

Structural Synthesis of Zhang Heng's Seismoscope with Cam-linkage Mechanisms*

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Abstract

This work synthesizes the topological structures of the lost Zhang Heng's seismoscope, which was invented in ancient China in 132 AD, with cam-linkage mechanisms. Based on the study of the literature and seismology, the design specifications of Zhang Heng's seismoscope are defined and concluded. According to the concepts of generalization and specialization subject to the concluded design specifications, all feasible interior mechanisms with cams and links that meet science theories and techniques of the subject's time period are recreated. Two examples, one with five members and six joints and the other with six members and eight joints, of the interior mechanism of Zhang Heng's seismoscope are derived with 2 and 11 feasible designs, respectively.

Key words: Zhang Heng's Seismoscope, Structural Synthesis of Mechanism, History of Machinery, Cam-linkage Mechanism

1. Introduction

From the documented literatures, it has been approved that the earliest seismoscope namely "Hou Feng Di Dong Yi" (候風地動儀) was invented by Zhang Heng (張衡) in ancient China in 132AD⁽¹⁾. Zhang's seismoscope is respected as a milestone invention since it can indicate not only the occurrence of an earthquake but also the direction to its source.

However, the records for the interior are too brief for understanding the real structure of the mechanism inside the seismoscope. Through the research of seismologists, it is believed that the principle of Zhang Heng's seismoscope and modern seismographs are based on the principle of inertia. In the past years, some scholars tried to recreate Zhang Heng's seismoscope⁽²⁻⁴⁾. However, the high accuracy and sensitivity as described in historic records are hardly achieved by their designs.

The purpose of this work is to synthesize the topological structures of Zhang Heng's seismoscope with cam-linkage mechanisms. The historical background of Zhang Heng's seismoscope is presented first. And then, the design specifications of Zhang Heng's seismoscope are defined and concluded. According to the concepts of generalization and specialization, the procedure of structural synthesis is introduced. Finally, two examples are proposed to illustrate the procedure.

2. Historical Background of Zhang Heng's Seismoscope

Zhang Heng (78-139 AD) was an extraordinary polymath in the Eastern Han Dynasty (25-220 AD),⁽⁵⁾. He was not only the astronomer royal but also a distinguished cartographer, mathematician, poet, painter, and inventor. He had many astonishing achievements in wooden machines. More reliable records of his works include the seismoscope^(1,6,7), armillary sphere⁽⁶⁾, and mechanical calendar⁽⁸⁾. He was referred to as the "sage of woodcrafts" together with Ma Jun (馬鈞) of the Three Kingdom Period

*Received 5 Jan., 2009 (No. 09-0008)
[DOI: 10.1299/jamdsm.3.179]

(220-280 AD). And, his seismoscope was the most famous one.

For a long time, some scholars thought that the Biography of Zhang Heng in the History of the Later Han Dynasty 《後漢書·張衡傳》⁽¹⁾ is the only record about Zhang Heng's seismoscope, Fig. 1(a). In this archive, there are 196 Chinese characters regarding Zhang Heng's seismoscope. In 2006, six additional historical records were introduced including Xu Han Shu 《續漢書》 by Si Ma-biao (司馬彪), Hou Han Ji 《後漢紀》 by Yuan Hong (袁宏), and the biography of Emperor Shun of the History of the Later Han Dynasty 《後漢書·順帝紀》 by Fan Ye (范曄) about Zhang Heng's seismoscope⁽⁷⁾. In these records, there are five earlier historical block-printed editions which had existed before the Biography of Zhang Heng in the History of the Later Han Dynasty by 70 to 150 years, such as Xu Han Shu, Figs. 1(b)-(e) and Hou Han Ji, Fig. 1(f). Figure 1(g) shows another record from the History of the Later Han Dynasty 《後漢書》.

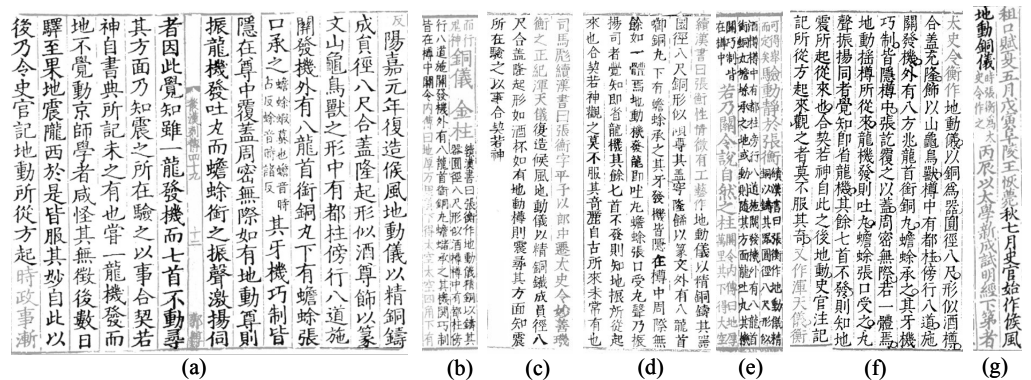


Fig. 1 Historical records about Zhang Heng's seismoscope

Compared with all the materials word by word, there are 238 Chinese characters regarding Zhang Heng's seismoscope. The description can be divided into three parts, such as the following descriptions:

1. During the first year of the Yang Jia (陽嘉) period (132 AD), July in the autumn, Zhang Heng constructed the Hou Feng Di Dong Yi (候風地動儀).

2. The instrument was made of bronze with a diameter of around two meters. The cover was protruded and it looked like a wine vessel. There was a Du Zhu (都柱, a pillar) in the center of the interior and eight transmitting rods near the pillar. There were eight dragons attached to the outside of the vessel, facing in the principal directions of the compass. A toad was below each dragon with open mouth toward the dragon. Each dragon's mouth contained a bronze ball. The intricate mechanism used was hidden inside the instrument. When the ground moved, the instrument shook and the ball located favorably to the direction of ground movement will drop out of the dragon's mouth and fall into the mouth of a bronze toad waiting below. And, each earthquake only made one ball drop. The direction faced by the dragon whose ball was dropped would be the direction from which the shaking came. The device worked accurately and surprised all viewers. From ancient times to the present, there was no record like it in the historical archives.

3. The device had ever worked once. The dragon spilled a ball but no earthquake was felt. Scholars in the capital city thought it was odd. Several days later, news came that an quake had indeed occurred in area Long Xi (隴西). People then realized its ingenuity. From then on, the historian was ordered to record the direction of the quake using this instrument.

The above descriptions provide important data for later investigations, especially the external of Zhang Heng's seismoscope. However, the records for the interior are too simple for understanding the real structure of the mechanism inside the seismoscope.

3. Design Specifications

Specification is a precise written statement describing a device, such as its topological

structure, motion type and range, driving power, efficiency, performance, ... etc. It should be defined in the beginning of the design process of any product. In the early stage of the conceptual phase for the reconstruction design of lost machines, only basic specifications regarding topological structures of mechanisms are of major concern. Those items relating to the dimension and the state of motion (position, velocity, acceleration) of members and mechanisms can be disregarded at this stage.

The reconstruction of Zhang Heng's seismoscope requires exhaustive literature study to clearly recognize and define the problem in order to develop design specifications. It is also important to be familiar with the available science and technology of the subject's time period. Mechanical elements and mechanisms of lost ancient machines may be different in different dynasties.

Based on literature and seismology study, design specifications of Zhang Heng's seismoscope are concluded through the following three parts: study of historical archives, investigation of seismology, and analysis of ancient seismographs, Fig. 2.

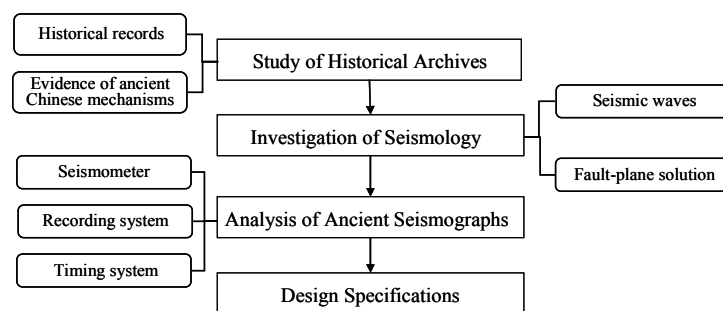


Fig. 2 Development of the Design specifications of Zhang Heng's seismoscope

3.1 Study of historical archives

Historical archives consist of mainly two parts including historical records regarding Zhang Heng's seismoscope and evidence of ancient Chinese mechanisms. There are totally seven historical records regarding Zhang Heng's seismoscope as mentions in the previous section. These records describe that the instrument was like a jar with an inner diameter of 2 meters, and it was cast with bronze. However, for the interior structure, the records only emphasize that "there was a Du Chu (都柱), a pillar, in the center of interior and eight transmitting rods near the pillar." This is the first design specification.

The transmitting rod is a channel to transport something. However, no detail descriptions about the transmitting rod can be found in historical records. Based on the ancient people often put a round rock on the other large-round rock to detect the occurrence of an earthquake, a basic concept that "a switch ball located on the top of the pillar is adapted; and, when an earthquake occurs, the switch ball can move on the transmitting rod." This is the second design specification.

Through the study of the history of ancient Chinese mechanisms, the developments of levers and cams were very mature, especially in military and agriculture technology. The assembly of levers and cams in ancient China involved the use of revolute joints, prismatic joints, and cam joints.

Cam-linkage mechanisms that had been in use for a long time in ancient China may be traced back to the Spring-Autumn and Warring Periods (770-222 BC). The trigger mechanism of the crossbow around 200 BC was an intricate cam-shaped swing arm. There are many bronze crossbows before the Western Han Dynasty (206 -222 BC) which are excavated in China, such as Fig. 3(a) and Fig. 3(b) ⁽⁹⁾.

Figure 4(a) shows a water-driven multiple tilt hammers described in the book Tian Gong Kai Wu ⁽¹⁰⁾. This is a typical simple cam mechanism with three members and three joints. Figure 4(b) shows its corresponding schematic drawing. The waterwheel (member 2, K_W) was connected to a long shaft (member 2, K_{Wa}) with paddles (member 2, K_{Ac}) as an

assembly. When the water flow moved the waterwheel, its cam effect on the assembly caused the tilt hammers (member 3, K_{Af}) to produce work. The long shaft was incident to the frame (member 1, K_F) with a revolute joint (J_R , joint a). The paddles were incident to one end of the tilt hammers with cam joints (J_A , joint c). The tilt hammers were also incident to the rack through a revolute joint (J_R , joint b).

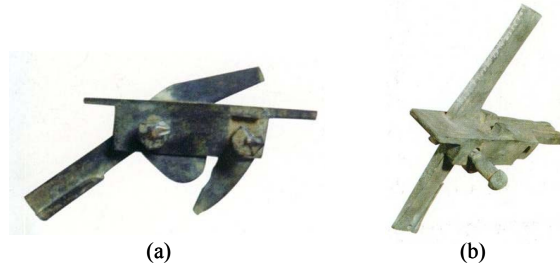


Fig. 3 Excavated bronze crossbows

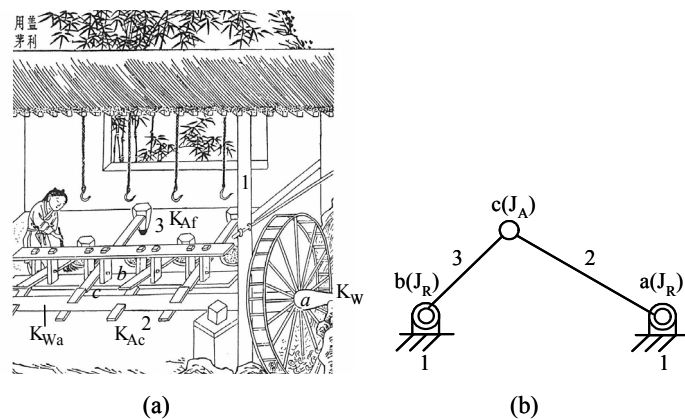


Fig. 4 A water-driven multiple tilt hammer

Since cam-linkage mechanisms were broadly used in ancient China, we define that “the interior mechanism of Zhang Heng’s seismoscope is a cam-linkage mechanism.” And, this is the third design specification.

3.2 Investigation of seismology

Seismic waves and fault-plane solution directly influence the design specifications of Zhang Heng’s seismoscope ⁽¹¹⁾. Seismic waves including P-wave, S-wave and surface waves are generated by earthquakes. When an earthquake occurs, the seismic waves will spread out and travel in specific directions. P-wave is the first-arriving wave from an earthquake. It forces the material in their paths to compress and expand in the direction of wave travel. The direction of P-wave travel is the same as the direction of the earthquake. S-wave is the second-arriving wave from an earthquake. Surface waves are the last-arriving waves that travel along Earth’s surface. An important aspect of the design specifications of Zhang Heng’s seismoscope is the first arrival of the P-wave. The motion of the ground from the initial P-wave arrival is known as the first motion. If Zhang Heng’s seismoscope can detect the direction of the first motion, the direction of the earthquake can be discovered by the instrument.

Although ground shaking can occur from many causes (such as volcanic eruptions), clearly the majority of earthquakes are related to movement along faults. There are three basic types of faults, namely normal, reverse and strike-slip faults. Fault-plane solution is a stereographic plot of earthquake-wave first motions that defines the orientation of the fault plane involved, as well as the type of faulting. According to fault-plane solution, the first motion can be either compressing or expanding ground motion. Therefore, “Zhang Heng’s seismoscope must detect the direction of the first motion, no matter whether it is compressing or expanding.” This is the fourth design specification.

3.3 Analysis of ancient seismographs

Through the analysis of ancient Western seismographs, the development and design principles of seismographs can be realized⁽¹²⁻¹³⁾. A seismograph produces a chronologic record of ground movement during an earthquake. A seismoscope is primarily intended to indicate that an earthquake had occurred but does not produce a permanent record of it. Early seismograph consists of three basic components: a seismometer, a timing system and a recording system. The clock provides absolute time. A number of different ways have been devised to put time marks on a seismic record. Different methods have been used to record earthquake ground motion, but the most common one is the recording drum.

A seismometer includes three parts: a sensing member, a magnifier and a long arm. A sensing member responds to ground motion. The motion is magnified before being recorded by a magnifier. The early magnifier has many types, such as, levers and cam-linkage mechanisms. The magnifier connects with a long arm as a scribing point which rests on the recording drum. The long arm scribes ground motion in the recording drum. During a quake, the ground moves simultaneously in three dimensions: east-west, north-south and up-down. A single device records only one of these three components of motion. According to the foregoing, we define that “there are eight devices in Zhang Heng’s seismoscope to detect eight principal directions. Each device has an interior mechanism as a seismometer inside and a recording system outside.” And, this is the fifth design specification.

4. Characteristics of the Interior Mechanism

According to the above concluded design specifications, we define that one complete interior mechanism should include a ground link, a sensing link, a magnifier (including a connecting rod and a cam), and a transmitting rod at least. It is a planar mechanism with one degree of freedom. The characteristics of each member are described as follows:

4.1 Ground Link

The pillar in the center of the interior is the ground link. The switch ball that is on the top of the ground link is held by eight transmitting rods.

4.2 Sensing Link

The sensing link is adjacent to the ground link to detect the first motion of P-wave, no matter whether it is compressing or expanding. When the first motion is compressing, the sensing link topples in the direction to its source. On the contrary, if the first motion is expanding, the sensing link topples in the direction away from its source.

4.3 Magnifier (a connecting rod and a cam)

The sensing link is adjacent to the magnifier as a driving member. The magnifier consists of a connecting rod and a cam at least. The cam is an irregularly shaped link that is adjacent to the transmitting rod with a cam joint. The cam joint has two degrees of freedom including rolling and sliding. The feature of the cam joint enables that the cam imparts a fall motion to the transmitting rod, when the transmitting rod is in the highest position. The purpose of such design is to make sure that the movement of the transmitting rod can follow its corresponding sensing link, no matter where the sensing link topples.

4.4 Transmitting Rod

The function of the transmitting rod is to connect the seismometer and the recording system, much like the long arm in ancient Western seismograph. When the sensing link topples, the magnifier makes the transmitting rod falling. The switch ball drops out of the pillar and moves to the wall of the vessel by the transmitting rod. Through the collision between the balls, the ball in the wall will drop out and fall into the mouth of a toad below. The direction of the earthquake can be shown by the dropping ball.

5. Procedure of Structural Synthesis

According to the historical records, the outer appearance of Zhang Heng’s seismoscope

is clear. The procedure of structural synthesis presented here focuses on the interior mechanism. It consists of the following three steps: generalized kinematic chains, specialized chains and reconstruction designs ⁽¹⁴⁻¹⁷⁾, Fig. 5.

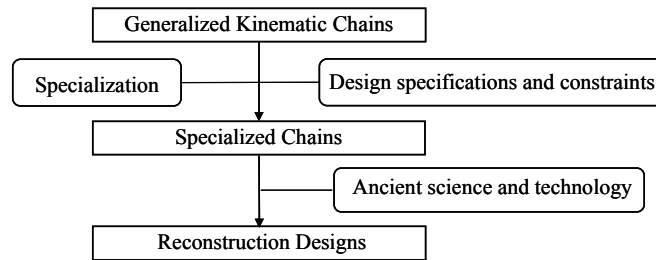


Fig. 5 Procedure of structural synthesis

5.1 Generalized kinematic chains

A generalized kinematic chain is a close and connected chain without any cut-links and with generalized joints. And, a generalized joint is a joint in general; it can be a revolute pair, a prismatic pair, a spherical pair, or others. Based on the design specifications, the corresponding generalized kinematic chain of Zhang Heng's seismoscope must have 5 members and 6 joints at least. Once the numbers of links and joints of generalized kinematic chains are concluded, the next step is to obtain the atlas of generalized kinematic chains with the same numbers of links and joints. Some of the important atlases of generalized kinematic chains have already been built in reference ⁽¹⁴⁾.

5.2 Specialized Chains

The procedure of assigning specific types of members and joints in the available atlas of generalized kinematic chains, subject to certain design specifications and constraints, is called specialization ⁽¹⁴⁾. And, a generalized kinematic chain after specialization is a specialized chain. Based on the procedure of specialization, all possible specialized chains can be identified according to the following steps:

1. For each generalized kinematic chain, identify the ground link.
2. For each case obtained in step 1, identify the sensing link.
3. For each case obtained in step 2, identify the transmitting rod.
4. For each case obtained in step 3, identify the cam.
5. For each case obtained in step 4, identify the connecting rod.

Specialized chains are identified subject to the following design specifications and constraints. The design constraints are defined based on the concluded characteristics of the interior mechanism. They can be flexible and are varied for different expectations.

Ground Link

There must be one ground link as the frame. It must be a link with multiple joints.

Sensing Link

The sensing link must be a binary link is adjacent to the ground link with a revolute joint (J_R).

Transmitting Rod (The channel of the switch ball)

The transmitting rod must be a binary link is adjacent to the ground link with a prismatic joint (J_P).

Cam

The cam must be a ternary link is adjacent to the transmitting rod with a cam joint (J_A).

Connecting Rod

The connecting rod that must be a binary link is adjacent to the cam.

6. Examples

Two examples are provided to illustrate the proposed procedure of structural synthesis.

Example 1: Reconstruction designs with five members and six joints

There are two generalized kinematic chains with five members and six joints as shown

in Fig. 6, and all feasible specialized chains are identified through the following steps.

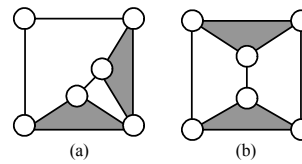


Fig. 6 Generalized kinematic chains with five members and six joints

Ground Link - link K_F

Since there must be a multiple link as the frame, the ground link K_F can be identified as follows:

1. For the generalized kinematic chain shown in Fig. 6(a), assign the ground link K_F to generate one non-isomorphic result, Fig. 7(a).
2. For the generalized kinematic chain shown in Fig. 6(b), assign the ground link K_F to generate one non-isomorphic result, Fig. 7(b).

Therefore, two specialized chains with one identified ground link K_F are available as shown in Figs. 7(a) and (b).

Sensing Link - link 2

Since there must be a binary link as the sensing link 2 that is adjacent to the ground link K_F with a revolute joint J_R , the sensing link can be identified as follows:

1. For the Fig. 7(a), assign the sensing link 2 to generate two results, Figs. 7(c) and (d).
2. For the Fig. 7(b), assign the sensing link 2 to generate one non-isomorphic result, Fig. 7(e).

Therefore, three specialized chains with identified ground link K_F and sensing link 2 are available as shown in Figs. 7(c)-(e).

Transmitting Rod - link 5

Since there must be a binary link as the transmitting rod 5 that is adjacent to the ground link K_F with a prismatic joint J_P , the transmitting rod can be identified as follows:

1. For the Fig. 7(c), assign the transmitting rod 5 to generate one result, Fig. 7(f).
2. For the Fig. 7(d), assign the transmitting rod 5 to generate one result, Fig. 7(g).
3. For the Fig. 7(e), assign the transmitting rod 5 to generate one non-isomorphic result, Fig. 7(h).

Therefore, three specialized chains with identified ground link K_F , sensing link 2, and transmitting rod 5 are available as shown in Figs. 7(f)-(h).

Cam - link 4

Since there must be a ternary link as the cam 4 that is adjacent to the transmitting rod 5 with a cam joint J_A , the cam can be identified as follows:

1. For the Fig. 7(f), there is no ternary link available to be identified as a cam. Therefore, Figure 7(f) is not qualified for the procedure of specialization.
2. For the Fig. 7(g), assign the cam 4 to generate one result, Fig. 7(i).
3. For the Fig. 7(h), assign the cam 4 to generate one result, Fig. 7(j).

Therefore, two specialized chains with identified ground link K_F , sensing link 2, transmitting rod 5, and cam 4 are available as shown in Figs. 7(i) and (j).

Connecting rod - link 3

Since there must be a binary link as the connecting rod 3, the connecting rod can be identified as follows:

1. For the Fig. 7(i), assign the connecting 3 to generate one result, Fig. 7(k).
2. For the Fig. 7(j), assign the connecting 3 to generate one result, Fig. 7(l).

Therefore, two specialized chains with identified ground link K_F , sensing link 2, transmitting rod 5, cam 4, and connecting rod 3 are available as shown in Figs. 7(k) and (l).

Atlas of (5, 6) reconstruction designs

By taking the motion and function requirements of mechanisms into account and keeping the types of links and joints unchanged, the interior mechanism of the

corresponding feasible specialized chains in Figs. 7(k) and (l) are represented as shown in Fig. 8.

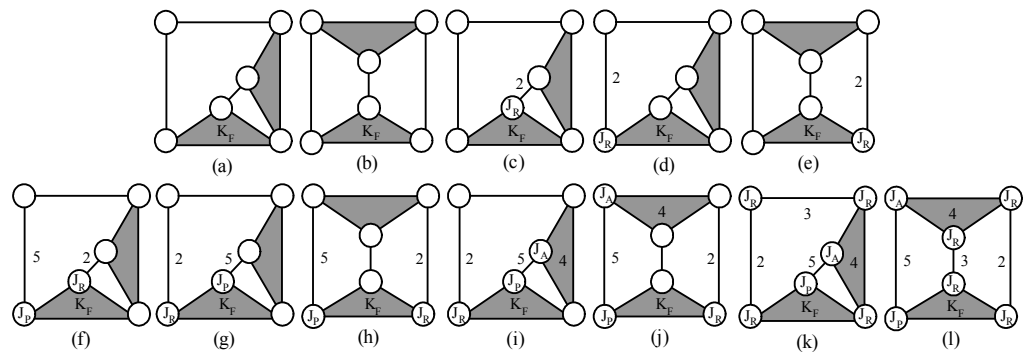


Fig. 7 Specialized chains with five members and six joints

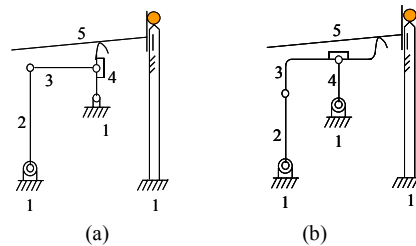


Fig. 8 Interior mechanisms with five members and six joints

Figure 9 shows the 3D solid model of a reconstruction design of Zhang Heng's seismoscope. A complete Zhang Heng's seismoscope with five members and six joints including the appearance and the inside is shown in Fig. 9(a). There are eight devices in the principal directions of the instrument, Fig. 9(b). A switch ball is held with the eight transmitting rods (link 5) on the top of the pillar. An interior mechanism, based on Fig. 8(a), is shown in Fig. 9(c). The sensing link (link 2) detects the first motion of P-wave, no matter whether it is compressing or expanding. When the first motion is compressing, the sensing link 2 topples in the left, Fig. 9(d). On the contrary, if the first motion is expanding, the sensing link 2 topples in the right, Fig. 9(e).

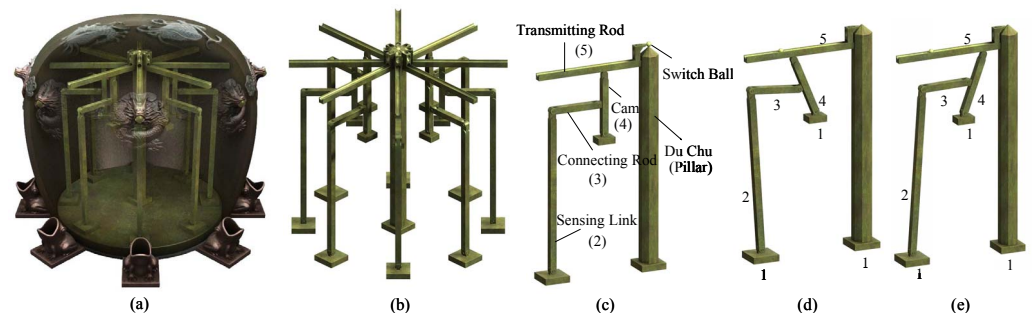


Fig. 9 A reconstruction design of Zhang Heng's seismoscope with 5 members and 6 joints

Example 2: Reconstruction designs with six members and eight joints

The interior mechanism with six members and eight joints can be synthesized by following the same approach. The design specifications and constraints that are different from the (5, 6) interior mechanisms described above are:

1. The (6, 8) interior mechanisms consist of a ground link (link K_F), a sensing link (link 2), a connecting rod (link 3), two cams (links 4 and 5), a transmitting rod (link 6), a prismatic joint (J_P), two cam joints (J_A), and five revolute joints (J_R).
2. The magnifier includes link 3, link 4, and link 5.
3. The ground link (link K_F) must be a quaternary link.
4. Two cam joints (J_A) must not be incident with the same link simultaneously.

There are nine generalized kinematic chains with six members and eight joints as shown in Fig. 10, and all possible feasible specialized chains are identified through the following steps.

Feasible generalized kinematic chains

Since the interior mechanisms with six members and eight joints must have one sensing link (link 2), one transmitting rod (link 6), and one connecting rod (link 3), a feasible generalized kinematic chain should have only three binary links. Therefore, only those three generalized kinematic chains shown in Figs. 10(a)-(c) are qualified for the process of specialization.

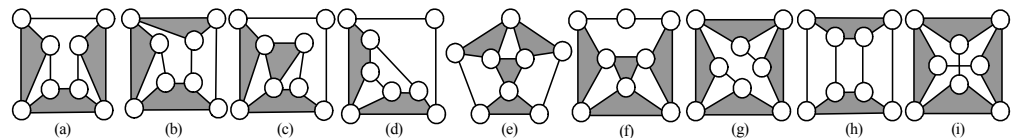


Fig. 10 Generalized kinematic chains with six members and eight joints

Ground Link - link K_F

Since there must be a quaternary link as the frame, the ground link K_F can be identified as follows:

1. For the generalized kinematic chain shown in Fig. 10(a), assign the ground link K_F to generate one result, Fig. 11(a).
2. For the generalized kinematic chain shown in Fig. 10(b), assign the ground link K_F to generate one result, Fig. 11(b).
3. For the generalized kinematic chain shown in Fig. 10(c), assign the ground link K_F to generate one result, Fig. 11(c).

Therefore, three specialized chains with one identified ground link K_F are available as shown in Figs. 11(a)-(c).

Sensing Link - link 2

Since there must be a binary link as the sensing link 2 that is adjacent to the ground link K_F with a revolute joint J_R , the sensing link can be identified as follows:

1. For the Fig. 11(a), assign the sensing link 2 to generate one non-isomorphic result, Fig. 11(d).
2. For the Fig. 11(b), assign the sensing link 2 to generate two non-isomorphic results, Figs. 11(e) and (f).
3. For the Fig. 11(c), assign the sensing link 2 to generate two results, Figs. 11(g) and (h).

Therefore, five specialized chains with identified ground link K_F and sensing link 2 are available as shown in Figs. 11(d)-(h).

Transmitting Rod - link 6

Since there must be a binary link as the transmitting rod 6 that is adjacent to the ground link K_F with a prismatic joint J_P , the transmitting rod can be identified as follows:

1. For the Fig. 11(d), assign the transmitting rod 6 to generate one result, Fig. 11(i).
2. For the Fig. 11(e), assign the transmitting rod 6 to generate one non-isomorphic result, Fig. 11(j).
3. For the Fig. 11(f), assign the transmitting rod 6 to generate two results, Figs. 11(k) and (l).
4. For the Fig. 11(g), assign the transmitting rod 6 to generate one result, Fig. 11(m).
5. For the Fig. 11(h), assign the transmitting rod 6 to generate one result, Fig. 11(n).

Therefore, six specialized chains with identified ground link K_F , sensing link 2 and transmitting rod 6 are available as shown in Figs. 11(i)-(n).

Cam - link 5

Since there must be a ternary link as the cam 5 that is adjacent to the transmitting rod 6 with a cam joint J_A , the cam 5 can be identified as follows:

1. For the Fig. 11(i), assign the cam 5 to generate one result, Fig. 11(o).

2. For the Fig. 11(j), assign the cam 5 to generate one result, Fig. 11(p).
 3. For the Fig. 11(k), assign the cam 5 to generate one result, Fig. 11(q).
 4. For the Fig. 11(l), assign the cam 5 to generate one result, Fig. 11(r).
 5. For the Fig. 11(m), there is no ternary link available to be identified as a cam 5.
- Therefore, Figure 11(m) is not qualified for the procedure of specialization.
6. For the Fig. 11(n), assign the cam 5 to generate one result, Fig. 11(s).

Therefore, five specialized chains with identified ground link K_F , sensing link 2, transmitting rod 6 and cam 5 are available as shown in Figs. 11(o)-(s).

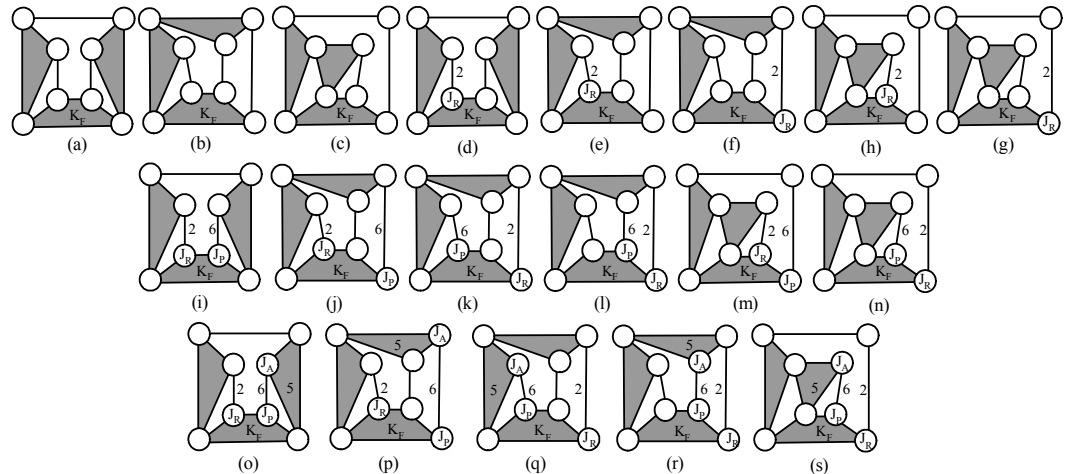


Fig. 11 Specialized chains with six members and eight joints

Connecting rod and cam - link3 and link4

Since there must be a binary link as the connecting rod 3 and another ternary link as the cam 4, the connecting rod 3 and cam 4 can be identified as follows:

1. For the Fig. 11(o), assign the connecting rod 3, the cam 4, a cam joint J_A , and the remaining revolute joints J_R to generate two feasible results, Figs. 12(a) and (b).
2. For the Fig. 11(p), assign the connecting rod 3, the cam 4, a cam joint J_A , and the remaining revolute joints J_R to generate two feasible results, Figs. 12(c) and (d).
3. For the Fig. 11(q), assign the connecting rod 3, the cam 4, a cam joint J_A , and the remaining revolute joints J_R to generate three feasible results, Figs. 12(e)-(g).
4. For the Fig. 11(r), assign of the connecting rod 3, the cam 4, a cam joint J_A , and the remaining revolute joints J_R to generate three feasible results, Figs. 12(h)-(j).
5. For the Fig. 11(s), assign the connecting rod 3, the cam 4, a cam joint J_A , and the remaining revolute joints J_R to generate one feasible result, Fig. 12(k).

Therefore, eleven feasible specialized chains with identified ground link K_F , sensing link 2, transmitting rod 6, connecting rod 3, and two cams 4 and 5 are available as shown in Figs. 12(a)-(k).

Atlas of (6, 8) reconstruction designs

Through particularizing the eleven feasible specialized chains in Fig. 12, the corresponding eleven interior mechanisms are obtained as shown in Fig. 13.

Figure 14 shows the 3D solid model of a reconstruction design of Zhang Heng's seismoscope. A complete Zhang Heng's seismoscope with six members and eight joints including the appearance and the inside is shown in Fig. 14(a). There are eight devices in the principal directions of the instrument, Fig. 14(b). A switch ball is held with the eight transmitting rods (link 6) on the top of the pillar. An interior mechanism, based on Fig. 13(k), is shown in Fig. 14(c). The sensing link (link 2) detects the first motion of P-wave, no matter whether it is compressing or expanding. When the first motion is compressing, the sensing link 2 topples in the left, Fig. 14(d). On the contrary, if the first motion is expanding, the sensing link 2 topples in the right, Fig. 14(e). Figure 15 shows the prototype of Zhang Heng's seismoscope based on the proposed approach. After the testing, the

performance of the prototype is workable. It proposes a possible way to detect the direction of the earthquake in the future.

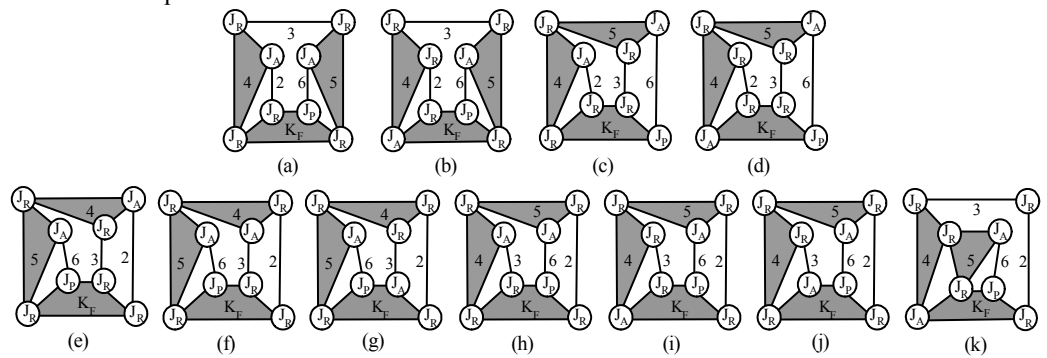


Fig. 12 Feasible specialized chains with six members and eight joints

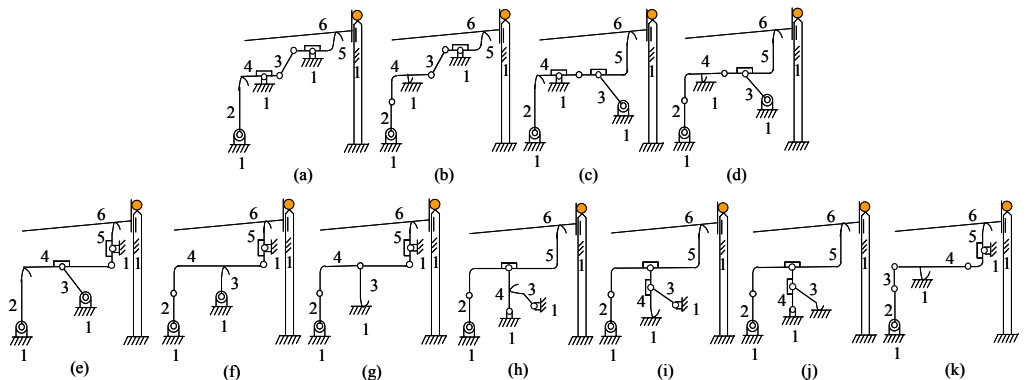


Fig. 13 Interior mechanisms with six members and eight joints

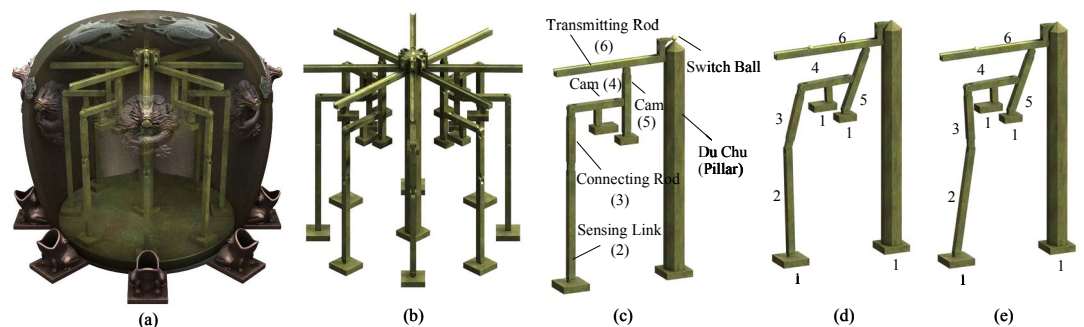


Fig. 14 A reconstruction design of Zhang Heng's seismoscope with 6 members and 8 joints



Fig. 15 A prototype of Zhang Heng's seismoscope

7. Conclusions

Through the study of the historical archives, seismology and ancient seismographs, the design specifications of Zhang Heng's seismoscope are concluded. Since cam-linkage mechanisms are full of various applications in ancient China, the interior mechanism of Zhang Heng's seismoscope may consist of links and cams. Based on the creative mechanism design methodology (generalization and specialization) subject to the concluded design specifications, all feasible topological structures of mechanism of Zhang Heng's

seismoscope that meet the science theories and techniques of the subject's time period are systematically synthesized. Two interior mechanisms of Zhang Heng's seismoscope with five members and six joints are obtained and eleven for the design with six members and eight joints are synthesized. Logically, one of the solutions is possible to be the inner mechanism of Zhang Heng's seismoscope. And, the result of this work provides an approach and feasible solutions for the reconstruction design of Zhang Heng's seismoscope before new and solid evidences are found.

Acknowledgement

The authors are grateful to the National Science Council (TAIWAN, ROC) under Grant NSC 95-2221-E-006-048-MY2 for the financial support of this work.

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