, designed for the use of nobility or scientific use as clocks or measuring machines and, the "utilitarian", with technically simpler machines that serve the economy of the country or the workers, such as mills, water elevators or textile machinery.

Meanwhile, in France the figure of Villard de Honnecourt emerges, who is pointed out as a forerunner of the Renaissance. In the first half of the thirteenth century, he travels throughout France writing down in his travel notebook both construction techniques and mechanical devices. Later, already in the Renaissance, great advances take place in the study of the machines and mechanisms, like those realized by Brunelleschi, Di Giorgio, Da Vinci, Agricola, Bessonus, Ramelli, Zonca, etc.

Although the aforementioned books by the Banu Musa and Al-Jazari brothers may be the most prominent in that Islamic era, there are other books from the Islamic world of great importance in the description of mechanisms, such as "The book on the construction of watches and their use" by Al-Saati Al-Khurasani (13th century) and "The book of secrets" by Al-Muradi (11th century).

2 The Book of Secrets

Ibn Khalaf al-Muradi was an important Andalusian engineer and inventor who lived in Granada and Cordoba in the 11th century and of whom we do not know much. He wrote a manuscript on mechanics of original name *Kitāb al-asrārfīnatā'iy al-afkār* and called "The Book of Secrets". It is preserved thanks to a copy made in Toledo back in

1266, by a translator of the court of Alfonso X the Wise, which is kept in the Medicea Laurenziana Library of Florence.

The manuscript, originally written in Arabic, is not kept complete as many of its pages are damaged. It consists of 31 chapters, each of which describes a fascinating mechanism such as water clocks, war machines, theaters, and many more complex mechanisms. Thanks to this manuscript, we can understand how mechanical engineering was about 1000 years ago.

The recovery of the old manuscript was made thanks to the patronage of the Emir of Qatar and the Museum of Islamic Art in Doha. They funded a research project that led to the publication of a facsimile with the reproduction of the original in Arabic, others with transcriptions and interpretations in Arabic and English; and another interactive 3D publication of the mechanisms in charge of the Leonardo 3.

This manuscript is of great importance in the field of engineering and science because it represents one of the first testimonies of complex mechanisms of antiquity. The manuscript contains a description in Arabic of each of the mechanisms, along with drawings and sketches of them (Fig. 1).

Fig. 1. Sample page of "The Book of Secrets"

In this chapter, Figures 26 and 30 of the manuscript will be analyzed and studied.

3 Figure 26. Mechanical Well

Figure 26 consists of a mechanism for its use in a water well. By animal force, it is generated an uniform circular movement that raises a bucket full of water from the well, dumps it, empties it in a ladle and moves it back to the well. The operation is performed in a repetitive fashion, without the animal having to stop or change the travel direction.

Transcription of the description:

"And (…) we want to put a mule by that well to run over it so that when one yard of the rope is pulled, the bucket is pulled out full of water, empties itself and goes back to the bottom of the well, while the beast remains running around constantly. So let the well be as was described concerning its division, the nails in it, the ropes and the arrangement of its pulleys and the bucket. However, the bucket has a spout protruding to let the water out. This spout is half a handbreadth or so shorter than the bucket. As to how the bucket comes up to the mouth of the well, it is as I describe if God so desires (Fig. 2).

Fig. 2. Page corresponding to figure 26

Let us make a rectangle, ABCD. This box has a cover on its top. Axis H stand in the middle of the figure. We install an orbit, FG, whose diameter is ten and a half-breadth. Thirty two teeth are fixed to half of its circumference. Two axes with four blades each are fixed (to the side of orbit FG). The blades are equal to the teeth in dimensions. Axes are C and I. Axes I has a one-finger-wide and one-finger-deep groove on its circumference. A rope extends inside the groove and passes to pulley E (which) has part of its circumference inside the well. The rope is attached to the spout of the bucket, which has the mark on it.

Install an axis, J, with four blades beside (axis I). The distance between (each two) blades is one handbreadth. A rope is attached to it and extends to pulley D. The rope then ascends to pulley G and passes to the mouth of the well. This rope has a pulley at its end.

Install an axis with four blades beside axis C. The distance between each two blades is one handbreadth. A rope extends from this axis to pulley C then to pulley G at the mouth of the well. The rope is attached to the (outside) of the bottom of the bucket.

A cane is attached to axis (H) on box (ABCD). This cane is tied to the beast, which runs around as in a waterwheel. And that is what we wanted to do if God so desired. And this is its image."

Transcription of the interpretation:

"The mechanical well is a series of pulley mechanisms that are applied to a well to help lift up the water, pour it and then send down the bucket again, and so on continuously. The main mechanism inside the well is the same as the one in figure 25. It is centered on lifting the bucket eight meters by pulling a one-meter-long rope (3,2 feet). The rope is attached to a mechanism that is put into motion by a big wheel that rotates thanks to a mule that turns around the well. The big wheel placed beside the well moves as well a second mechanism that sends the bucket down the well. The two systems of lifting the bucket and sending it down function alternately, because only one half of the big wheel is toothed. Thus, the two systems are engaged alternately. A third rope is linked to the traction system to lift the bucket once it reaches the top of the well and the water out of spout of the bucket. This apparently simple system contains some mechanical and geometrical inconsistencies which make its execution, as it is described. The drawing has some damaged segments, but the bucket and the spout are shown clearly on the top left corner. At the bottom, we can see the big wheel, and, to its left, the axis which is diverted from it. At L is the axis that should be attached to the mule in order to put the system into motion".

4 Figure 30. The Clock of the Small Stones

This figure is based on a clock that works thanks to water. The mechanism consists of a container full of water, with a floating buoy, which is unloaded slowly. The buoy goes down with the water that triggers a mechanism consisting of a gearwheel attached to the clock hands, with 12 h. At the same time, this wheel moves another with 12 holes, each hole contains a ball and, every hour, a figure throws the ball emitting a sound. Once the cycle is finished, the container is refilled with water and the process starts again.

Transcription of the description:

"We want to make a figure which moves by the hours. (This figure) is a circle similar to the astrolabe. There is a statue below, which throws a pebble each hour.

So let us make a rectangle, ACBD, where line AD is twice as long as line AC. Draw another line, EF, from line AD to line CB. An axis, GH, is installed from line AE to line CF. Point G is on line AD, while point H is on line BF. Point H protrudes by two fingers. Install an alidade like as the astrolabe, which runs over a circle of copper or any other metal. The metal circle is fixed. This circle is divided by two perpendicular lines into four quadrants. The first line passes through the centre of the earth to the centre of the sky and is the line of midday. The second line passes from East to West. Draw the hours one half of the circumference of (the circle above) the Earth and draw on the other half the degrees of the orbit, which are a hundred and eighty degrees, so that the alidade passes the hours and the degrees. And this is its image.

Install on axis BA an orbit, IJ, whose circumference (is divided into twice as many parts) as those of the water tank of this figure. The thickness of its circumference is two fingers. It has a groove on its circumference and teeth on one half of its circumference. The teeth are equal in dimensions.

Install another orbit, KL, opposite point J. The diameter of orbit KL is half that of orbit IJ. Divide the circumference of orbit (KL) into twelve equal parts, equal to those of the water tank (…) (Fig. 3).

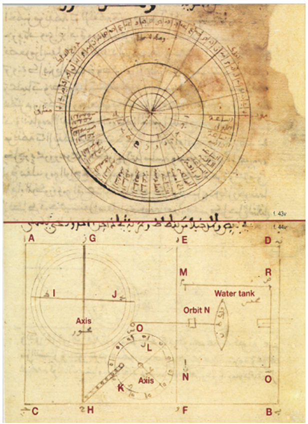

Fig. 3. Page corresponding to figure 30

Make a hole, whose diameter is one finger, at the beginning of each part. Install orbit (KL) on another orbit (…). On the circumference of (this) orbit make a hole. This hole should correspond to each hole of orbit (KL), which passes over it. A canal, K, extends from this hole to (…) the head of the statue, which throws a pebble.

Attach (a rope) in the groove (of orbit KL) at point L. The rope extends in the groove and passes to a pulley, L. The rope then passes to a pulley, C, which touches the circumference of orbit IJ. (The rope then extends in the groove or orbit IJ and is attached at point J.

Orbit (KL) has teeth on its circumference which are equal in dimensions to those of orbit IJ. That is because orbit IJ has sixty teeth on its circumference from (point) J to point I. The teeth (of the two orbits) engage with each other.

Extend a rope from point I inside the groove to end at point J. The rope then passes to pulley O and then to pulley M. Pulley M is on the water tank. The rope passes from pulley (M) to an orbit, N, inside water tank MNOP. The spout of this tank is similar to what was described. The tank is managed in the same manner as that of the figure of the mirrors. And that is what we wanted to do if God so desires".

Transcription of the interpretation:

"At the top of each hour, a statue throws a pebble from his mouth making a distinctive sound. Above the statue, a disc similar to that of an astrolabe is installed to point out the hours and the degrees of zodiac constellations. This machine is moved by the movement of a floating orbit which descends following the descent of the water level in a water tank. As the floating orbit descends, it pulls on a rope which moves the main disk on top of the machine. Half the circumference of the top disc is toothed. These teeth function to move the orbit, which holds the twelve pebbles. As the diameter of this orbit is half that of the main disc, the orbit moves a whole circle as the disc moves for 180 degrees. On top of each hour, a pebble falls through the hole and reaches the mouth of the statue through a tube. As the orbit turns, the pointer on the orbit turns as well. The pointer and the orbit function similar to an alidade and an astrolabe. The pointer has two heads, each of which turns for 180 degrees. While the lower head indicates the passage of hours, the upper head points at the zodiac constellations. As the constellations are drawn on the front of the orbit, the correct position of the machine can be depicted. The front of the orbit should face north and thus the Eath and the West will be in their correct positions. The diagram of the dial is shown on page 43 and explained clearly to some extent. The diagram of the clock is on page 44 separated from the first diagram by the misplaced diagram of the twenty-eighth figure (which we have placed in its correct position on page 160). The diagram shows the floating orbit on the right side inside the water tank. On the left side, the main disc is drawn and is attached to the axis. The axis ends at the alidade at the bottom of the diagram, while the outer orbit is not shown in the diagram. In the center of the lower part of the diagram, the orbit with its twelve pebbles it shown as well as the tube through which the pebbles reach the statue".

5 Geometric Modeling

For modeling the mechanisms, we will use powerful software, specifically Catia V5 developed by Dassault Systems, for design and manufacturing assisted by computer. One of its important features is to assemble an indefinite number of parts, assigning a material to each of them, and carrying out a simulation of the whole, without having to develop real prototypes, among other advantages.

5.1 Figure 26. Mechanical Well

We start by modeling the main structure, whose dimensions are not defined in "The Book of Secrets". So, we will assign dimensions that conform to the scale that we will apply to the parts of which we have approximate real dimensions in meters, such as gearwheels. Then gearwheels, shafts, and secondary parts, such as the bucket and pulleys are modeled.

The main structure is composed of three parts, the main support (built of bricks), the structure of wooden beams containing the mechanisms, and the well (Fig. 4).

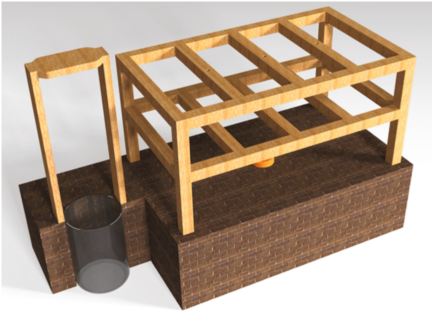

Fig. 4. Main structure of the mechanical well

The modeling is done through simple operations such as circles and rectangles that are extruded to obtain the different parts that integrate the main structure. Next, holes are made for the shafts, which will carry the gearwheels. We also create pillars and roof beams in the same way, also using wood. Finally, we create the well, transparent to appreciate its interior, creating a circle, extruding it and creating a void, to give it a container shape that will contain water in its interior.

The next step is to model each of the three shafts. These are: the main shaft, which contains the main wheel that is only half-serrated, and two similar shafts, with the secondary wheels, guidelines of the main wheel, and which alternately rotate in opposite directions (Fig. 5).

Fig. 5. Main and secondary shaft of the mechanical well

The procedure for modeling the already presented shafts is the same as described above. We use extruded circles with a desired thickness and suitable length for the shafts, and a small keyed cylinder for the teeth, in which a 180° matrix to arrange teeth in the middle of the wheel is made.

5.2 Figure 30. The Clock of the Small Stones

Initially, the main structure is modeled, with dimensions that approximate with precision to the scale of the real figure in "The Book of Secrets", since we do not have them defined. Later, the remaining parts are modeled and, finally, it will be assembled so that the whole machine is completed.

The modeling of the main structure is carried out with the same procedure described above, by means of squares, rectangles and circles that are extruded with the thickness and length appropriate to each part, in which the necessary drilling, keyway machining operations, etc. are carried out (Fig. 6).

Fig. 6. Main structure of the water clock

Finally, the bottom part, which is a similar wood structure, but rectangular, with four legs a little wider, which will be used to put a second tank. This tank will be filled with water when unloading the container where the buoy is placed.

A circle of certain dimensions is extruded. The teeth, a smaller secondary wheel so that the thread attached to the buoy pulls this shaft, the rod that forms the shaft and, finally, the hand to mark the hours and the degrees of the constellations are drawn. For the teeth, it is a small cylinder, chamfered and, then, a 360º matrix is made. We assign the material (Fig. 7).

Fig. 7. (a) Main shaft and water clock hand. (b) Ball wheel with holes for balls

The procedure is the same, with a small difference, this shaft carries only one wheel, but with twelve holes that serve to carry the balls. To make the deposits, similar steps have been followed, a rectangle and a circle are extruded with adequate length; later, corners are rounded and emptied.

6 Assembly

For the assembly, we have the "Assembly design" command that allows importing single parts, the main structure, the shafts, and the secondary elements such as animal, bucket, pulleys and ropes.

With the "Snap" command, we can move with precision in millimeters the shafts to their respective holes and, with the "Manipulation" command, we move the different parts along the Z axis to their position, with the relations of position and movement. The result is the complete mechanisms, in the following way (Figs. 8 and 9):

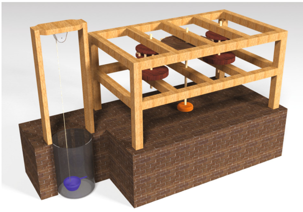

Fig. 8. Figure 26 assembly, mechanical well

Fig. 9. Figure 30 assembly, water clock

7 Analysis

The performed geometric modeling, by means of the appropriate modules of "Analysis & Simulation" modules of the Catia V5 software, allow us carrying out the mechanical analysis of the mechanisms, especially of its most vulnerable parts. For the case of the clock, we will analyze the main shaft that contains the hand and the gearwheel. For the case of the well, we will analyze the beams of the wooden structure.

For the analysis, the contour conditions (distributed and point loads, supports, materials, etc.) are applied to the model, the meshing is arranged and, then, the analysis can be carried out, obtaining the corresponding results.

7.1 Figure 30. The Clock of the Small Stones

The part to analyze is the main shaft, with hand and gearwheel. It is the most vulnerable part because it is in motion all the time.

As we can see in Fig. 10, we assign fixed supports and then insert the loads, two on the sides, where the shaft is fixed to the main structure and, one, on the small wheel, which is pulled by the buoy. Then, we can obtain a mesh and analyze both deformations and stresses.

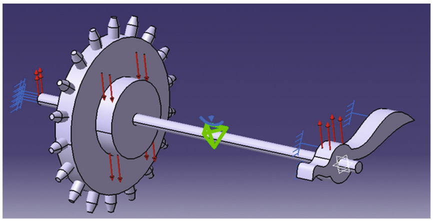

Fig. 10. Main shaft with hand and gearwheel of the clock water

The material of this whole part is pine wood, with a Young's modulus of about 7000 MPa. This value can vary according to the type of wood used.

We analyze the Von Mises stresses, the part is deformed just a little since the structure weighs very little. But, nevertheless, we appreciate that the area more prone to stresses is on both sides of the gearwheel, in red color, as we can see in Fig. 11.

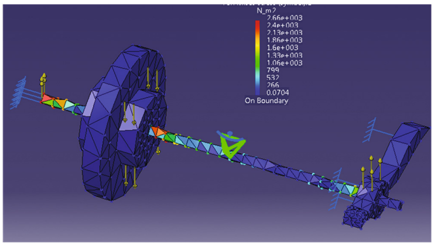

Fig. 11. Von Mises stresses in the main shaft of the water clock

7.2 Figure 26. Mechanical Well

For the well, one of the six wooden joists that form the main structure will be analyzed. They contain the different shafts in vertical position.

First, the fixed supports are set. In this case, they are placed at the ends of the beam. Subsequently, a load is inserted downwards, which is the shaft with gearwheels. This one has very little mass so, the deformation will be minimal (Fig. 12).

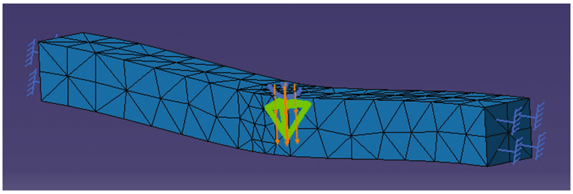

Fig. 12. Wooden beam deformation of the main structure of the mechanical well

The material assigned is pine, we can appreciate the Von Mises stresses being the most vulnerable area, just the center of the beam, where the load is placed. We can appreciate the reddish colors in Fig. 13.

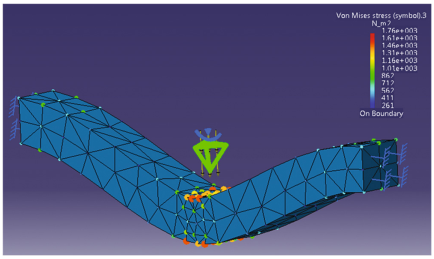

Fig. 13. Deformation and Von Mises stresses in the wooden beam of the main structure of the mechanical well. (Color figure online)

8 Three-Dimensional Reconstruction

For the three-dimensional reconstruction at scale, we have chosen not to use any manufacturing method, such as molds, machining (lathe, milling machine, etc.) or the novel 3D printing. In addition, because they are machines of the Middle Ages, to build prototypes to scale of the mechanical devices, common materials have been used as wood, plastic and iron, which work with water.

The materials used are: wood, for the main structures, beams, shafts, details, gearwheels; metal, for the brackets to join wooden beams, screws, pulleys; plastic, for the water tanks, figure that throws the balls in the clock; thread, for the ropes. To join the parts, it was chosen white glue or, in some cases, screwing to give greater strength, and avoid possible breakage (Figs. 14 and 15).

Fig. 14. Reconstruction at scale of the mechanical well

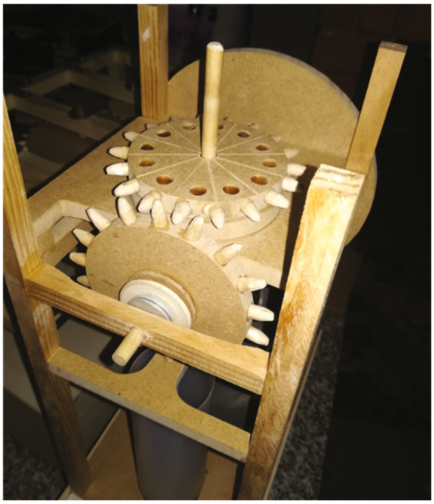

Fig. 15. Reconstruction at scale of the clock of the small stones.

9 Conclusions

By means of modeling and simulation modern techniques, we can carry out a virtual reconstruction to scale of old mechanisms, understanding their operation and deepen in the field of the History of Machines and Mechanisms.

The study of a mechanism to raise water from a well, as the one in Figure 26, and a water clock, as the one in Figure 30, of the manuscript “The Book of Secrets”, written in the 12th century by Ibn Khalaf al-Muradi has been carried out.

The geometric modeling allows us to simulate and analyze the different parts of the set, as well as the real reconstruction at scale of the mechanism.

These studies can be applied in teaching of different engineering subjects, and to the virtual and real recovery of mechanical devices.

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