Historical-technological study, modeling and reconstruction to scale of the six-cylinder pump of Taqī ad-Dîn

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Abstract: This work presents both a historical study and a technological analysis of one of the most ingenious Middle Ages' mechanisms in the East. This time can be considered one of the darkest stages, as far as technological progress is concerned. However, we can refute this qualification by contributions such as the Taqī Ad-Dîn (1526-1585) one. This article has addressed a study of the great work of this inventor, "Al-Turuq al-samiyya fi al-alat al-ruhaniyya" or "The Sublime Methods for Spiritual Machines" (1551). Thus, within this work, we focus on his most relevant hydraulic machine, "The Six-Cylinder Pump": a hydraulic machine for lifting water. This functionality is obtained through the use of six cylinders in line, unheard of at that time, with their corresponding pistons. We explain its operation and describe the mechanism's multiple components, their role within this device, and its most significant characteristics and peculiarities. A virtual interpretation of "The Six-Cylinder Pump" has been made using CAD software. A virtual animation has also been carried out to appreciate the mode of operation. It is possible to accomplish the mechanical analysis of its most characteristic elements through the assisted engineering modules. Finally, we show a mock-up of the mechanism using different technologies and materials, which helps appreciate its performance.

Keywords: History machines and mechanisms, Geometric modelling, Mechanical design, Additive manufacturing.

1. Introduction
The Arab civilization, historically, has promoted the evolution of the mechanical sciences of the East at the hands of numerous scholars, geniuses, inventors, expert scientists in or of various kinds and subjects. Among the above, we will fix our attention on one of those scholars, Taqī Ad-Dîn, who around 1551, wrote his magnum opus “The Sublime Method of Machines”. Oriented towards the geometric-mechanical structure of machines, using the analysis method used previously by Banū Mūsā and Al-Jazarī [1,2]. In the aforementioned work, there are numerous inventions such as hourglasses, devices to lift weights, fountains and even a rotating steam engine, long before Giovanni Branca's in 1629.

This book has a simple, intelligible, and precise approach and style. He also highlights the value of the schemes of his inventions, very close to the style of representation of recent engineering. A curiosity of this writing is that Dr. Ahmad Y. Hassam, from the University of Aleppo succeeds in reproducing it at the I World Congress of the History of Sciences among the Arabs (1976), despite being 35% damaged due to humidity and poor conservation.

What shows the importance of the treaty is that it “completes a missing link in the history of Arab technology and, in particular, in the history of Arab mechanical engineering. Furthermore, it describes
several new machines that were not mentioned in previous books" [3]. Likewise, the importance of the work lies in its uniqueness compared to other engineers such as Agricola, his most relevant work: "De Re Metallica" in 1556, and Ramelli: "Le diverso et Artificiose Maquina" in 1588, who described various types of bombs but none similar to that of Taqī ad-Dīn.

If we focus on Taqī ad-Dīn's most relevant invention, the six cylinder pump, the author proudly describes it in the following verbatim words: “This is an immaculate method. It is the most perfect of any of the above”.

The bibliographic evidence of this invention in the manuscript “Al-Turuq al-Saniya fī al-‘ālat al-rūhaniya”, can be found in the Chester Beatty Library in Dublin, which has a handwritten copy of this work, dated 1551 and 1552 And it is in its first three pages where the study machine is described (see in figure 1) [4].

Figure 1. First three pages the six cylinder pump description in Chester Beatty from Al-Turuq al-Saniya.

2. The six Cylinder Pump

2.1. Composition and operation

In this section, we will go deeply into the explanation of the operation and composition of this machine. Once the energy source of the pump has been specified, the next question resides in its material composition, in which wood will be its majority component.

Figure 2. Virtual proposal of the six-cylinder pump.

There are no vestiges that this machine was ever built, but if it were, and considering the geographical location of the engineer, Damascus, it makes us think that the material used could be oak or pine.
Although Syria can be considered, a location with arid and semi-arid zones, it is distinguished by an important gradient of phytogeographic diversity [5].

When the axle rotates, the corresponding cam pushes down the end of a rocker arm, which pivots on pins housed in a structure supported by two strong pillars. This upward movement of the rocker arm raises the piston, which has a lead weight at its upper end. In this upward movement (figure 3(a)), a vacuum is created inside the cylinder, which begins to fill with water, passing through a clack valve (nº 1) (lower part of the cylinder), which then opens. Another clack valve (nº 2) (lower side of the cylinder) placed in the pipe connecting the supply pipe and the cylinder is closed by the suction of the piston.

![Figure 3. (a) Upward movement of the piston. (b), (c) Downward movement of the piston.](image)

As the camshaft exerts its full force, the rocker arm is released. At this point, the wooden rod no longer has a force to keep it lowering, thus determining the stroke of the piston inside the cylinder. Subsequently, the piston, by its own gravity and that of the cutting weight of the lead, pushes the mass of water downwards, causing the clack valve nº 1 to close. Thus, this flow of water is forced to look for another outlet, and finds little resistance in the clac valve nº 2, and provides supply, see figure 3(b) and figure 3(c). At the end of the route, these pipes will join in one, the central pipe.

3. **Geometric modelling**

For the virtual design of the device, the CAD support software chosen was Inventor Professional 2018, a product designed by Autodesk, within its Product Design Collection range [6]. This software has the ability to work with T-Splines, a tool that allows us to work on complex surfaces more easily.

3.1. **Initial background**

The measurements that have been used for this virtual work have been calculated from the only two data that Taqī ad-Dīn left in his book "The Sublime Method of Machines". The length of the cylinder block and the height of the piston cylinders, referring to the latter two components he quotes literally in his work: "Take a block of wood two arms long and divide it into six identical divisions" [4].

We can interpret the two-armed measure as referring to a fathom, which according to the Spanish Metrology Centre, is defined as "the height of the human body, but is formed by placing the arms in a cross with the tips of the fingers stretched out" [7]. So the standard for this unit of measurement is one metre and sixty-six centimetres. However, there are nuances depending on the region. In short, it has been decided to average out by setting the breaststroke measurement at one and a half metres.

Due to the aforementioned premises, we have had to resort to the assumption of several measurements. Nor can we resort to the sketches provided by the author. They are not dimensioned, so it is more appropriate to consult the approximations in the translations of the manuscript.

The reference study that we have chosen for the calculation and interpretation of the machine contains virtual sketches, calculations, as well as animated videos of the operation of the assembly [4].
3.2. Camshaft motion system
This system is comprised of supports on both sides of the river, although they may also be submerged by the river, and between these supports is a camshaft with a paddle wheel embedded in one end.

We will start by looking at the camshaft, which will have a hexagonal shape, and will be extruded. This part needs to be of large dimensions as it will be subjected to constant torsional stresses, especially in the areas where it has cams. These cams will be distributed equidistantly every 60º. At the ends a series of extrusions have been added, which are housed in a wooden block, supports, to allow it to rotate, while the shaft rests on this block. On the other hand, at the opposite end, a square-shaped hollowing has been made to achieve a mutual restriction that allows simultaneous rotation, as can be seen in figure 4.

![Figure 4. Camshaft motion system.](image)

The paddle wheel, it is responsible for harnessing the kinetic energy contained in the water carried by a river. The modelling of this part involves designing a shaft with extrusions for a male-female connection with the cam shaft and the support. As far as the design of the scoops is concerned, a 360º revolution of the wheel axis will be used, with twelve units.

3.3. Pumping system
The cam has an angle of incidence on the rocker arms which will result in vertical movement of the pistons. These rods pivot a structure, which will have supports on either side of the river or submerged in it. This structure consists of a long wooden beam, with six housings delimited by two rectangular pieces of wood extruded perpendicularly to the beam. The connection of the structure and the outriggers will be made by means of bolts.

The connections of both the frame to the rocker arms and the rocker arms to the pistons are both made by bolts. However, the latter have a caveat, the openings at the ends, which serve to avoid stresses in the transition from circular to linear movement. In short, the connecting bolt of these elements will rotate and move along these openings. The assembly of this pumping system can be seen in figure 5.

![Figure 5. Pumping system assembly.](image)

As far as the cylinders are concerned, Taqī ad-Dīn only indicates that they should be a simple hollow
trunk and this has been considered. The cylinder is open at the bottom, the reason for which is to suck in the water below the opening. This passage of water and its restriction, which is very important, is also regulated by a clack valve. In order to place this valve in the cylinder, holes will be drilled in the lower part of the cylinder, while screws will be used to fasten it.

3.4. Piping system

To make up this system, we would start with the main outlet pipe, where the different flows are joined. Thus, the latter is highlighted in figure 6(a), which shows a cut-away view of the part of the sub-pipes converging into a single one.

Since this clack valve that connects the cylinder with the piping system must be opened towards the piping system, a housing is required for this purpose. This housing will allow freedom of movement for the valve in its movement to open and close the water passage. The reason for the increase in diameter is also given by the restriction of the passage section that this implies, as shown in the following figure 6(b).

![Figure 6. (a) Piping system section. (b) Housing for free movement of the clack valve within the system.](image)

4. Analysis of the mechanism

In order to carry out this section, we have used the SolidWorks 2020 tool from the company Dassault Systemes [8].

The calculations will lead us to assess the real usability of the artefact. Consequently, this section will consist of analysing the machine. To the further detriment or general ignorance of the machine at this point, we do not have any references of reconstructions of the machine on a considerable scale. This fact opens the debate, once again, as to whether the machine was really built and tested, given the late recovery of the copies of the original manuscripts [4].

4.1. Operating calculations

One of the measurements to be assumed is the stroke of the piston in the cylinder. This measurement will be crucial to identify the cam actuation angle in the rocker arm.

Next, a parameter for the correct operation of the machine is to determine the minimum weight that the plummets above the pistons must have. This is because it will be the action of gravity on these plummets that will provide the necessary pressure to pump the fluid into the pipes in the required time.

In order to pump water into the pipelines, the pressures on both sides of the clack valve linking the cylinders to the piping system must be equalised. In addition, the piston has to be at bottom dead centre before it can be actuated again. So the calculation involves the participation of different factors:

- Weight of the fluid contained in the piping system.
- Friction losses inside the pipes.
- Friction losses of the piston inside the cylinder.
- Use of the weight of the piston to reduce the volume of the plummets.
Once this weight has been calculated for the machine in an extreme case, a simulation is carried out for this behaviour. Knowing the diameter for the stem and once all the parameters have been entered into the software, the result can be seen in the figure 7.

![Figure 7. Von Mises stress map, pistons.](image)

### 4.2. Motion analysis

Due to the complexity of the framework, the motion analysis has been carried out on the symbolic kinematic scheme of the machine.

The most vulnerable part of this machine may be the rocker arms. For this reason it is the first part to be analysed. In view of the above we will propose the following conditions previously calculated:

- Camshaft rotational speed: 2.5 rad/s.
- Weight force of plumb bobs: 52.7 N.

The absorption force of the piston rising in the cylinder has not been added in this analysis.

We chose the Von Mises stress map, at the point where the acceleration is maximum. The result of the simulation is shown in figure 8(a).

![Figure 8. Von Mises stress map. (a) Rocker-piston rod connection. (b) Cam.](image)

We continue with the analysis of the line that would drive the rocker arms on the camshaft. This part is very robust and it can be shown with the Von Mises graph (figure 8(b)), where the stresses have their maximum at the contact with the rocker arm.

Finally, thanks to the SolidWorks software, the acceleration curves of the piston along the cylinder, from bottom dead centre to top dead centre, can be used to approximate the absorption force of the piston, and consequently the water inlet. This analysis starts when the camshaft connects with the rocker. The camshaft may still be in contact with the rocker arm but their positions will be increasingly perpendicular to each other. A key graph for the compression of this calculation is the resultant of the acceleration, as shown in figure 9(a).

With these data, we will obtain the curve of the pressure exerted by the piston as it rises in the cylinder, thus creating a depression inside it and this cavity will be filled with fluid. Using the formula of Newton's second law, we find the applied force. The mass used is the weight of the piston and the
plummet. Additionally, knowing that the pressure is the applied force divided by the section and the equation being time-dependent, we are left with the following graph shown in figure 9(b).

![Graphs](image.png)

**(Figure 9.** (a) Graph of the acceleration resulting from the piston movement, stroke. (b) Graph of the pressure distribution inside the cylinder as the piston rises during its stroke.

5. Real scale reconstruction

We have opted for reconstruction by 3D printing, using the fused deposition modelling (FDM) method. The virtual reconstruction made in Inventor Professional 2018 has been transferred, piece by piece, to the CURA 3.6 environment, a 3D printing software, for its simplicity and intuitive handling.

The hardware used is the Witbox printer from Bq, and the material used is the plastic filament PLA + (polylactic acid with additives) [9], with the following characteristics:

- Filament diameter: 1.75 mm
- Density: 1.24 g/cm³ (ASTM D792)
- Modulus of elasticity in bending: 3600 MPa (ISO 178)
- Bending strength: 108 MPa (ISO 178)
- Hardness: 85 Sh D (ASTM D2240)
- Recommended printing temperature: 200/220 °C
- Bending temperature under load: 56 °C (ISO 75/2B)
- Glass transition temperature: 56/64 °C (ASTM D34 18)

According to the printer's environment, it is decided that the scale to be represented will be 1:4, in order to have a more perceptible view.

Finally, Taqī ad-Dīn's "Six Cylinder Water Lift Pump" can be seen fully assembled in figure 10.

![Assembly](image.png)

**(Figure 10.** Taqī ad-Dīn six-cylinder pump assembly.)
6. Conclusions

Contemporary technology, through virtual modelling software and complex simulations, links the understanding of our past with the present. Although in ancient times the means to express and record their legacy were scarce, today we can interpret these writings in a way that is close to the reality of the time. The importance of historical reconstruction is a very valuable pedagogical discipline for present and future civilisations, since knowing the origin of some objects sometimes leads us to reinvent new ones.

With regard to design tools in engineering, reference can be made to those used in this project, such as CAD software (Computer Aided Design), where a system allows the creation, modification, analysis and optimisation of two- and three-dimensional plans. Another fundamental software is CAM software (Computer Aided Manufacturing), computer systems that with the help of numerical control are able to manufacture parts. Finally, another type of software used are CAE (Computer Aided Engineering), these systems verify the elements designed by CAD, to see if they meet the desired expectations [10].

Regarding the 3D printing process, by FDM, an attempt has been made to apply optimal printing parameters.

With the materials proposed and the small dimensions provided by Taqī ad-Dīn for the construction of this machine, it is likely that, if it were to be built, it would not last very long due to the degradation of the materials when exposed to the humidity of the water. Notwithstanding the above, there is no denying the genius of the device for its time, and we can see, how the style of this machine was very different from its analogues in other parts of the world, and hundreds of years apart.

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