Innovation of Mechanical Machinery in Medieval Centuries, Part III: Hydraulic Control Components and Feedback Control Systems

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Abstract: The Islamic civilization paid great attention to mechanical engineering. Banu Musa invented 100 ingenious devices including automatic devices and automatic feedback level control systems. Al-Jazari invented 50 mechanical devices including automatic devices, clocks, positive displacement pumps and robotics. Taqi Al-Din invented a 6-cylinder positive displacement pump. Their inventions put the base stones of modern systems related to industrial automation. Banu Musa set the concept of automatic feedback for better accuracy of the control system. They invented various flow control valves and used siphons, floats, levers and dead-weights in operating their valves.

Keywords: Directional and flow control valves; hydraulic control components; siphons; floats; levers; automatic feedback level control systems.

I. INTRODUCTION

Automatic control engineering originated in the 9th century AC in the Arabic world by the three pioneers known in the scientific history as Banu Musa. They invented feedback control system to accurately control liquid level in various applications. Their work is continued by Ibn Ismail Al-Jazari of the 12th / 13th century AC who invented automated devices to control his clocks, fountains and robotics. They left written manuscripts describing 10’s of their inventions. The whole world heard about those pioneers through the translation of their books and too many articles braising their inventions.

Hill (1974) translated an annotated Al-Jazari manuscript on ingenious mechanical devices. As mechanical engineers he reproduced some of the manuscript drawings and provided modern explanations for their operation. He also handled the Islamic technology up to Al-Jazari including the works of Banu Musa, Al-Khuwarizmi and Ridwan [1]. Al- Hassan (1977) presented the manuscript of Al-Jazari after redrawing some of Al-Jazari machines with English letters concentrating on Al-Jazari machines for raising water. He provided an English-Arabic Glossary for the terms used in Al-Jazari manuscript [2]. Coomanswamy (1994) pointed out that the Museum of Fine Arts of Boston possesses six leaves of the Arabic manuscript on Automata. He inferred that Al-Jazari was first and foremost a craftsman and secondarily an author. His writing was intelligible and his diagrams were clear explaining his practical experience [3]. Hill (1998) claimed that until modern times there was no other document from any cultural area that provides a comparable wealth of instructions for the design, manufacture and assembly of machines like that of Al-Jazari who was a creative added several mechanical and hydraulic devices. The impact of Al-Jazari inventions (as he said) was seen in the later design of steam engines and internal combustion engines [4].

Mansour (2002) pointed out that there were recorded contributions to the area of automatic control. He investigated the work of Banu Musa, Al-Muradi, Ridwan Al-Saati and Al-Jazari [5]. Shakerin (2004) provided a review of innovative fountains developed through history including Al-Jazari’s fountains [6]. Hassaan (2004) introduced Banu Musa as the founders of feedback automatic control in the 9th century AC and reviewed their scientific activities with emphasis on their book “Kitab al-
Hyalīn̂ (Ingenious Mechanical Devices). He analyzed two of their level control systems [7]. Al-Hassan (2007) described the operation of the elephant clock of Al-Jazari and the characteristics of a physical model built and located in Ibn Battota Mall, Dubai. The model weighs 7.5 ton and has 7 m height. He also described some of Banu Musa inventions such as the mechanical jars [8]. Nadarajan (2007) declared mechanical devices were the most comprehensive and methodical compilation of the most current knowledge about automated devices and mechanics [9]. Al-Hasssan (2008) analyzed the geometric and physical principles lying behind the mechanical devices of Banu Musa with the help of basic line drawings and 3D computer generated representation. He presented the basic shapes of Banu Musa fountain outputs which are: lily, shield and spear styles. He referred to the use of Banu Musa of wind/water turbine to alternate water shapes [10]. Uzun and Vatansever (2008) stated that Al-Jazari invented the crankshaft and some of the first mechanical clocks driven by water and weight. They said that his use of crankshaft came before the western engineers Francesco Martini and Leonardo Davinci [11]. Abdallah (2009) focused the light on the fact that Muslim scholars, inventors and mechanical engineers used dynamics of water and its power to design and control mechanical devices. He presented the elephant clock of Al-Jazari and its available physical model. He stated that this clock is classified as fine technology as it is used for amusement or for astronomical observation and computation [12].

Romdhane and Zeghloul (2010) pointed out that two of Al-Jazari machines are most remarkable: his elephant clock and one of his water pumps. The elephant clock was the most sophisticated clock at that time, and the water pump used a crank-slider-like system which was the first known machine to use a crank [13]. Ambrosett (2010) pointed out that in the Arabic world from Baghdad to al-Andalos, mechanical culture and practice underwent an extraordinary development. She mentioned the work of Banu Musa, Al-Jazari and Al-Muradi as witnesses of the extraordinary level of development of the mechanical devices [14]. Masood (2010) declared that Banu Musa designed industrial and scientific machines. They described devices in their book about ingenious devices such that each one had a master piece of ingenuity [15]. Shuriye and Faris (2011) pointed out that in the Islamic history of knowledge, engineering ranked high and their engineers have made immense contributions to this field. Early scholars including Al-Battani, Al-Bairuni, Al-Razi, Jabin Ibn Hayyan and Al-Zarqali have mastered engineering sciences for the service of mankind [16]. Bruton (2011) presented Al-Jazari elephant clock as in one of his manuscript copies and a physical model built for the clock. He also presented a physical model for Al-Jazari castle clock, a copy and physical model of his cup clock and one of his positive displacement pumps [17]. Dergisi (2012) presented and described the colored design of Al-Jazari for the elephant clock and the two-cylinder positive displacement pump [18]. Still (2013) praised the work of Banu Musa, Al-Jazari as designers of programmable music players, humanoid automata that depicted many machines such as one that measures bloodletting was established with a pair of automatic scribes [19]. Mangun (2014) acknowledged the Islamic civilization emerged around 750 and prolonged until around 1500 where theoretical studies, discoveries, innovation and inventions had been encouraged to improve the lives of people during the Islamic Golven Age [20]. Ul-Haque (2014) pointed out that in the Islamic society, several individuals and groups of scientists devoted their life towards mechanical engineering and automation. He talked about the three brothers (Banu Musa) and Al-Jazari and how they contributed to the development of mechanical engineering [21]. Hasaan (2014) studied the innovation of some important machinery in the medieval centuries by Muslim engineers. His work covered windmills, water wheels, automatic fountains, water pumps, clocks and robotics [22,23].

II. HYDRAULIC CONTROL COMPONENTS

Banu Musa of the 9th century and AlJazari of the 12th/13th century were pioneers of automatic control systems. They invented a number of important hydraulic control components used in their designs of control systems, clocks, fountains and music instruments.

2.1 LIQUID CONTROL SIPHONS

Banu Musa used control valves to control the direction and flow rate of liquids in their automatic feedback level control systems and in their ingenious mechanical jars. Here is some of their designs:
Banu Musa used the technology of siphons for different purposes:

(a) Delivering constant volume intermittently (see Fig.1)

![Fig.1 Constant volume liquid delivering [24].](image1)

When liquid is poured into the jar, nothing flows through the jar output port at $\rightarrow$. When the liquid level reaches the top edge of the siphon tube at $\rightarrow$, all the volume in the jar flows out from the jar. This application is useful in processes requiring constant specific volume of a liquid.

(b) Opening a flow control valve automatically (see Fig.2)

![Fig.2 Opening a flow control valve automatically [25].](image2)

The liquid flows to the jar from the top. When a small float-tank $\rightarrow$ is filled to the neck $\leftarrow$ of the siphon, all the liquid volume in the small tank flows through the siphon to the main jar-tank $\rightarrow$. In this case the float $\rightarrow$ and the valve stem frame drops down to open the flow control valve allowing the flow through the jar outlet port at $\rightarrow$.

(c) Sealing tanks (Fig.3)

![Fig.3 Sealing the main tank in a level control system [26].](image3)

In the level control system of Fig.3, a siphon $\rightarrow$ is used to seal the main tank of the system against any air entrance to the tank except through the tube $\downarrow$. This system is a one of the level control systems invented by Banu Musa.
(d) Driving siphon (Fig.3)

In this application, Banu Musa used a siphon نم as a hydraulic power supply to drive a float ف to connect to a u shaped-valve stem to close the conical valve جـ.

(e) Double reversed siphons (Fig.4)

![Double reversed siphon of Banu Musa](image1)

Banu Musa, the pioneer of automatic control engineering used a double reversed siphon to stop the flow of liquid from one reservoir to another one if the input flow rate is stopped [28]. The application in Fig.4 is for a pitcher in which it accepts liquid pouring and stopping twice. If the liquid is poured for the third time the pitcher will not accept any more liquid.

Ibn Ismail Al-Jazari also used siphons for a number of engineering applications:

(a) Sealing and discharging tanks (Fig.5)

![Al-Jazari siphon for tank sealing and discharge](image2)

Water driving the water wheel is collected in an open tank to discharge to a sealed tank ر as shown in Fig.5. The purpose of the siphon is to seal the tank against air escape except through the whistle tube as a music instrument. When the water level reaches the neck of the siphon, the whole amount of water discharges automatically outside the sealed tank for automatic operation of the music band.

(b) Driving robot hands (Fig.6):

![Robot hand driving siphon](image3)
In this Al-Jazari's design, the hand is a first class level ended by a small tank with a siphon inside it. As the residual liquid increases in the tank, the hand turns clockwise until the liquid reaches the top of the siphon to discharge all the liquid through the siphon to another tank and driving the hand back to the original position.

(c) Discharging waste water automatically (Fig.7)

Al-Jazari is a genius mechanical designer. He tried to make all the components of the robotic designs automatic. In the design of Fig.7, a robot pours washing water from a pitcher to an outside basin. The wasted water is discharged from this basic using a duck-shaped siphon to another bigger tank underneath the robot. The he used a manually operated flow control valve to discharge the tank when it is filled. This is known by the position of the left hand of the robot which is driven by a float in the tank (level sensor).

2.2 LIQUID CONTROL VALVES

Banu Musa used extensively liquid control valves to control direction and flow rate. They used different techniques to power the valves as will be illustrated in the following applications:

(a) Manually operated flow control valves:

- Two-way valve (Fig.8): In this design, the manually operated valve is connected through its plug by a chain to the plug of another conical valve allowing the output flow to be one of two different liquids.

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- 3 way/2 position flow control valve (Fig.9).

This is another design achieving the objective of the mechanical jar of Fig.5. Instead of using 2 conical valves, here Banu Musa presents one conical valve of the 3 way/2 position type. Each position will allow one of the liquids to flow through the valve with possible control of its flow rate.

- 4 way/3 position flow control valve (Fig.10).

This is a 4 way/3 position valve driven manually to allow 3 different liquids to flow from a mechanical jar. Each position of the flow control valve will allow one liquid to flow out of the jar.

(b) Float operated flow control valves:

- Direct float operation of a single plug valve (Fig.11).

Fig.11 shows a mechanical jar used to receive three different liquids poured in series from one opening. When the user stops pouting the third liquid, the first liquid starts discharging from the jar output tube, then the second liquid, and finally the third liquid. Each of the two plugs of the conical valves at $\text{\textcircled{1}}$ and $\text{\textcircled{2}}$ are directly connected to a float. When liquid enters to the float tanks, the float raises up closing the valve. When the liquid level drops in the float tank it moves down opening the valve.
- Direct float operation of a twin plug valve (Fig.12).

![Fig.12 Direct-float operation of a Banu Musa twin plug valve][36].

The twin plug flow control valve of Fig.12 is used as a hydraulic component in a feedback level control system invited by Banu Musa. The valve plugs are directly driven by the float through the plugs stem. When the output tank is empty, the float which is the liquid level sensor will be in its downward position, thus closing the flow control valve through its plug at J. To operate the system, a little liquid is poured in the output tank, the level in the float tank increases moving the valve step upward to open the flow port at J allowing the flow from the main tank to the output tank. This action moves the float upward closing plug gradually until the desired level in the output bowl is reached then the valve closes completely. Upon liquid flow out of the bowl, the float starts to drop allowing flow through port J until the desired level is reached again.

- Indirect float operation (Fig.13).

![Fig.13 Indirect-float operation of a Banu Musa conical valve][37].

The design in Fig.13 is for a boiler for heating liquids. With the manual outlet valve open, the hot liquid will flow only through the conical valve driven indirectly by the float through a U-shaped structure. The valves open only when a cold liquid is poured into the hopper leading to raising the float and plug driving structure to open the valve.

(c) Lever operated flow control valves:

This is a one type of Banu Musa automatic operation of flow control valves. They used a lever to operate a single valve-plug, a 2 series valve-plugs and a 2 parallel valve-plugs.

- Lever operated single valve-plug (Fig.14).
In the design of Fig.14, Banu Musa designed a mechanical jar with two outlet tubes. When liquid is poured from the input hopper of the jar for a while and stopped, then liquid flows through one of the outlet tubes. If this tube is blocked either by hand or by a tap, the liquid flows through the other tube. If the first tube is opened to atmosphere, nothing will flow through it. But when the second tube is blocked, the process is repeated. They used a lever from the first class to drive the valve plug at \( \alpha \). There is a small tank at one end of the lever and the valve and its stem at the other end. When the tank is filled with liquid the lever rotates counter-clockwise and the valve closes. When the tank discharges its contents through a hole at its bottom, the lever rotates clockwise and the conical valve opens.

- Lever operated twin valve-plugs connected in series (Fig.15).

The objective of the mechanical jar in Fig.15 is to allow multiple liquids to flow out of the jar in a specific sequence. That is a liquid is poured from the jar hopper. When a second liquid is poured, the first liquid flows from the jar outlet tube. If the pouring of the second liquid is stopped, the flow of the first liquid out of the jar will also stop. If a third liquid is poured in the hopper, the second liquid will start flowing out of the jar tube, and so on. The lever is from the first-type and carries a small tank at each end. At the end of each side of the lever there are two pins moving the stem of twin valve plugs. When the lever turns counter-clockwise when the left tank is full with liquid, the 2 series plugs \( \beta \) and \( \zeta \) open, while the 2 series plugs \( \lambda \) and \( \nu \) close. Thus, allowing liquid to flow out or stop flowing through the jar outlet at \( \delta \).

- Lever operated twin valve-plugs connected in parallel (Fig.16).
The mechanical jar of Fig.16 aims at interchanging two different liquids flowing out of the jar. The jar has two outlet tubes and one input hopper. After the two liquids are poured into the jar without mixing, each liquid flows out of the jar from one of the tubes. After a while, the two liquids interchange automatically. That is the liquid flowing from tube $\text{ع}$ will flow from tube $\text{ف}$ and vice versa. This application of Banu Musa uses the scientific fluid mechanics fact that the flow velocity out of a tank depends on the head inside the tank. The first-class lever drives two valve plugs connected in parallel through their curves stems joined to one side of the lever. This design allows closing or opening the flow control valves at $\text{هـ}$ and $\text{د}$ (valve per tank) simultaneously. During pouring the liquid from the hopper, the lever rotates clockwise and the 2 valves close. Upon stopping liquid pouring, tank $\text{م}$ discharges to tank $\text{ن}$ and the lever rotates counter-clockwise allowing the flow control valves in the 2 tanks to open.

(d) Crankshaft operated flow control valves:

Using crankshaft in mechanical designs was established by Banu Musa in some of their automatic level control systems [ , ]. They used the crankshaft within a mechanism aiming at transferring a translational motion to an angular to drive some of their flow control valves. Banu Musa used the crankshaft in different ways as follows:

- Crank-slider mechanism diving one valve (Fig.17).

Banu Musa used the crank-slider mechanism shown in Fig.17 to operate the flow control valve. The slider here is the float which senses the liquid level in the output bowl and feedbacks this signal which is a translational motion to the flow control valve of a plug rotational motion through the connecting rod and the crankshaft.

A little liquid poured in the bowl will open the valve a little bit to start opening the flow control valve which will continue opening and increasing the liquid level in the output bowl until the desired level is reached and the valve closes. Any discharge from the bowl will cause the valve to open gradually to increase the flow rate through the valve. This flow will increase the level in the bowl and moves the float upward in a feedback signal to re-close the valve gradually until the desired level is reached again.

- Crank-slider mechanism diving two valve (Fig.18).

![Fig.17 Crank-slider mechanism driving a single valve [41].](image1)

![Fig.18 Crank-slider mechanism driving twin valves [42].](image2)
Here, Banu Musa used a single crank-slider mechanism to operate twin valves each valve controls the flow from a tank. The two tanks are filled with different liquids. This design can be considered as an automatic mixer where two different liquids or a cold and hot liquid are mixed together in the output bowl.

- Lever-crankshaft mechanism (Fig.19).

![Fig.19 Lever-crank mechanism of Banu Musa [43].](image)

In this application the great inventors, Banu Musa, used a lever with small tanks at its two ends as a type one lever to replace the float of the design in Fig.18. In this application it is one control system used to control the liquid level in two bowls. The desired levels in the output bowls are defined by the level of the entrance of the two tubes and . The discharge from or to the small tanks at the lever ends causes the lever to rotate clockwise or counter-clockwise to control the flow rate through the valves.

**(e) Dead-weight operated flow control valves:**

Banu-Musa used dead weight as a source of mechanical energy sufficient to drive some of their flow control valves as illustrated in Fig.20 [44].

![Fig.20 Dead-weight operated flow control valve [44].](image)

In the design of Fig.20 the conical valve operated by a constant dead weight and a variable dead weight which is a tank with orifice at . Both weight are secured to the valve U-shape stem. In the beginning, the tank is empty and the fixed dead weight exerts a clockwise moment on the valve plug to close the valve completely and no liquid flows to the output basin. If a liquid is poured in the basic, the liquid flows to the tank and its weight increases increasing the counter-clockwise moment acting on the valve plug. When this moment overcomes the moment from the fixed dead weight, the plug rotates counter-clockwise to open the valve allowing the liquid to flow to the output basin. If the manual pouring liquid in the basin is stopped, after a while, the process is reversed and the valve closes. The design depicts the deep knowledge of Banu Musa of the fluid mechanics and dynamics basic laws.
Non-return valves:

Using non-return valves in mechanical engineering was of utmost importance in the recent mechanical engineering technology. The reason for this is because non-return valves facilitated the design of internal combustion engines and reciprocating compressors. Ibn Ismail Al-Jazari initiated and applied this technology and used it in designing his 2 cylinder positive displacement pump driven automatically by an undershot water wheel as shown in Fig.21.

Taqi Al-Din Ibn Ma'rouf (died 1585) continued the work of Al-Jazari and applied the non-return valves to his 6-cylinder positive displacement pump shown in Fig.22 [46]. This design was the last step before designing the internal combustion engine.

III. FEEDBACK AUTOMATIC CONTROL SYSTEMS

Banu Musa bin Shakir of the 9th century AC invented the principles of feedback automatic control by inventing different designs of feedback level control systems [8]. Here, only two of their designs will be studied different than those studied by Hassaan [7]. Figs.3, 12, 17, 18, 19 and 20 show some of their level control systems.

In the level control system of Fig.17, Banu Musa used a flow control valve to control the flow rate of the liquid from a main reservoir to the outlet jar. A float in a separate specially designed tank senses the level of the liquid in the output jar. When the liquid in the jar is consumed either continuously or in an intermittent way, the liquid level decreases and the float drops. The
float drives a crankshaft through a connecting rod to transfer the translational motion of the float to an angular motion of the valve plug (this is exactly the slider-crank mechanism). This feedback motion opens the valve for more flow rate to the jar. The action increases the level in the jar and the float moves up to decrease the flow rate of the valve until the desired level in the jar is reached, and then the valve closes completely the flow rate. This is the feedback technology used for accurate control of a physical variable.

The other level control system of Fig.3 is for animal drinking without any manual operation. The feedback technique in this design is completely different than that in the design of Fig.17. It depends on using floats and siphons. The main tank is filled through a manually operated valve. The main tank discharges into the adjacent tank through the siphon and a conical valve at since the float at will be in its lowest position. When the water reaches the desired level shown by the red color line and going through the ventilation tube end point at , the siphon will pass some of the water to the small chamber of float . This action raises the float and closes the conical valve at preventing any more water to pass to the second tank. To operate the level control system, some little water is poured externally in the output tank. This will raise the float and opens the conical valve at to discharge the water to the output tank from the middle tank. The water level in the outer and middle tanks will drop and no more water can flow to the float chamber at and its water will be discharged through a small hole at . The action of which is moving down the float and valve at to open the valve to discharge from the main tank to the middle on and the ventilation tube will be open between the two tanks allowing this flow. The level of the water in the middle and output tanks increases by this action until the desired level is reached and the ventilation tube in closed at and no more liquid can enter the middle tank.

IV. CONCLUSION

- The Arabic mechanical engineers contributed in building the scientific and technological bases of the modern civilization.
- They invented very important machinery such as the wind and water wheels, positive displacement pumps, automatic fountains, automatic feedback control systems and robotics.
- Their discoveries helped the humanity through detailed description of their inventions in very clear manner written in manuscripts with two colors and colored drawing with complete labeling of the various elements of each machine.
- Their work was considered as the foundation of new technologies and sciences in the fields of feedback control and robotics.
- They used hydraulic control components such as siphons, floats, valves and cylinders.
- All academic scholars researching and teaching automatic control have to refer to the work of Banu Musa and Al-Jazari as pioneers of automatic control.

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