ISSN : 2347 - 8446 (Online)
ISSN : 2347 - 9817 (Print)

Innovation of Mechanical Machinery in Medieval Centuries, Part IV: Mechanisms, Gear Trains and Cranes

Galal A. Hassaan
Emeritus Professor, Dept. of Mechanical Design and Production, Faculty of Engineering, Cairo University, Giza, EGYPT

Abstract
The Islamic civilization paid great attention to mechanical engineering during the medieval centuries. The mechanical engineers of the Islamic Empire used various type of mechanisms to design their machinery and dynamic systems. They used crank-slider, crank-lever, crank-oscillating lever-slider and four-bar mechanisms. They used gear trains to transmit power between prime movers and output links. Almost all types of gear trains were known to them including: simple, compound and epicyclical gear trains. In the 16th century, they designed gear-train based crane with mechanical advantage up to 600 and a pulley-based-crane with mechanical advantage up to 16.

Keywords
Mechanical Machinery – Medieval Centuries - Mechanisms - Gear Trains – Cranes.

I. Introduction

Machine design is a key factor in the development of industrial and domestic machinery. Muslim mechanical engineers knew this fact and paid extensive attention to machinery design since the 9th century AC. The work of Banu Musa of the 9th century, Al-Jayyani of the 11th century and Al-Jazari of the 12th/13th centuries is outstanding in this context.

Hill (1974) translated an annotated Al-Jazari manuscript on ingenious mechanical devices. As a 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]. Coomamswamy (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-Hiyal" (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 was 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 engineeris 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) braised the work of Banu Musa , Al-Jazari as designers of programmable music players, humanoid automata that depicted many machines such as one that measures blood letting 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]. Hassaan (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. Mechanisms

Banu Musa of the 9th century and AlJazari of the 12th/13th century were pioneers of using mechanisms in their outstanding designs of mechanical machinery. They invented a number of mechanism types used in their designs of control systems, clocks, fountains and music instruments.

1. Banu Musa mechanisms

(a) Slider-crank mechanism

- Banu Musa used a slider-crank mechanism for the purpose of transferring a rectilinear translational motion to a rotational one as illustrated in Fig.1.

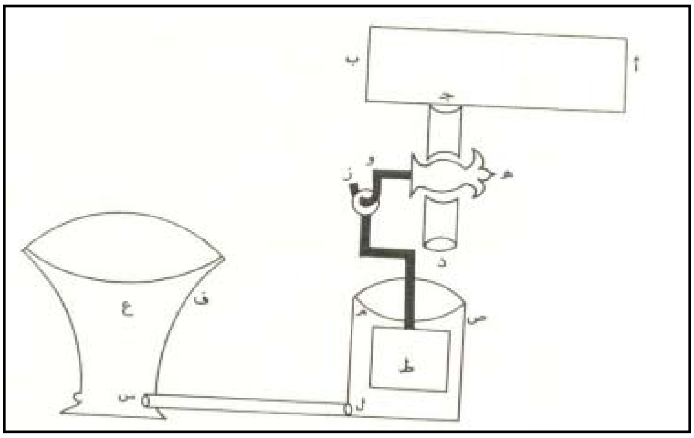


Fig.1: The slider-crank mechanism of Banu Musa [24].

- The slider is level sensor which is a float, joined to a connecting rod. The rod is joined to the crank using a revolute joint.
- The crank rotates the plug of a flow control valve.

(b) Lever-crank mechanism

- Banu Musa used a lever-crank mechanism for the purpose of transferring the angular motion of a lever to another angular motion of the crank as shown in Fig.2.

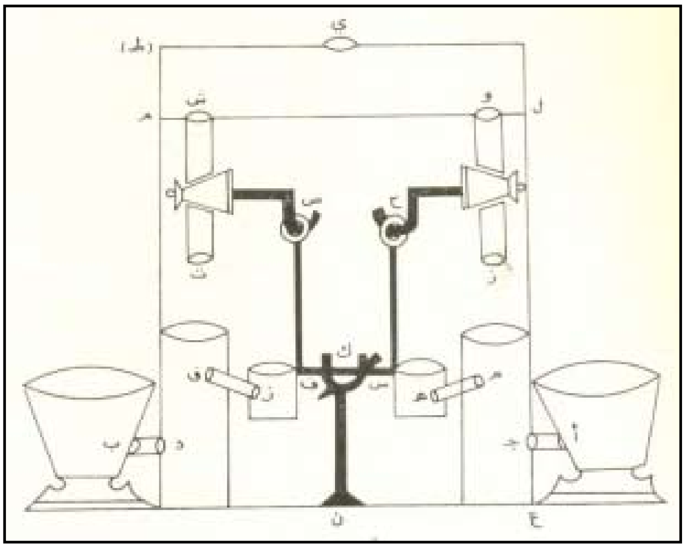


Fig. 2: The slider-crank mechanism of Banu Musa [25].

- The lever in the level control system of Fig.2 moves according to the level in the output jars of the level feedback control system. Thus providing a feedback signal to the flow control valves through rotating their plugs using the two cranks.
- In this design, they replaced the float (slider) in Fig.1 with a lever operating two connecting rods and two pistons.

(c) Four-bar mechanism

- Banu Musa used a four-bar mechanism with two flexible links for the purpose of designing an underwater picking-up machine as shown in Fig.3.

Fig.3 The four-bar mechanism of Banu Musa [26].

- The dynamic bucket consists of two halves 2 and 3 joined together using two revolute joints.
- The two flexible links in the mechanism are link 3 and link 4 which are used to open or close the bucket halves.

2. Al-Jazari Mechanisms

(a) Crank-intermittent motion lever mechanism

- Ibn Ismail Al-Jazari used a crank-oscillating mechanism for the purpose of transferring the rotational continuous motion of the crank to an intermittent angular motion of a lever to operate a single bucket positive displacement pump as illustrated in Fig.4.

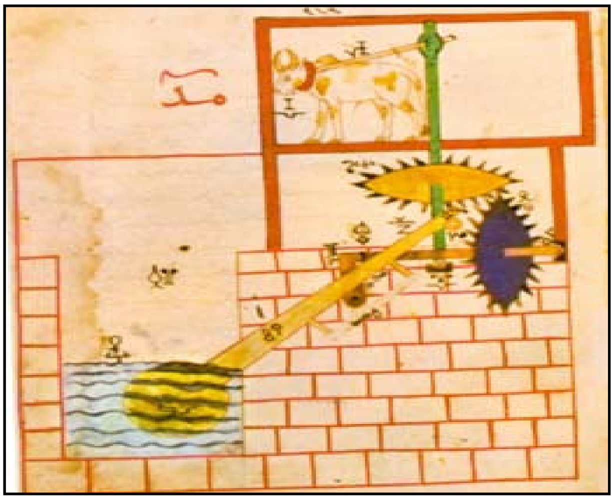


Fig.4 : Al-Jazari crank-intermittent lever mechanism [27].

ISSN : 2347 - 8446 (Online)
ISSN : 2347 - 9817 (Print)

- The crank is powered by a simple gear train driven by an animal.

(b) Crank-oscillating lever-slider mechanism
- Al-Jazari invented a 7-links mechanism consisting of a crank, oscillating lever, 2 connecting rods and 2 pistons to power automatically his 2-cylinders positive displacement pump as shown in Fig.5.
- The mechanism incorporates 6 revolute joints, 2 prism joints and one higher joint.
- The mechanism has one degree of freedom and receives its input power from a simple gear train driven automatically by an undershot water wheel.

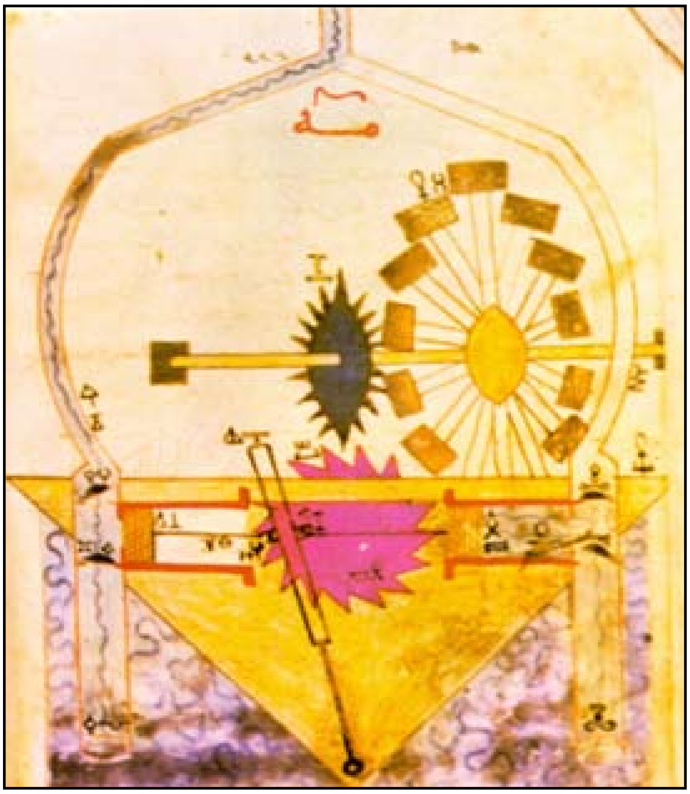


Fig.5 : Al-Jazari 2-cylider positive displacement pump [28].

3. Taqi al-din mechanisms

(a) Six Cams-followers mechanism
- Taqi Al-Din bin Ma'aroof (died 1585) designed the cam-follower mechanism shown in Fig.6.

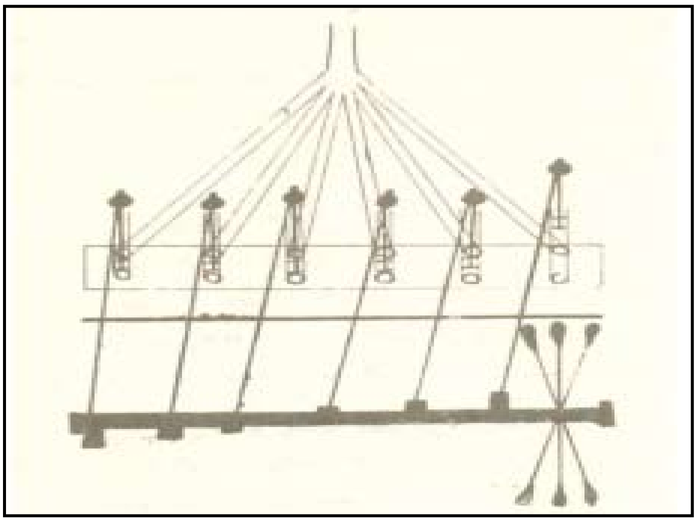


Fig.6 The 6-cams-followers mechanism of Taqi Al-Din [29].

- The cam shaft is driven by an undershot water wheel and carries 6 phase-shifted cams.
- Each cam drives a flat faced follower joined to the piston rod of a hydraulic cylinder (slider).
- A dead weight at the top of each piston rod helps the follower to be in contact with the can during one revolution of the cam-shaft. It is used instead of the helical springs used in nowadays designs of internal combustion engines.
- The cam-follower mechanism of Taqi Al-Din is used to drive a 6-cylinder positive displacement pump invented by him.

(b) Four cams-followers mechanism
- In a different application Taqi Al-Din used a 4-cams power shaft to drive four drums as shown in Fig.7 [30].
- The cam shaft is powered by two undershot water wheels and carries four phase shifted disc-cams.
- Each cam drives a flat-faced follower hitting one قلبط.
- This design is one of Taqi Al-Din designs of automatic music bands providing whistling and drumbeat.

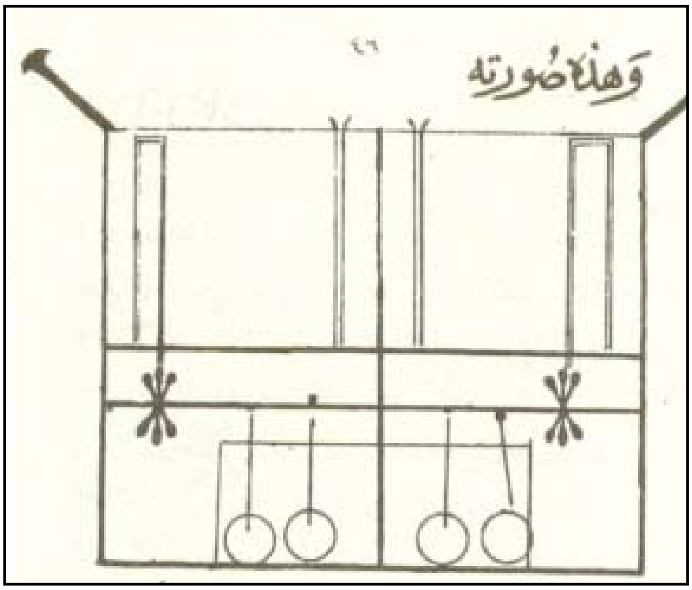


Fig.7 : Taqi Al-Din 4 cams-followers mechanism [30]

III. Gear Trains

Gear trains have wide application in a lot of engineering applications. The Muslim scholars appreciated this fact and used gear trains over centuries starting from the 9th century AC. Some of their application of gear trains appear in the engineering designs of Banu Musa, Al-Jayyani, Al-Jazari and Taqi Al-Din.

1. Banu Musa gear trains

(a) Worm and wheel gear train
- Banu Musa of the 9th century used a worm and wheel gear train to operate one of their automatic dynamic fountains shown in Fig.8 [31].

ISSN : 2347 - 8446 (Online)
ISSN : 2347 - 9817 (Print)
Vol. 2, Issue 4 (Oct. - Dec. 2014)

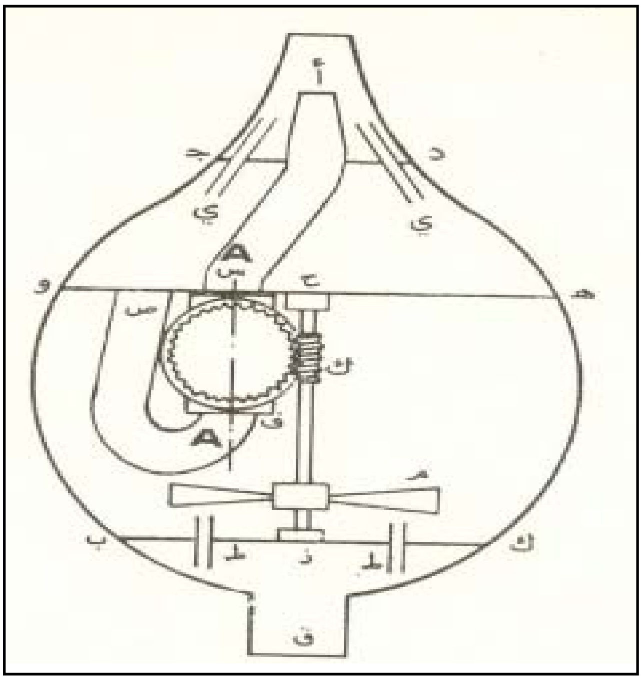


Fig. 8 : Banu Musa worm-wheel gear train [31].

- The worm is driven by a water wheel, and the gear is used to drive the plug of a flow control valve at much lower speed than the worm.
- The valve directs the water flow to go either through pipe س or pipe ص to affect the shape of the fountain output pattern.

(b) Pinion and curved rack gear train
- Banu Musa used a pinion-curved rack gear train in the design of an automatic lamp with automatic filament compensation. The design is shown in Fig.9 [32].

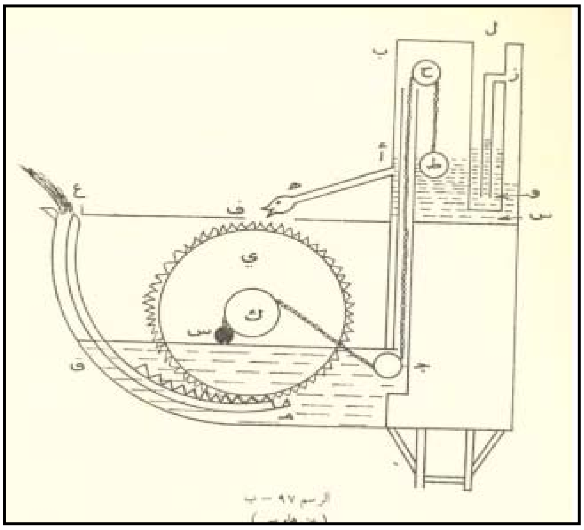


Fig. 9: Banu Musa pinion-curved rack gear train [32].

- The pinion is driven by a rope going around three pulleys.
- The rope carries a dead weight at one end and a float at the other end used as a fuel level sensor.
- The curved rack is secured to a filament such that the pinion rotates clockwise as the fuel level decreases in the main tank.
- This action allows the curved rack to move upward with filament compensating its consumption due to fuel-filament burning.

2. Al-Jayyani Gear Trains

(a) Simple gear trains
- Ibn Muadth Al-Jayyani (died 1079 AC) used simple gear trains in his design of clocks and toys. Fig.10 shows one of his gear trains [33].

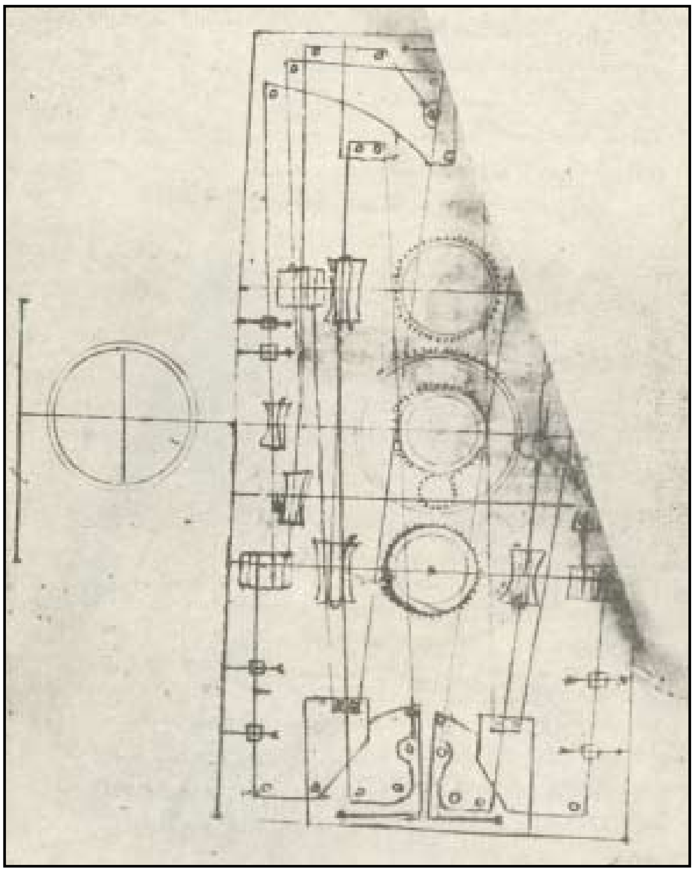


Fig.10 : Al-Jayyani gear train [33].

- Hill announced that this gear train has a big gear of 64 teeth on half its perimeter in mesh with two outer gears of 32 teeth on their complete perimeter [33].
- This means that it is a simple gear train providing intermittent motion to the smaller gears.

(b) Epicyclic gear train
- The same gear train of Fig.10 depicts that there is a sun gear and planets which gives a great evidence that it incorporates an epicyclic gear train.
- The British mechanical engineer Donald Hill said: "Taking the illustrations of Al-Jayyani manuscript on machines leaves little room for doubt that Al-Jayyani machines contained epicyclic gearing" [34].

3. Al-Jazari Gear Trains

(a) Al-Jazari simple gear train
- Al-Jazari used simple gear trains to transmit power between shafts in some of his ingenious machines. Fig.4 shows one of his applications of simple gear trains [27].
- The gear train consists of two external gears with perpendicular centrelines.
- The objective of the gear train is to transmit power from the driving shaft to the crank shaft.
- The crank shaft drives a third-class lever in a mechanism acting as a positive displacement pump.

(b) Al-Jazari compound gear train

ISSN : 2347 - 8446 (Online)
ISSN : 2347 - 9817 (Print)

- Al-Jazari used compound gear trains as mechanical means to transmit power and reduce speed in a number of his mechanical machines.
- Fig.11 shows a 3-shafts compound gear train used to drive a 4-buckets positive displacement pump [35].

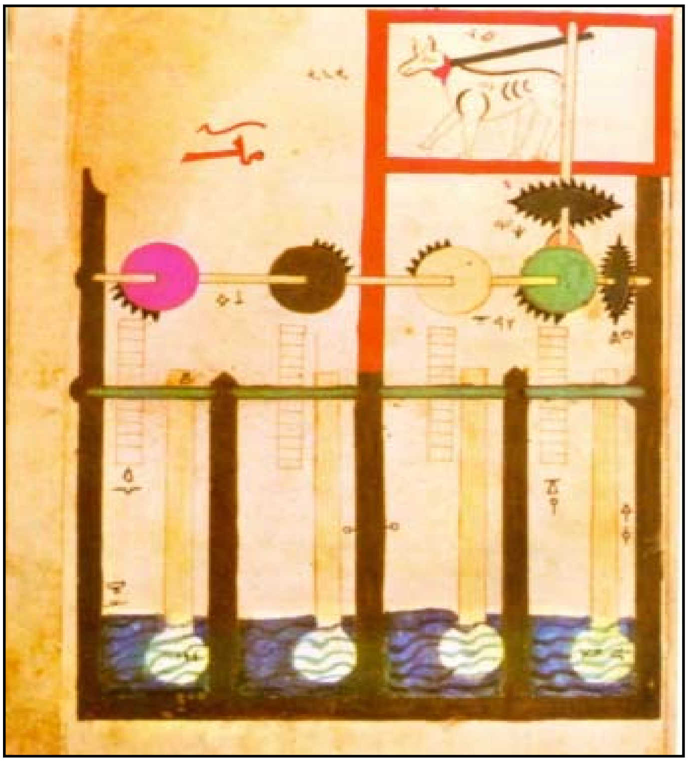


Fig.11 : Al-Jazari compound gear train [35].

- Two shafts are perpendicular.
- Another two shafts are parallel.
- The second shaft carries one complete gear and four segmental gears.
- The third shaft carries four complete gears.
- The gear train is driven by an animal.

4. Taqi Al-Din Gear Trains

(a) Taqi Al-Din simple gear train
- Taqi Al-Din used a simple gear train to drive automatically his screw pump shown in Fig.12 [36].

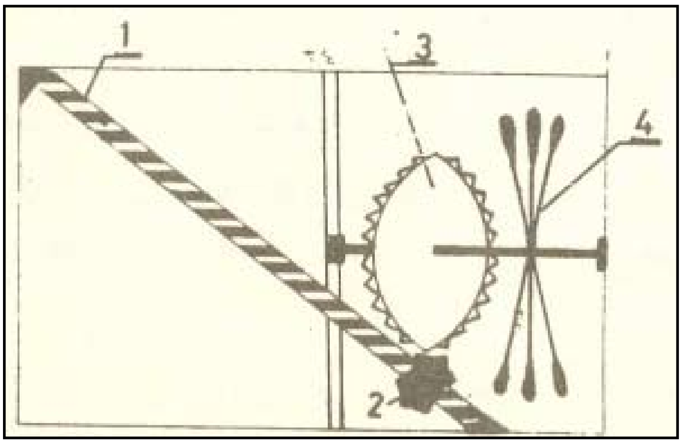


Fig.12 : Taqi Al-Din simple gear train [36].

- It consists of a pinion and gear.
- The pinion is connected to the screw while the gear is connected to the water wheel.
- The gear train increases the speed of the screw to increase the flow rate of the driven screw pump.

(b) Taqi Al-Din compound gear train
- Taqi Al-Din used a complex compound gear train in his mechanical clock shown in Fig.13 [37]

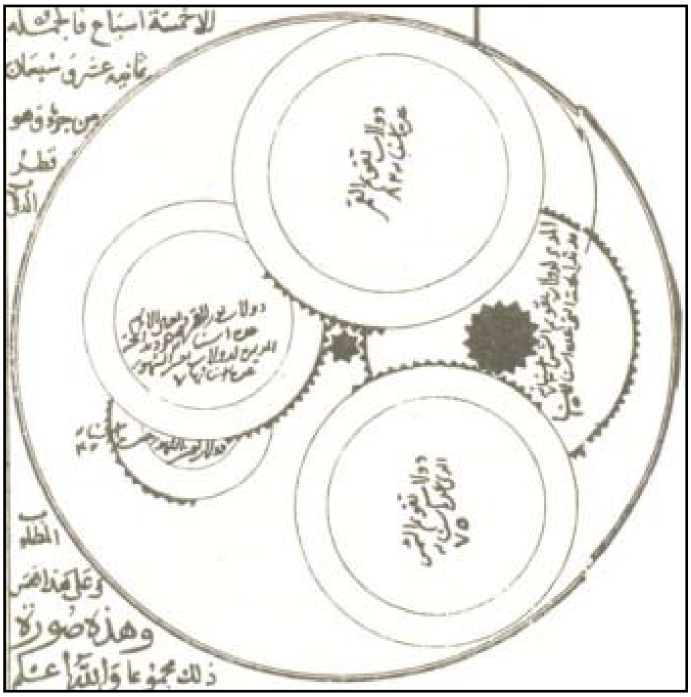


Fig.13 : Taqi Al-Din compound gear train [37].

- It is used in a mechanical clock providing solar and Moon calendaring.
- It incorporates 6 shafts.
- His gears of the external types having odd number of teeth such as 15, 75, 77 and 83 teeth.

IV. Cranes

Cranes are used as a mechanical amplifier used to overcome higher loads using small manual or electrical inputs. Taqi Al-Din in the 16th century designed a number of cranes in his treatise on spiritual machines [38].

(a) Compound gear train based crane
- Taqi Al-Din designed a mechanical crane based on using a compound gear train as shown in Fig.14 [39].

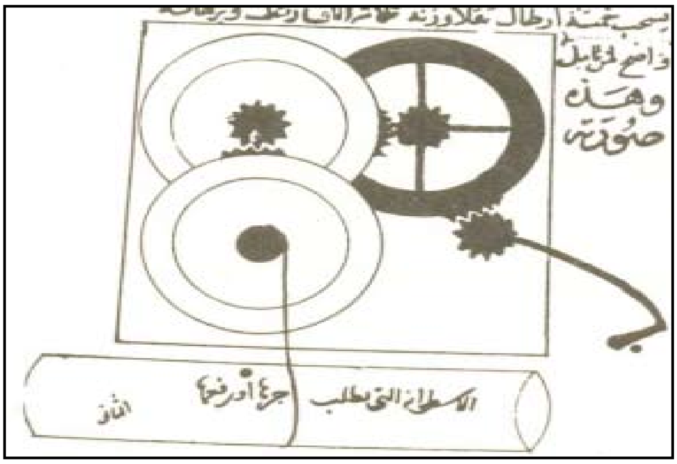


Fig.14 : Taqi Al-Din compound gear train based crane [39].

- It consists of three stages, each stage provides a speed reduction through a pinion and gear.
- It has four power shafts. The first shaft carries the input pinion and the last shaft carries the last gear in the train and a pulley with rope to lift the load.
- According to Taqi Al-Din, this crane is driven manually by a force up to 5 lb and is capable of lifting a load of 3000 lb [39].
- This means that this crane designed by Taqi Al-Din Ibn Ma'roof has 1 : 600 mechanical advantage using the nowadays mechanical terminology.

(b) Taqi Al-Din pulleys-based crane

- As a mechanical engineer, Taqi Al-Din designed another type of cranes proving less mechanical advantage and of more simple design. That is the pulleys crane shown in Fig.15 [40].

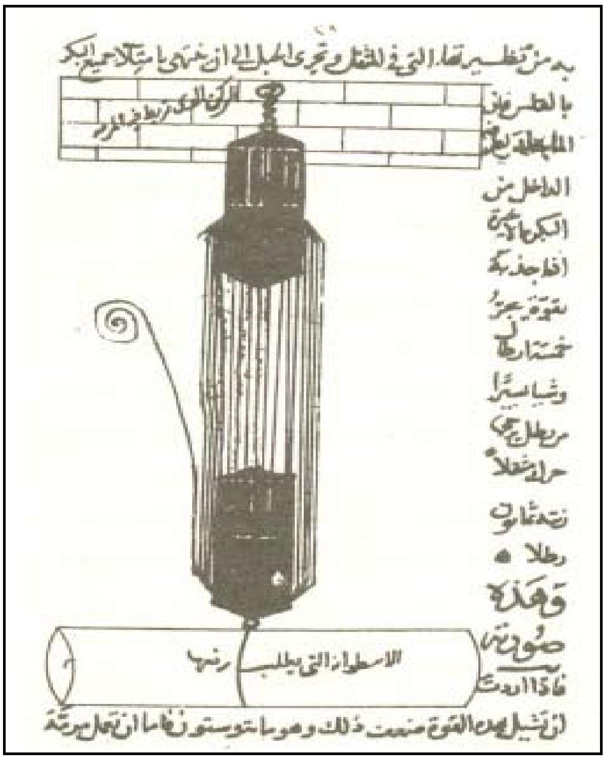


Fig.15 : Taqi Al-Din pulleys crane [40].

- It consists of two sets of adjacent pulleys each on a separate axle.
- Each set incorporates four Pulleys.
- A rope goes around the pulleys.
- One of the rope terminals is used to apply the input manual force.
- This crane according to Taqi Al-Din assignment of the possible input and output forces has a 1 : 16 mechanical advantage.

V. Conclusions

- The Muslim mechanical engineers contributed in building the scientific and technological bases of the modern civilization.
- They invented very important machinery such as mechanisms, gear trains and cranes.
- Their work enhanced the mechanical design of industrial and domestic machinery.
- They designed different types of mechanisms such as crank-slider, crank-lever, crank-oscillating lever-slider, four-bar and cam-follower mechanisms.
- They used simple, compound and epicyclic gear trains in their design of automatic fountains, positive displacement pumps, automatic music bands and cranes.
- They succeeded to design two different types of cranes with small mechanical advantage (up to 16) and large mechanical advantage (up to 600).

References

[1] D. Hill, *"The book of knowledge of ingenious mechanical devices", D. Reidal Pub. Co., USA, 1974.*

[2] A. Al-Hassan, *"The Arabic text of Al-Jazari", Journal for the History of Arabic Sciences, Vol.1, No.1, 1977, pp.47-64.*

[3] A. Coomamswamy, *"The treatise of Al-Jazari on automata", Museum of Fine Arts, Boston, 1994.*

[4] D. Hill, *"Studies in medieval Islamic technology from Philo to Al-Jazari", Edited by D. King, Aldershot, Eng/Brookfield, Ashgate, 1998.*

[5] M. Mansour, *"A review of early Muslim control engineering", www.muslimheritage.com/article/review-early-muslim-control-engineering (2002).*

[6] S. Shakerin, *"Water fountains blend art and engineering: A resource for engineering education", Proceedings of the 2004 American Society for Engineering Education Annual Conference and Education, 2004.*

[7] G. A. Hassaan, *"Banu Musa, the founders of automatic control in the 9th century", Proceedings of the MDP-8, Cairo University Conference on Mechanical Design and Production, Cairo, Egypt, 1-6 January, 2004.*

[8] T. Zielinska, *"Machines initiating living creatures motion: historical review", IFToMM World Congress, Besancon, June 18-21, 2007.*

[9] G. Nadarajan, *"A reading of Al-Jazari's book of ingenious mechanical devices (1206)", Foundation for Science Technology and Civilization, pp.1-16, August, 2007.*

[10] S. Al-Hassani, *"The self changing fountain of Banu Musa bin Shakir", http://muslimheritage.com/article/self-changing-fountain-banu-musa-bin-shakir (2008).*

[11] A. Uzun and F. Vatansever, *"Ismail Al-Jazari machines and knowledge", Acta Mechanica, Vol.2, No.3, 2008.*

[12] M. Abdallah, *"Art and Science of feedback control", Cleveland State University, Department of Electrical and Computer Engineering, February, 2009.*

[13] L. Romdhane and S. Zeghloul, *"Al-Jazari (1136-1206)" in "Distinguished figures in mechanisms and machine science", Edited by M. Ceccarelli, Springer, 2010.*

[14] N. Ambrosetti, *"Cultural roots of technology: an interdisciplinary study of automated systems from the antiquity to the renaissance", Ph.D. Thesis, Universta Degli Studi di Milano, 2010.*

[15] E. Masood, *"Ingenious devices", Al-Noor, Vol.28, No.2, February, 2010.*

[16] A. Shuriye and W. Faris, *"Contributions of early Muslim scientists to engineering studies and related sciences", Iium Press, Malaysia, 2011.*

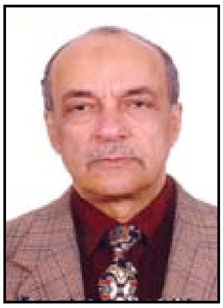
[17] M. Bruton, *"Opportunities created by acknowledging the multi-cultural roots of science", 6th Science Center World Congress, September, 2011.*

[18] Y. Dergisi, *"Mekanigin ortacaggdaki ustalari", http://temizyasam.net/php/index.php?option=com_content&tas*

ISSN : 2347 - 8446 (Online)
ISSN : 2347 - 9817 (Print)

k=view&id=1262&Itemid=2 (November 2012).
[19] C. Still, "A survey of Andalos and audiences: 285BCE to the present day", Degree of Master of Arts, Simon Fraser University, Canada, 2013.
[20] M. Mangun, "Early Muslim scholars contribution in modern mathematics and modern engineering", International Islamic University, Malaysia, Report Paper, 5th April, 2014.
[21] A. Ul-Haque, "Automation and Muslim scientists", International Journal of Pathol., Vol.12, No.1, pp.52-56, 2014.
[22] G. A. Hassaan, "Innovation of mechanical machinery in medieval centuries: Part I: Windmills, water wheels and automatic fountains", International Journal of Innovations in Applied sciences (under publication).
[23] G. A. Hassaan, "Innovation of mechanical machinery in medieval centuries: Part II: Water pumps, clocks and robotics", International Journal of Engineering Research and Management, Vol.1, No.7, 2014, pp.99-104.
[24] Banu Musa bin Shakir, "The book of ingenious devices", Edited by A. Y. Al-Hassan, University of Aleppo, 1981, p.281.
[25] Banu Musa bin Shakir, p.311.
[26] Banu Musa bin Shakir, p.339.
[27] A. Al-Hassan, "A compendium on the theory and practice of machines" (in Arabic), Journal for the History of Arabic Sciences, Vol.1, No.1, 1977, p.138.
[28] A. Al-Hassan (in Arabic), 1977, p.130.
[29] Taqi Al-Din Ibn Ma'roof, "Treatise on spiritual machines", Ireland Manuscript No. 5232, , p.49.
[30] Taqi Al-Din Ibn Ma'roof, p.46.
[31] Banu Musa bin Shakir, p.349.
[32] Banu Musa bin Shakir, p.371.
[33] D. Hill, "A treatise on machines by Ibn Muadth Al-Jayyani", Journal for the History of Arabic Science, Vol.1, No.1, 1977, pp.33-46.
[34] D. Hill, 1977, p.40.
[35] A. Al-Hassan (in Arabic), 1977, p.148.
[36] Taqi Al-Din Ibn Ma'roof, p.34.
[37] Taqi Al-Din Ibn Ma'roof, p.9.
[38] Taqi Al-Din Ibn Ma'roof, pp.15-29.
[39] Taqi Al-Din Ibn Ma'roof, p.16.
[40] Taqi Al-Din Ibn Ma'roof, p.28.

Authore Profile



Galal Ali Hassaan, Emeritus Professor of System Dynamics and Automatic Control, Now with the Faculty of Engineering, Cairo University, EGYPT. Research on History of Mechanical Engineering, Automatic Control, Mechanical Vibrations and Mechanism Synthesis. Published 10's of research papers in international journal and conferences. Author of books on Experimental Systems Control, Experimental Vibrations and Evolution of Mechanical Engineering.