國立成功大學
機械工程學系
博士論文

張衡地動儀感震機構之系統化復原設計
Systematic Reconstruction Design of the Detecting Mechanism of Zhang Heng's Seismoscope

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本論文業經審查及口試合格特此證明

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中華民國九十六年六月二十九日

摘要

西元 132 年的古中國，張衡建構世界上最早的測震儀器，名為候風地動儀，此儀器不但可以感應地震的發生，亦可以測出地震的方向。由於現有的史料對於內部構形描述不清，且無實物流傳，因此，對於候風地動儀需要進一步探討。本研究的目的，即系統化地進行張衡地動儀感震機構的復原設計。

本研究首先回顧張衡地動儀的歷史文獻資料與現有的復原設計，探討地震波、斷層面解、以及西方地震儀器的發展，進而釐清張衡地動儀感震機構的設計原理。接著，提出一套系統化的復原方法，首先基於文獻回顧，訂定出張衡地動儀的設計需求，再根據機構一般化與特殊化的概念，合成出所有符合當代科學理論與工藝技術的可行張衡地動儀感震機構。本研究並以連桿機構與繩索滑輪機構為例，分別合成出 8 個與 1 個五桿六接頭，以及 26 個與 6 個六桿八接頭之可行張衡地動儀感震機構；根據推論，所有可行的復原設計之中，應有真正的張衡地動儀內部機構。

本研究所提出之復原方法，可系統化合成出所有的張衡地動儀感震機構，在還沒有更具體的證據之前，此一方法提供合理的依據來復原張衡地動儀的感震機構。

關鍵詞：張衡地動儀、復原設計、地震儀、機械史、機構創新設計。

ABSTRACT

In 132 AD, the earliest earthquake instrument in the world named Hou Feng Di Dong Yi was invented by Zhang Heng in ancient China. This instrument was designed to indicate not only the occurrence of an earthquake but also the direction to its source. However, the relevant literary description is so brief that it is difficult to realize the actual structure of the mechanism inside the seismoscope. Moreover, there are no survived historical remains today for providing evidence to trace Zhang Heng's seismoscope. Hence, the aim of this work is to reconstruct the detecting mechanism of Zhang Heng's seismoscope.

The historical archives and existing reconstruction designs of Zhang Heng's seismoscope are reviewed. Seismic wave, fault-plane solution, and the development of ancient earthquake instruments are investigated for defining the design specifications of Zhang's seismoscope. A reconstruction design approach for the lost Zhang Heng's seismoscope is proposed. Based on literature review, the design requirements of Zhang Heng's seismoscope are concluded and defined. Then, according to the concepts of generalization and specialization of mechanisms, all feasible Zhang Heng's seismoscope designs that are in accordance with the science theories and techniques of the subject's time period are recreated. Based on linkage mechanisms and rope-and-pulley mechanisms, four design examples are provided for tracing the detecting mechanism of Zhang Heng's seismoscope. For linkage-type Zhang Heng's seismoscope, 8 and 26 feasible designs are resulted from those with five members and six joints as well as with six members and eight joints, respectively. For rope-and-pulley-type Zhang Heng's seismoscope, 1 and 6 feasible designs are resulted from those with five members and six joints as well as with six members and eight joints, respectively.

The approach developed in this work provides a logical foundation for reconstructing Zhang Heng's seismoscope. Before new and solid evidences are found, it is believed that one of above the reconstruction designs is possible to be the detecting mechanism of Zhang Heng's seismoscope.

Keywords: Zhang Heng's seismoscope, Reconstruction design, Seismograph,
History of machinery, Creative mechanism design.

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1　Introduction

From the characteristics of ancient cultural and philosophical thinking, China was the first country to observe and study the earthquake in the world. Since China has always been plagued of earthquakes, the detection earthquakes were always with great concerns in ancient China, as well as in Europe and Asia.

The earliest seismoscope named Hou Feng Di Dong Yi (候風地動儀) was invented in ancient China by Zhang Heng (張衡) in 132 AD. This instrument was designed to indicate not only the occurrence of an earthquake but also the direction to its source. Since there are no clear historical documents and physical remains, Zhang Heng’s seismoscope is still a famous but mysterious instrument today. Hence, the reconstruction of Zhang Heng’s seismoscope appears to be an important research topic in the study of reconstruction design of lost ancient machinery.

This Chapter introduces the motivation of this study first. Then, those literature relevant to historical records and reconstruction designs of Zhang Heng’s seismoscope are reviewed. And, the objectives and the organization of the dissertation are presented.

1-1　Motivation

By studying the historical development of machines, one is able to trace the paths and logics of the target machines. It also guides one to understand past developmental patterns of mechanical technology.

Historically, ancient China was outstanding in its mechanical technology. Numerous ingenious machines were invented before the 15th century. However, due to insufficient literature and lost finished objects, most original ancient machines cannot be verified and many inventions were not passed down to later generations. Furthermore, later generations could only regard some inventions as novelties, and even questioned them as being senseless. To solve this problem, Lin and Chen [01, 02] proposed a methodology namely reconstruction of ancient machinery, which seeks to reconstruct various designs based on the existing literature and the known mechanical principles and technique skill. Through this methodology, the reconstructed machines can be used to demonstrate the level of mechanical technology of their times.

From a reconstruction viewpoint, ancient Chinese machines can be divided, based on their historical archives, into three types: documented and proven, undocumented but proven, and documented but unproven [03, 04]. Here, historical archives refer to ancient manuscripts, historical artifacts, archeological data, and existing physical evidences. Accordingly, ancient manuscripts refer to words and images found in official and unofficial historical records; historical artifacts include buildings, implements, and paintings; archeological data include images and language characters on archeological findings; and existing physical evidences include excavated ancient machines and original historical materials. Because literature and images on artifacts show only the outer appearance but not the internal structure and dimension of parts, they are considered documented but unproven. Here, “documented” refers to the one being only described on non-physical historical materials, while “proven” refers to the one that remains the actual object today. The detailed description of the three catalogs is given as follows [04].

Type I - Documented and Proven

This type refers to the actual ancient machines which were included in historical documentation. Generally, they are ancient machines that were widely used and some of which are excavated ancient machines with relevant literary records from their times. The development of some machines such as the waterwheels (水輪), water-driven tilt hammers (水碓), dragon-bone water lifts (龍骨水車), winnowing fans (扇颺), and weaving machines are so practical and mature so that they are still being used today and their relevant descriptions can often be found in historical archives, e.g. the bed sheet censer (被中香爐) and old gears.

Type II - Undocumented but Proven

This type refers to the excavated ancient machines which have no relevant historical documentation. For example, the copper horse chariot (銅車馬) from the Qin (秦) Imperial Tomb around 210 BC, ancient Chinese paddle locks, and the pointed porcelain flask (尖底陶瓶) excavated from the Yangshao (仰紹) relic site are classified into this type.

Type - III Documented but Unproven

This type refers to the ancient machines which have historical records but have no actual evidence of existence. These machines can be further classified as those with written descriptions and illustrations, with written descriptions but without illustrations, and without written descriptions but with illustrations. Particularly, for the ancient Chinese machines, there are many cases with written descriptions but without illustrations, such as Lu Ban's (魯班) wooden horse chariot (木車馬) during the Eastern Zhou Dynasty (東周, 770-221 BC), Zhu Ge-liang's (諸葛亮) wooden cow and gliding horse (木牛流馬) during the period of Three Kingdoms (三國, 220-280 AD), Zhang Si-xun's (張思訓) tai ping hun yi (太平渾儀) during the Northern Song Dynasty (北宋, 960-1127 AD), Yan Su's (燕肅) south-pointing chariot (指南車) during the Northern Song Dynasty, and Zhang Heng's (張衡) seismoscope (地動儀) during the Eastern Han Dynasty (東漢, 25-220 AD).

Zhang Heng' seismoscope named Hou Feng Di Dong Yi (候風地動儀) was the earliest earthquake detecting instrument invented in 132 AD. As described above, Zhang Heng's seismoscope is with literary records [05, 06] and without surviving hardware. Furthermore, the existing records focused on the outer appearance only. The detecting mechanism embedded in this instrument was less concerned. For the outer appearance, the most popular one is shown in Figure 1-1 [07]. It was cast with bronze and was like a jar with an inner diameter of 8 chi (尺) (around 2 meters). There were eight dragons attached to the outside of the vessel, facing in the principal directions of the compass. Below each dragon rested a toad with its mouth open toward the dragon. Each dragon's mouth contained a ball. For the inner mechanism, the historical descriptions only note that there was a *du zhu* (都柱, a pillar) in the center of the interior and eight transmitting rods near *du zhu*. When the earthquake is occurring, the ball located in the corresponding direction of ground movement will drop out of the dragon's mouth and fall into the mouth of a toad below. Therefore, the direction faced by the dragon that had dropped the ball indicated the direction where the shaking came from.

Figure 1-1 An external of Zhang Heng’s seismoscope [07]

Therefore, due to insufficient literature on the inner design of the instrument, it has been very difficult to investigate and reconstruct the inner detecting mechanism of this seismoscope. According to the study of historical records, some scholars had tried to reconstruct Zhang Heng’s seismoscope in the past centuries [07-15]. They proposed and built some different reconstruction designs. Although these works had their contributions in some aspects, the accuracy and sensitivity of the reconstruction designs were never in accordance with historical records.

1-2 Objectives

Based on the efforts of many scholars, the principle and outer appearce of Zhang Heng’s seismoscope have been realized gradually. However, the detecting mechanism of Zhang Heng’s seismoscope still has a lot of issues to be studied. The objectives of this study are:

1. To realize the cause of earthquake and the development of ancient earthquake instruments by investigating literature and seismology so as to define the principle of Zhang Heng’s seismoscope.

2. To conclude and define the design requirements of Zhang Heng’s seismoscope through the study of ancient Chinese historical archives, the investigation of seismology, and the analysis of ancient Western seismographs.

3. To propose a reconstruction approach based on the concept of generalization and specialization of mechanisms subject to the concluded design requirements, from which all feasible designs concepts of Zhang Heng’s seismoscope that meet the science theories and techniques of the subject’s time period can be systematically reconstructed.

4. To integrate computer and CAD software to establish the 3D model of Zhang Heng’s seismoscope so as to build the reconstructed model physically.

1-3 Dissertation Organization

As shown in Figure 1-2, this dissertation is organized with the following seven chapters:

1. Chapter 1 is an introduction to this dissertation, including the motivation, objectives, and the organization of this work.

2. Chapter 2 presents the historical records and reconstruction designs of Zhang Heng’s seismoscope. The developments of ancient Chinese machinery including linkage and rope-and-pulley mechanisms are also introduced.

3. Chapter 3 describes the development of seismology. Two important topics, namely seismic waves and fault-plane solution, which directly influence the design requirements of Zhang Heng’s seismoscope, are discussed.

4. Chapter 4 presents the development of ancient earthquake instruments and analyzes the ancient seismometers.

5. Chapter 5 proposes a reconstruction approach for the detecting mechanism of Zhang Heng’s seismoscope.

6. Chapter 6 presents four design examples to illustrate the proposed approach.

7. Chapter 7 builds a prototype to verify the proposed concept.

8. Chapter 8 concludes the results of this study and states the suggestions for the future works.

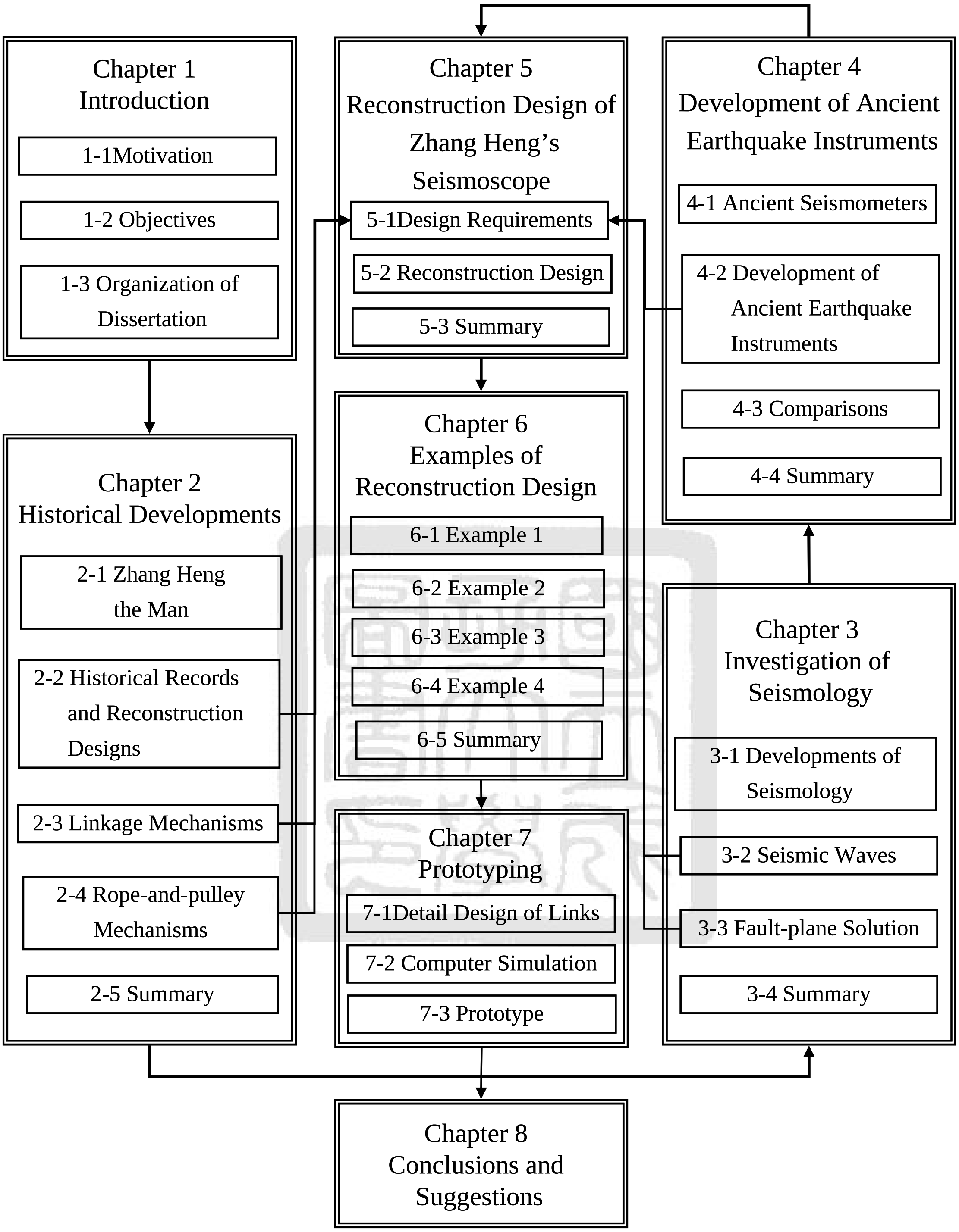


Figure 1-2　Organization of the dissertation

Chapter 2　Historical Developments

The reconstruction of Zhang Heng’s seismoscope requires detailed literature study for realizing the problem. It is also important to comprehend the science theories and technologies of the subject’s time period. In this chapter, Zhang Heng’s biography is introduced. The historical records and relevant reconstruction models of Zhang Heng’s seismoscope are proposed. To this end, the developments of two machine members, linkages and rope-and-pulleys, which are possible to form Zhang Heng’s seismoscope are presented.

2-1　Zhang Heng the Man

Zhang Heng (張衡) (78-139 AD) was an extraordinary polymath in the Eastern Han Dynasty (東漢, 25-220 AD) in ancient China [05, 08], Figure 2-1. He was not only an astronomer royal but also a distinguished cartographer, mathematician, poet, painter, and inventor. He was born in the third year (78 AD) of the reign of Emperor Zhang (章帝) of the Eastern Han Dynasty in ancient China in Xi E (西鄂) County in Nan Yang (南陽). He died at the age 62 during the fourth year (139 AD) of the reign of Emperor Shun (順帝) of the Eastern Han Dynasty.

Zhang was born in a distinguished family and was educated in the moral and political philosophy of Confucianism. For several years, he studied literature and trained as a writer. When Zhang was 17 to 23 years old (94 to 100 AD), he studied in Chang An (長安), the capital city of the Western Han Dynasty (西漢, 206 BC-8 AD), and the Lo Yang (洛陽), capital city of the Eastern Han Dynasty. He also traveled many cultural cities and scenic spots so that a huge mass of writing data were accumulated through the trips. At age 23 (100 AD), he accepted the invitation of Nan Yang governor Bao De (鮑德) to be a clerk to manage official documents in his hometown and assisted Bao in government affairs.

Figure 2-1　Picture of Zhang Heng (78-139 AD) [08]

Between ages 31 to 34 (108 to 111 AD), Zhang stayed in his hometown and studied hard. His interests turned from literature to scientific matters, and at that time he became particularly interested in astronomy. He specialized in Yang Xiong’s (揚雄) Tai Xuan Jing《太玄經》, which was a philosophical work on cosmic phenomena that discusses astronomy, calendar calculation, and spherical heaven theory. He was then called to the capital city to serve as a palace attendant when he was 34 (111 AD). He became an assistant minister at 37 (114 AD). At age 38 (115 AD), he became a chief of the observatory responsible for observing astronomical phenomena, preparing calendars, and managing time devices. Since Zhang held the position, abundant resources were provided to him to study scientific matters and design some skillful devices.

At age 40 (117 AD), Zhang constructed the armillary sphere. The celestial globe was with a water drive ("clepsydra"), which rotated accurately once a day. It was one meter in diameter and was inlaid with 1449 stars that show the ecliptic and the equator. At age 41, he published Ling Xian《靈憲》, which was a summary of astronomical theories at the time. The book contains discussions on the evolution of heaven and earth, the cosmos, and the theory of planetary movements. It also contains accurate data on star observations and scientific explanations on the lunar eclipse. At age 42 (119 AD), he wrote the Suan Wang Lun《算罔論》, a collection of works on the general theory of mathematics. Unfortunately, the book was lost in time. Zhang also used asymptotic fraction and calculated the ratio of a circle’s circumference to its diameter (pi) to be the square root of 10, the value of which is between 3.1466 and 3.1622. At age 44 (121 AD), he was made a prefect of official carriages, responsible for protecting the imperial palace, transmitting written reports to the emperor, collecting tributes from officials and the public, and receiving envoys to the capital city. Later, he completed the Suan Wang Lun 《算罔論》 as well as the design and construction of the south-pointing chariot and the odometer. At age 49 (126 AD), Zhang again became a chief of the observatory and wrote Ying Jian《應間》in response to the cold shoulders of the ruling class and ridicules of the traditionally influential.

At age 55 (132 AD), Zhang invented the Di Dong Yi (地動儀), a device for detecting the direction of earthquakes. At age 56 (133 AD), he became a palace attendant who served as a consultant and adviser to the emperor. He became governor administering river channels at age 59 (136 AD) and a minister at age 61 (138 AD). He died at the age of 62 (139 AD) while serving as a minister.

Zhang was also a famous poet in the Han Dynasty, and his works of literatures made him distinct in the history of Chinese literature. His accomplishment includes the writing of poems, rhapsodies, literatures, inscriptions, introductions, imperial mandates, eulogies, and calligraphy, as well as figurine sculpture. He had a lot of works of literatures, such as, poems《Lyric Poems on Four Sorrows or Si Chou Shih (四愁詩), Tong Sheng Ge (同聲歌), Ge (歌), and Yuan Pian (怨篇)》 and rhapsodies 《Wen Guan Fu (溫泉賦), Er Jing Fu (二京賦), Nan Du Fu (南都賦), Si Xuan Fu (思玄賦), Gui Tian Fu (歸田賦), and Ding Ging Fu (定情賦).》 Zhang was also one of the 12 famous painters of the Han Dynasty. Furthermore, Zhang could also draw maps. No only could he draw the locations of major mountains and rivers all over China, but he was able to show the geographical features and customs of the areas.

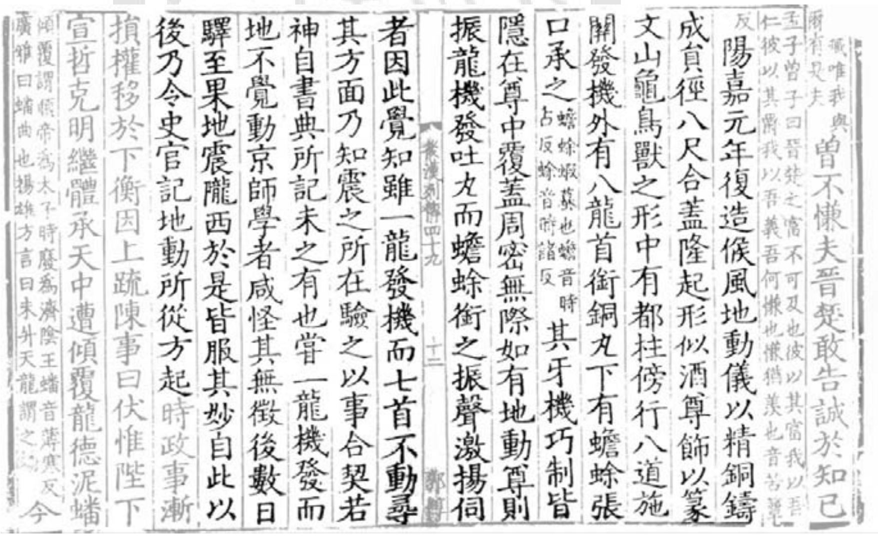
Zhang had many astonishing achievements in wooden machines. He designed and constructed many skillful instruments. More reliable records of his works include the earthquake detecting instrument, armillary sphere, mechanical calendar, and wooden flying device. He was referred to as the “sage of woodcrafts” together with Ma Chun (馬鈞) of the Three Kingdom Period (三國, 220-265 AD).

Zhang was an extremely knowledgeable and learned man. Not only was he a great inventor, engineer, and scientist, but also a prolific scholar and artist. In conclusion, Zhang Heng can be respectfully referred to the Leonardo da Vinci of ancient China.

2-2 Historical Records and Reconstruction Designs

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》[05] is the only record about Zhang Heng’s seismoscope, Figure 2-2. In this archive, there are 196 Chinese characters regarding Zhang Heng’s seismoscope. In 2006, Feng Rui et al. [06] proposed 6 new historical records including Xu Han Shu《續漢書》authored by Si Ma-biao (司馬彪), Hou Han Ji《後漢紀》authored 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》authored by Fan Ye (范曄) about Zhang Heng’s seismoscope. In these historical records, there are 5 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, Figures 2-3(a)-(d) from Xu Han Shu《續漢書》and Figure 2-3(e) from Hou Han Ji《後漢紀》. There is another record from the History of the Later Han Dynasty《後漢書》, shown as Figure 2-3(f).

Compared with all the materials word by word, there are 238 Chinese characters regarding Zhnag Heng’s seismoscope. The description can be divided into three parts. The first and final sections mainly come from the Biography of Zhang Heng in the History of the Later Han Dynasty, such as the following descriptions:



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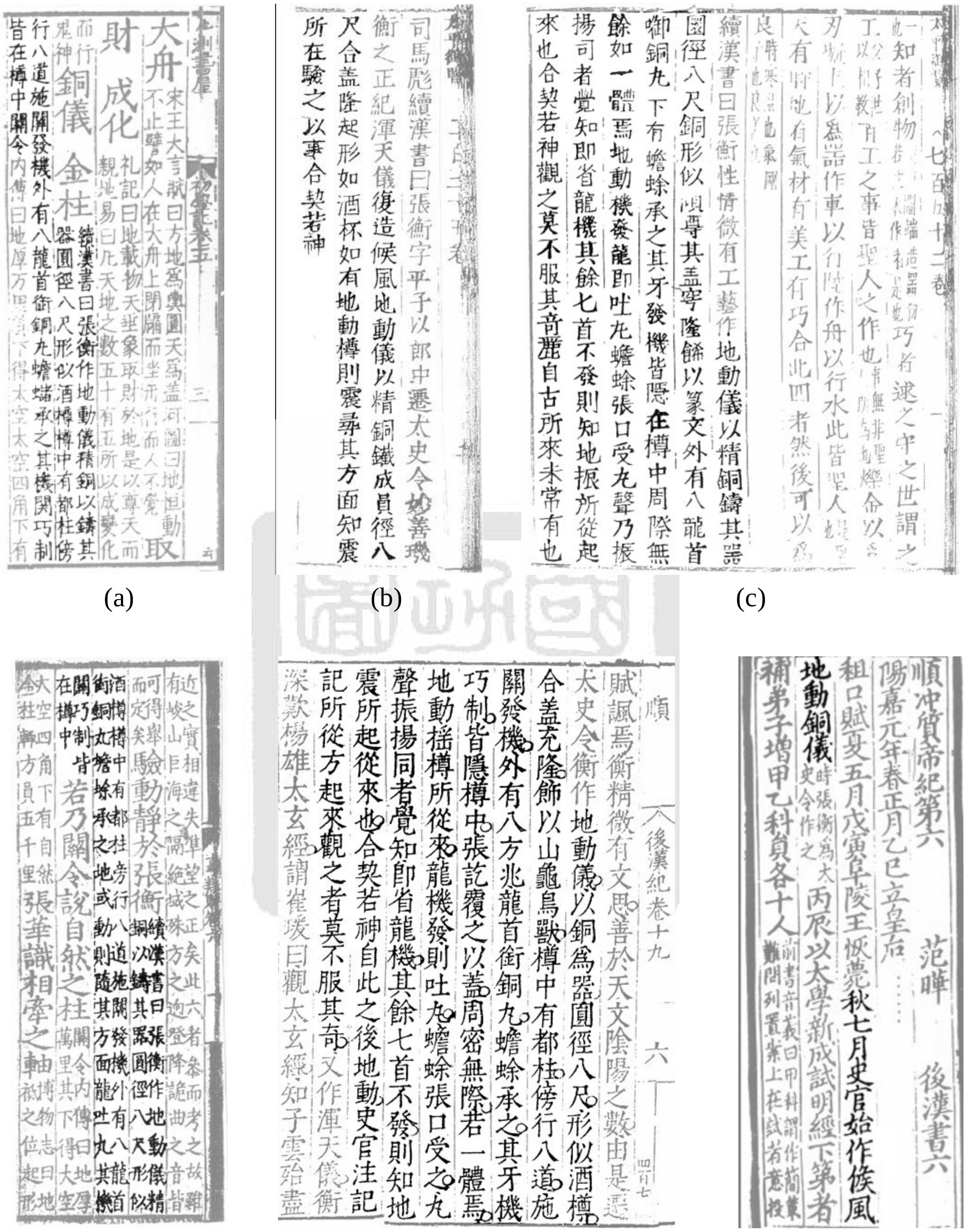
反）陽嘉元年復造候風地動儀以精銅鑄
成員徑八尺合蓋隆起形似酒尊飾以篆
文山龜鳥獸之形中有都柱傍行八道施
關發機外有八龍首銜銅丸下有蟾蜍張
口承之（蟾蜍蝦蟆也蟾音時占反蜍音餘諸反）其牙機巧制皆
隱在尊中覆蓋周密無際如有地動尊則
振龍機發吐丸而蟾蜍銜之振聲激揚伺
後漢列傳四十九　十二
者因此覺知雖一龍發機而七首不動尋
其方面乃知震之所在驗之以事合契若
神自書典所記未之有也嘗一龍機發而
地不覺動京師學者咸怪其無徵後數日
驛至果地震隴西於是皆服其妙自此以
後乃令史官記地動所從方起　時政事漸
損權移於下衡因上疏陳事曰伏惟陛下
宣哲克明繼體承天中遭傾覆龍德泥蟠
（傾覆謂帝為太子時廢為濟陰王蟠音蒲寒反廣雅曰蟠曲也揚雄方言曰未升天龍謂之蟠）今

Figure 2-2 Description of Zhang Heng’s seismoscope in the Biography of Zhang Heng in the History of the Later Han Dynasty 《後漢書‧張衡傳》[05]



(a)

初學記卷五

大舟（宋王大言賦曰方地爲輿圓天爲蓋河圖曰地恒動不止譬如人在大舟上閉牖而坐舟行而人不覺）取

財成化（礼記曰地載物天垂象取財於地是以尊天而親地易曰凡天地之數五十有五所以成變化）

（而行鬼神）銅儀　金柱（續漢書曰張衡作地動儀精銅以鑄其器圓徑八尺形似酒樽樽中有都柱傍

行八道施關發機外有八龍首銜銅丸蟾蜍承之其機關巧制

皆在樽中關令內傳曰地厚万里其下得太空太空四角下有

(b)

司馬彪續漢書曰張衡字平子以郎中遷太史令妙善璣

衡之正紀渾天儀復造候風地動儀以精銅鐵成員徑八

尺合蓋隆起形如酒杯如有地動樽則震尋其方面知震

所在驗之以事合契若神

(c)

太平御覽　卷七百五十二

一知者創物（[illegible]）巧者述之守之世謂之

工（[illegible]）百工之事皆聖人之作也（[illegible]）爍金以爲

刃（[illegible]）以爲器作車以行陸作舟以行水此皆聖人（[illegible]）

天有時地有氣材有美工有巧合此四者然後可以爲

良（[illegible]）

續漢書曰張衡性情微有工藝作地動儀以精銅鑄其器

圜徑八尺銅形似酒尊其蓋穹隆飾以篆文外有八龍首

啣銅丸下有蟾蜍承之其牙發機皆隱在樽中周際無

餘如一體焉地動機發龍即吐丸蟾蜍張口受丸聲乃振

揚司者覺知即省龍機其餘七首不發則知地振所從起

來也合契若神觀之莫不服其奇麗自古所來未常有也

(d)

（近之實相違失準望之正矣此六者參而考之故雖有峻山巨海之隔絶域殊方之迥登降詭曲之音皆

可得舉而定矣）驗動靜於張衡（續漢書曰張衡作地動儀精銅以鑄其器圓徑八尺形似

酒樽樽中有都柱傍行八道施關發機外有八龍首銜銅丸蟾蜍承之地或動則隨其方面龍吐丸其機

關巧制皆在樽中）若乃關令說自然之柱（關令內傳曰地厚萬里其下得大空

大空四角下有自然金柱輛方員五千里）張華識相牽之軸（博物志曰地祇之位起形

(e)

順　後漢紀卷十九　六　四百七

賦諷焉衡精微有文思善於天文陰陽之數由是遷

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合蓋充隆飾以山龜鳥獸樽中有都柱傍行八道施

關發機外有八方兆龍首銜銅丸蟾蜍承之其牙機

巧制皆隱樽中張訖覆之以蓋周密無際若一體焉

地動搖樽所從來龍機發則吐丸蟾蜍張口受之丸

聲振揚同者覺知即省龍機其餘七首不發則知地

震所起從來也合契若神自此之後地動史官注記

記所從方起來觀之者莫不服其奇又作渾天儀衡

深歎楊雄太玄經謂崔瑗曰觀太玄經知子雲殆盡

(f)

順冲質帝紀第六　范曄　後漢書六

陽嘉元年春正月乙巳立皇后……

租口賦夏五月戊寅阜陵王恢薨秋七月史官始作候風

地動銅儀（時張衡爲太史令作之）丙辰以太學新成試明經下第者

補弟子增甲乙科員各十人（前書音義曰甲科謂作簡策難問列置案上在試者意投）

Figure 2-3　Six new historical records about Zhang Heng’s seismoscope [06]

During the first year of the Yang Jia period (132 AD), July in the autumn, Zhang Heng constructed the Hou Feng Di Dong Yi. (陽嘉元年，秋七月，史官張衡始作候風地動銅儀。)

The instrument was cast with bronze. Its outer appearance was like a jar with a diameter eight chi (around two meters). The cover was protruded and it looked like a wine vessel. There were decorations of inscriptions and animals on it. There was a du zhu (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 is below each dragon where its mouth opens toward the dragon. Each dragon's mouth contained a bronze ball. ***The intricate mechanism used was hidden inside the device.*** *When the ground moved, 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. The clang will signify where an earthquake has occurred. The direction faced by the dragon whose ball was dropped would be the direction from which the shaking came. And, each earthquake only made one ball drop. The device worked accurately. (以精銅鑄其器，圓徑八尺，形似酒尊，其蓋穹隆，飾以篆文，山龜鳥獸之形。尊中有都柱，傍行八道，施關發機。外有八方兆，龍首銜銅丸，下有蟾蜍承之。其機關巧製，皆隱在尊中。張訖，覆之以蓋，周密無際，若一體焉。如有地動，地動搖尊，尊則振，則隨其方面，龍機發，即吐丸，蟾蜍張口受丸。丸聲振揚，司者因此覺知。雖一龍發機，而其餘七首不動，則知地震所起從來也。驗之以事，合契若神。來觀之者，莫不服其奇。自古所來，書典所記，未常有也。)*

The device had ever worked once. The dragon spilled a ball but no earthquake was felt. Scholars in the city thought it was odd. Several days later, news came that an earthquake had indeed occurred in area Long Xi. People then realized its ingenuity. From then on, the historian was ordered to record the direction of the quake origins using this instrument. (嘗一龍發機，而地不覺動，京師學者咸怪其無征。後數日驛至，果地震隴西，於是皆服其妙。自此之後，乃令史官記地動所從方起。)

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.

In the past centuries, some scholars had tried to reconstruct Zhang Heng’s seismoscope [06-16] but failed to achieve the high accuracy and sensitivity as described as in historical records. The Japanese scholar H. Kazumi was the first person to reconstruct Zhang Heng’s seismoscope in 1875 [09], Figure 2-4. But, he just drew the external of Zhang Heng’s seismoscope. The dragons and the toads are in the appropriate positions and the shape of the vessel conforms to the historical records.

Figure 2-4 Reconstruction design of Zhang Heng’s seismoscope by H. Kazumi (1875) [09]

The English seismologist John Milne designed the external of reconstruction design of Zhang Heng’s seismoscope in 1883 [10], Figure 2-5. However, the *du zhu* (a pillar) was too tall to conform to the historical records. Milne was the first person to propose that the principle of Zhang Heng’s seismoscope and modern seismographs are based on the principle of inertia.

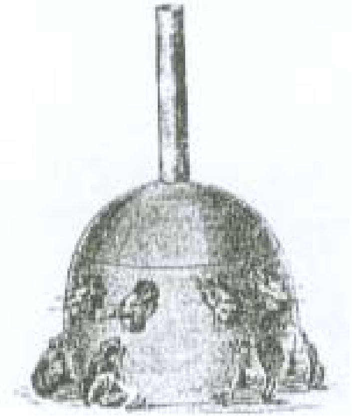
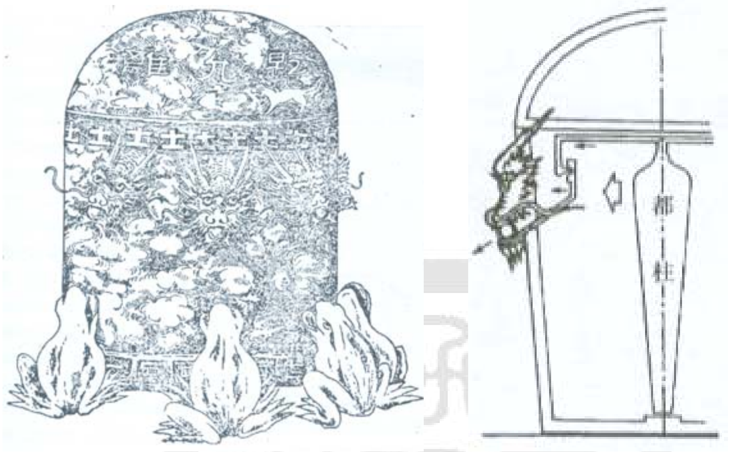


Figure 2-5 Reconstruction design of Zhang Heng’s seismoscope by John Milne (1883) [10]

The first Chinese person to reconstruct Zhang Heng’s seismoscope was an architect Lu Yan-zhi (呂彥直) [08]. In 1917, he just redrew John Milne’s the external of reconstruction design with more graceful painting. Beside, the Chinese seismologist Lee Shan-bang (李善邦) proposed two reconstruction designs [06, 07]. In 1931, he merely modified H. Kazumi’s external appearance of reconstruction design with a different painting method, Figure 2-6(a). In 1981, he considered that *du zhu* is a suspended pendulum to function as a sensing element, Figure 2-6(b), and the toads are omitted.

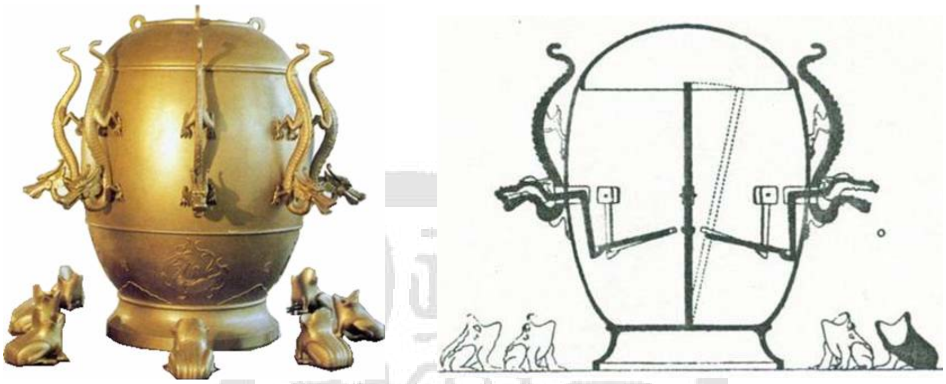


(a) (b)

Figure 2-6 Reconstruction designs of Zhang Heng’s seismoscope by Lee Shan-bang (1931, 1981) [06, 07]

The Chinese scholar Wang Zhen-duo (王振鐸) was the first person to reconstruct the real prototype of Zhang Heng’s seismoscope. He proposed two reconstruction designs. In 1936, he presented a reconstruction design of Zhang Heng’s seismoscope [11], Figure 2-7 (a). In this design, *du zhu* is a suspended pendulum to function as a sensing element. Once a seismic wave shakes the pendulum, the pendulum will press the nearby linkage mechanism to release the ball from the dragon’s mouth. In 1963, he presented another reconstruction design of Zhang Heng’s seismoscope [07], Figure 2-7(b). In the second design, *du zhu* is an inverted pendulum to function as the sensing element. Once the shake comes, the pendulum loses its equilibrium and topples in one of eight channels to push the linkage mechanism. Then the linkage mechanism opens the dragon’s mouth and the ball in the dragon’s mouth falls in the toad below.

(a) First design (1936) [11]



(b) Second design (1963) [07]

Figure 2-7 Reconstruction designs of Zhang Heng’s seismoscope by Wang Zhen-duo

In 1937, the Japanese seismologist T. Hagiwara built an instrument which only has an inverted pendulum to function as the sensing element, without the dragons and the toads [09, 12], Figure 2-8. Once an earthquake occurs, the pendulum loses its equilibrium and topples in the center of a horizontal circular plate which is perforated with a circular hole at the center with 8 equidistant slits. Then the pendulum goes into the nearest slit and pushes the slide to show the direction of the earthquake.

Figure 2-8 Reconstruction design of Zhang Heng’s seismoscope by T. Hagiwara (1937) [09]

In 1939, the Japanese seismologist A. Imamura used an inverted pendulum with its foot tapered to function as the sensing element, Figure 2-10 [09, 12]. The top is tied a thin cord with a hoop. A device is provided for correctly setting the pendulum which consists of a micrometer fixed on the top of a vertical metal frame crossing over the pendulum. A nut allows the micrometer to be slowly up and down without undergoing any rotations. Once the seismic wave comes, the pendulum loses its equilibrium and topples over to show the direction of the earthquake.

Figure 2-9 Reconstruction design of Zhang Heng’s seismoscope by A. Imamura (1939) [09]

In 1978, the American seismologist Bruce A. Bolt proposed a reconstruction design of Zhang Heng’s seismoscope based on John Milne’s concept [13], Figure 2-10. In 1983, Sleeswyk and Sivin presented an instrument such that *du zhu* is a frame and the vessel is suspended from *du zhu* [14], Figure 2-11. Once the seismic wave shakes the vessel, the vessel presses *du zhu* and the ball on the top of *du zhu* will roll into the corresponding dragon’s mouth.

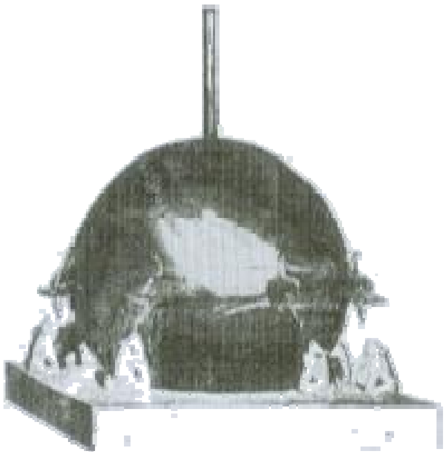


Figure 2-10 Reconstruction design of Zhang Heng’s seismoscope by Bruce A. Bolt (1978) [13]

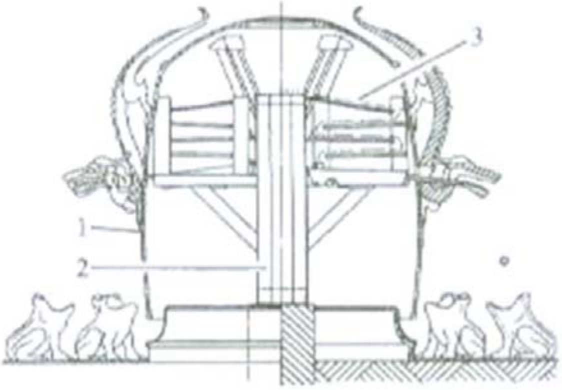


Figure 2-11 Reconstruction design of Zhang Heng’s seismoscope by Sleeswyk and Sivin (1983) [14]

In 1991, the Chinese scholar Wang Jian (王湔) designed and built a reconstruction design of Zhang Heng’s seismoscope [06], Figure 2-12. The inverted pendulum is in the bottom of the instrument to function as a sensing element. The inverted pendulum detects the shake to drive the linkage mechanism. The linkage mechanism makes the center pendulum to topple over. The ball in dragon’s mouth falls by the toppling center pendulum.

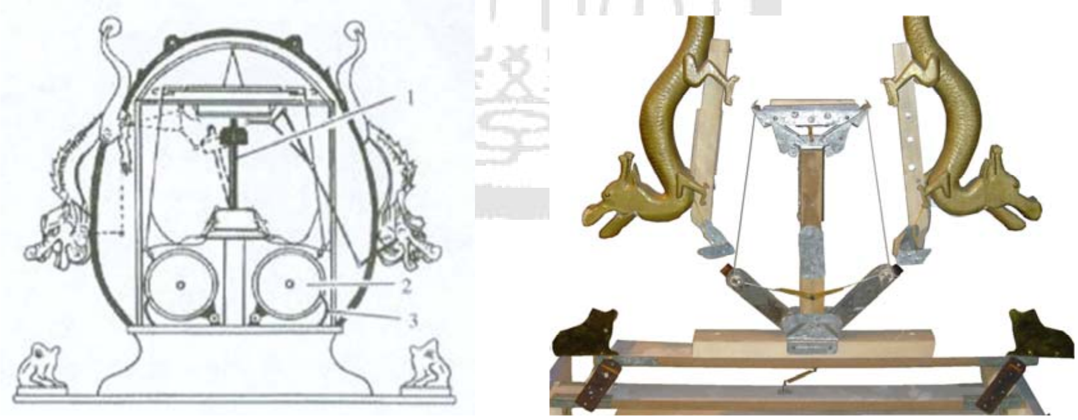


Figure 2-12 Reconstruction design of Zhang Heng’s seismoscope by Wang Jian (1991) [06]

In 1994, the Chinese scholar Lee Zhi-chao (李志超) proposed a reconstruction design of Zhang Heng’s seismoscope [15], Figure 2-13. In this design, *du zhu* is a cylinder with eight small balls below. Once the shake comes, *du zhu* can move in the inside plane of the instrument to press the nearby lever mechanism. The ball in the vessel will fall after the linkage mechanism functions.

Figure 2-13 Reconstruction design of Zhang Heng’s seismoscope by Lee Zhi-chao (1994) [15]

In 1994, the Chinese industrialist Liang Shao-jun (梁紹軍) built a reconstruction design of Zhang Heng’s seismoscope [06] , Figure 2-14. The mercury container is in the bottom of the instrument to function as a sensing element. Once the shake occurs, the mercury container topples over to force *du zhu* driving the nearby lever mechanism.

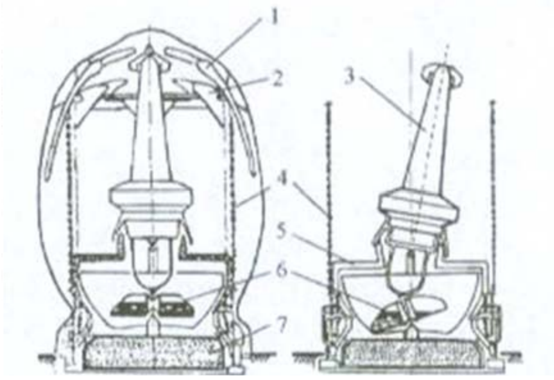


Figure 2-14 Reconstruction design of Zhang Heng’s seismoscope by Liang Shao-jun (1994) [06]

In 2006, the Chinese seismologist Feng Rui (馮銳) and his colleague reported and built a reconstruction design of Zhang Heng’s seismoscope, Figure 2-15 [16]. In this design, *du zhu* is a suspended pendulum to function as the sensing element. The inner structure consists of five components named zhu (柱, pendulum), guan (關, ball below pendulum), dao (道, channel), ji (機, lever mechanism), and wan (丸, ball in dragon’s mouth). The seismic wave shakes the pendulum, the ball below the pendulum moves in one of eight channels to press the lever mechanism. The linkage mechanism opens the dragon’s mouth and the ball in dragon’s mouth falls into the toad below.

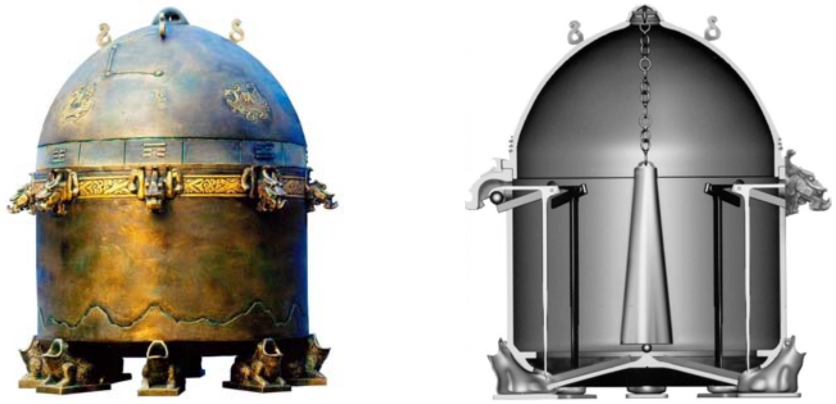


Figure 2-15 Reconstruction design of Zhang Heng’s seismoscope by Feng Rui et al. (2006) [16]

After reviewing the historical development of Zhang Heng’s seismoscope, it is also important to realize the technique standard of ancient machinery. Ancient Chinese devices and machines were extremely intricate and with various mechanical elements and mechanisms, such as, linkage mechanisms, rope-and-pulley mechanisms, cam mechanisms, gear mechanisms, and flexible mechanisms etc. Among them, linkage and rope-and-pulley mechanisms are the most possible to form the detecting mechanism of Zhang Heng’s seismoscope.

Ancient China has a very long history on the use of the linkage mechanisms and rope-and-pulley mechanisms [08, 17-19]. But it is hard to trace their exact using dates via the literature and artifacts. The developments of linkage mechanisms and rope-and-pulley mechanisms were from simple to complex. It also shows the close relationship of our daily life and machines, such as agricultural machines, weaving machines, and handicraft machines. In the following, the historical development of linkage mechanisms and rope-and-pulley mechanisms are introduced via their applications.

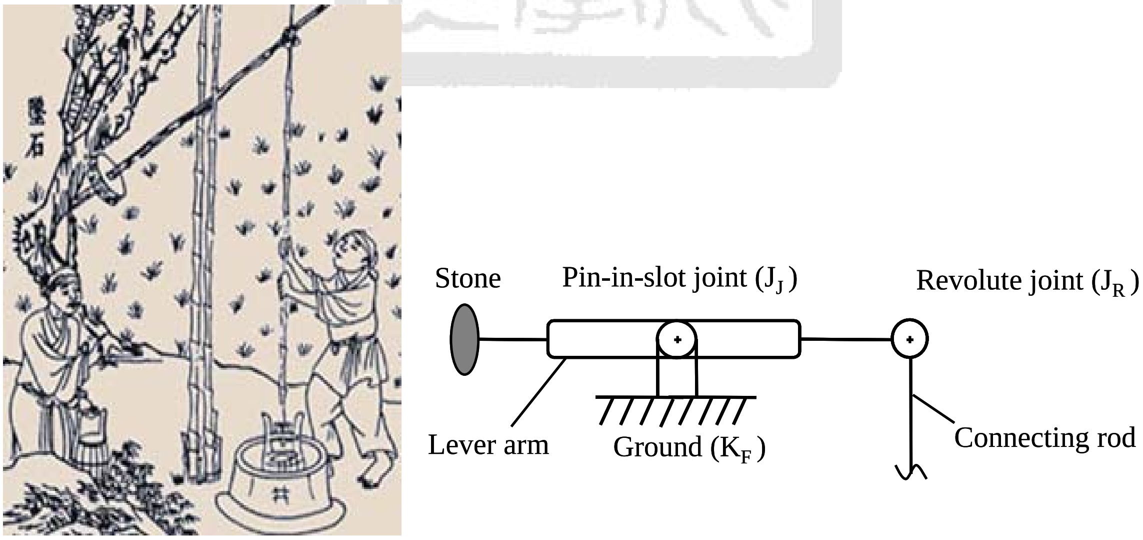
2-3 Linkage Mechanisms

The earliest application of levers may by found during the Old Stone Age in order to save labors and work efficiently. The book Mohist Canon《墨經》[20] developed during the Spring-Autumn Period and the Warring Period (春秋戰國時代, 770-221 BC) was the earliest book to explain the principle of the lever. This understanding of the lever has promoted the good use in the making of crossbow triggers. Another application of levers in ancient China was the weighing balance (權衡) that composes of a measuring weigh and a balancing lever.

In the beginning of the application of linkage mechanisms, it was only a simple crank or link, but later, links were interconnected to form linkage mechanisms to boost work efficiency. Furthermore, the term lian gan (link, 連桿) is seldom seen in ancient manuscripts; instead, qu bing (crank, 曲柄), gang gan (lever, 槓桿), or hua jian (slide, 滑件) are common. They are all referred to as the “link” today.

Jie Gao (桔槔) --- Lever mechanism

The oldest and simplest linkage mechanism for lightening the human labor of dipping, carrying, and emptying buckets was a device named Jie Gao (a lever mechanism). This design was familiar before the Qin Dynasty (秦朝, 221-206 BC) in ancient China, and it has been continuously used until the present day. It uses the lever involving a rotary motion. A lever arm is supported near its center, weighted with a stone at one end, and loaded by a bucket at the other end [21], Figure 2-16(a). The corresponding lever mechanism (Jie Gao) consists of a connecting rod and a lever arm, Figure 2-16(b). The joint between the lever arm and the ground link is a pin-in-slot joint. The lever arm can slide and rotate around the ground link.



(a) Jie Gao [21]

(b) Lever mechanism

Figure 2-16 Structure of Jie Gao (a lever mechanism)

Man-powered Mill

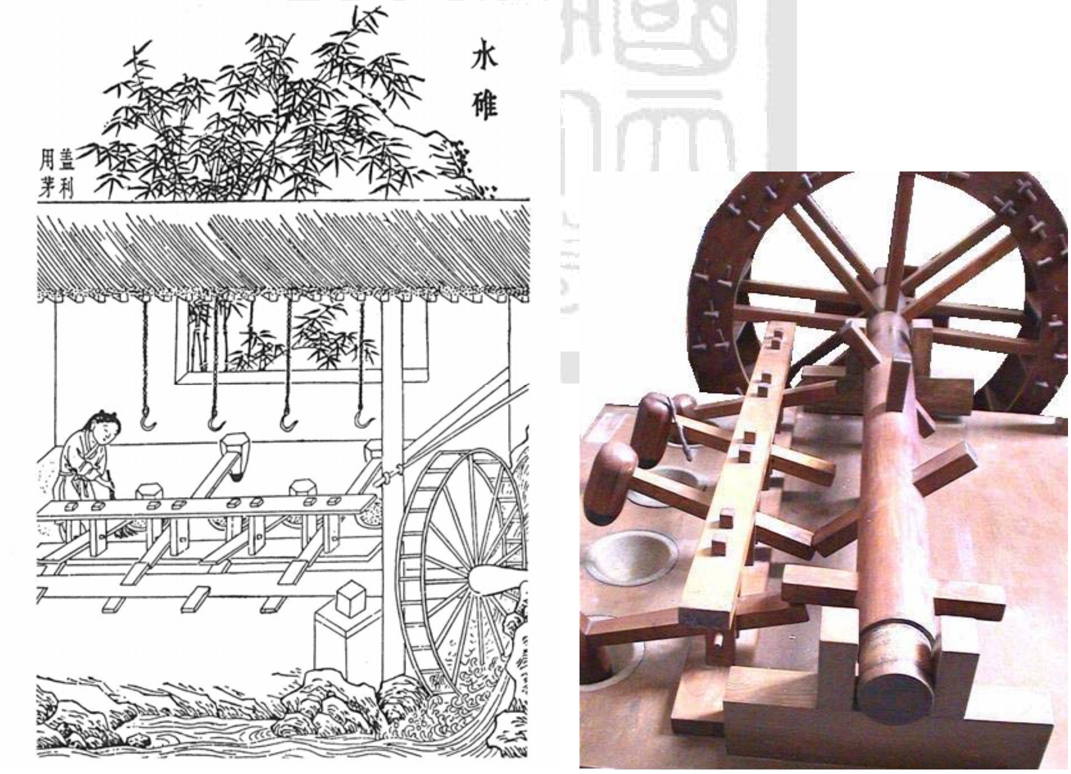
A mill is a device for removing rice hulls [21], Figure 2-17. The books Tian Gong Kai Wu《天工開物》[21], Nong Shu《農書》[22], and Nong Zheng Quan Shu《農政全書》[23] have records and illustrations of this device.

The man-powered mill is a crank-linkage mechanism, which is an assembly of two ropes, a horizontal rod, a connecting link, a crank, and a grinding stone. One end of the rope is secured to the three-legged rack and the other end is attached to the horizontal rod. The connecting link and the horizontal rod move in parallel with the ground as one assembly and it drives the crank to rotate. The crank and the grinding stone on the top of the mill is another assembly. During operation, the operator uses both hands to push the horizontal rod back and forth with slight swaying. This causes the mill to operate continuously to remove the rice husks.

Figure 2-17 A man-power mill [21]

Water-driven Tilt Hammers

The scholar Huan Tan (桓譚) in later Western Han Dynasty wrote a book entitled Huan Zi Xin Lun《桓子新論》[24] which records a water-driven tilt hammer that “… used water to pound, the benefit was hundred times ...”『… 役水而春，其利乃且百倍…』. The complex connected water-driven tilt hammers appeared as early as the Jin Dynasty (晉朝, 265-420 AD). Jin Fu-chang's (晉傅暢) book Jin Zhu Gong Zan《晉諸公讚》[25] states that "Du Yu (杜預) and Yuan Kai (元凱) constructed connected water-driven tilt hammers." 『杜預元凱作連機水碓』. There are also many records of connected water-driven tilt hammers in literature of the later periods. The connected water-driven tilt hammers described in book Tian Gong Kai Wu《天工開物》[21] is a typical simple linkage mechanism, Figure 2-18(a). Figure 2-18(b) is a reconstruction design of water-driven tilt hammers by Wang Zhen-duo (王振鐸) at China Nation Museum in Beijing. It is composed of three members and three joints. The waterwheel is connected to a long shaft with paddles as an assembly. When the water flow moves the waterwheel, its cam causes the tilt hammers to produce work. The long shaft is adjacent to the frame with a revolute joint. The paddles are adjacent to one end of the tilt hammers with cam joints. The tilt hammers are also adjacent to the frame with revolute joints.



(a) [21]　　(b)

Figure 2-18　A water-driven tilt hammers

Foot-operated Spinner

The most elaborate use of linkage mechanisms in ancient China was in spinning machinery, in which levers and links were united with pedals to form complicated linkage mechanisms. The foot-operated spinner was developed based on the hand-operated spinner. Wang Chen’s (王禎) book Nong Shu《農書》[22] records the use of foot-operated spinner is named cotton thread rack (木棉線架), Figure 2-19. The cotton thread rack is also a type of crank linkage mechanism, which is an assembly of a pivot, a pedal, a crank, and a big rope wheel. One end of the pivot is secured to the machine, while the other end is adjacent to the foot pedal with a spherical joint. The other end of the foot pedal is also adjacent to the crank with a spherical joint. The crank is adjacent to the big rope wheel with a revolute joint. When the foot pedal is being stepped on its two sides alternately, the crank rotates the big rope wheel and the machine spins.

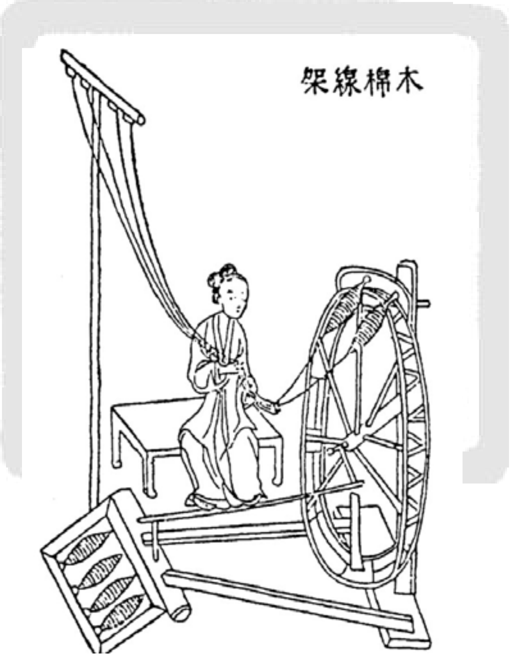
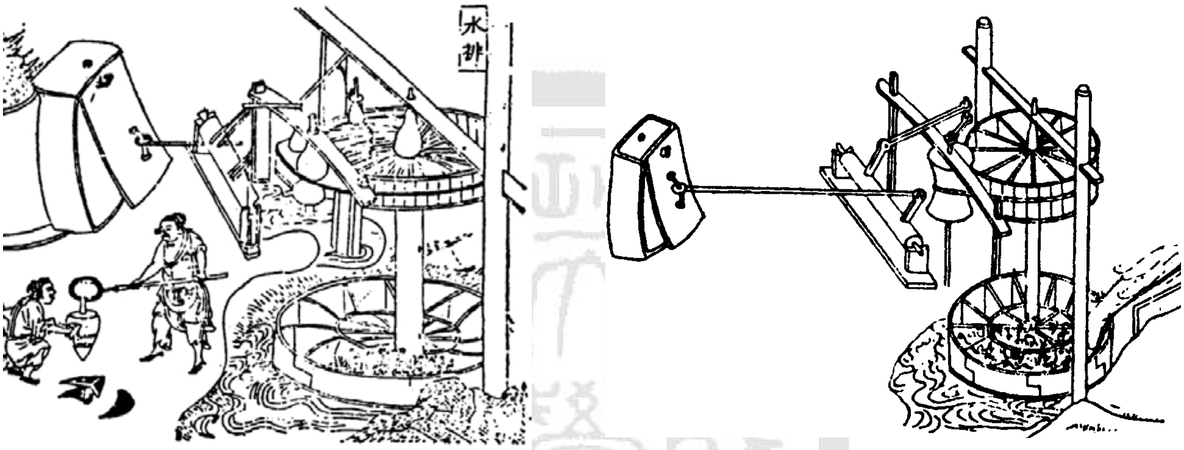


Figure 2-19 A foot-operated spinner [22]

Water-driven Wind Box

In a traditional wind box, water was used as the motive force that was transmitted through linkage mechanisms to move the fan. The earliest record of water-driven wind boxes is found in the Biography of Du Shi (杜詩) in the later Han Dynasty《後漢書・杜詩傳》[05], which claims that “on the seventh year of Jian Wu (建武七年，31 AD) during the

Eastern Han Period, an official of Nan Yang, Du Shi, constructed a water-driven wind box … doing more work with lesser effort. It was a convenience to the people.” 『建武七年，南陽太守杜詩，造作水排 … 用力少而見功多，百姓便之。』 The illustration of a horizontal-wheel water-driven wind box in Wang Chen’s (王禎) book Nong Shu《農書》[22] is not clearly, especially the linkage mechanism for the transmission of motion and power, Figure 2-20(a). Though Liu Xian-zhou (劉仙洲) redrew this illustration, Figure 2-20(b) [17], it is still not easy to realize the topological structure. This is also one major difficulty in the study of ancient machines. From a practical standpoint, this machine’s movement should be restricted with the big rotating water wheel as the input and the swaying fan as the output.



(a) [21] (b) [17]

Figure 2-20 A water-driven wind box

2-4 Rope-and-pulley Mechanisms

In ancient China, ropes were initially used in the New Stone Age over 4000 years ago. During the Shang Dynasty (商朝, 1600-1100 BC), ropes was used in pulley blocks, agricultural machines, and weaving machines for transmitting force. On the other hand, a pulley which is a grooved rim used to retain a rope or cord wrapping on it was used in China from very early times. The application of rope-and-pulleys had been described in the early historical archives including the books Mohist Canon《墨經》[20] and Li Ji《禮記》[26].

Lu Lu (轆轤) --- Winch

A popular mechanism with a rope-and-pulley was the winch, which was used to draw water from wells [21], Figure 2-21. This design was familiar before the Qin Dynasty (秦朝, 221-206 BC) in ancient China, and it has been continuously used until now. The rope is coiled around a drum, the bucket was counterweighted, and the drum is turned by a crank. It should be noticed that because the radius of rotation of the crank is greater than that of the drum, this device could provide the function of force magnification.

Figure 2-21 An ancient Chinese winch [21]

Weaving Machine

The evolution of force transmission devices using ropes in the machine was closely related to the development of weaving technology in ancient China. Primitive weaving technology, which was developed from the lashing craft, was already widespread during the New Stone Age. In the beginning, weaving method involved twisting fibers section by section. Until the Fang Zhui (紡墜, a spinning device) was developed, the weaving method was improved to be able to twist and ply. After, the spinner, a weaving machine came after the Fang Zhui, represented a fully developed weaving technology.

Force transmission by sling was often seen in weaving machines of ancient China. In the beginning, the spinner was single-spindle and hand-driven. The main parts were a crank, a rope wheel, a sling, and a spindle. Figure 2-22 [08] shows a picture of the spinner from the wall painting inside a tomb from the Han dynasty. It is a hand-driven single-spindle spinner. The crank is used to rotate the rope wheel, the sling, and the spindle shaft. In this way, the spindle can be turned at a high speed to spin the thread.

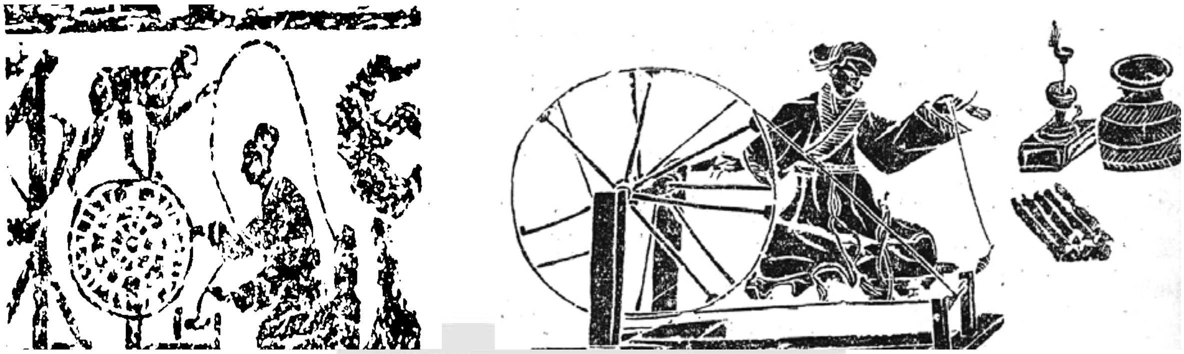


Figure 2-22 A spinner [08]

The single-spindle spinner was evolved into the multiple-spindle spinner and the large spinner, Figure 2-23. The earliest record of the spinner can be found in book Nong Shu 《農書》[22]. The force transmission mechanism of a large spinner is divided into two sections. One is the spindle transmission and the other is the reel transmission. Bamboo wheels are installed on both sides of the machine, and they are connected by a belt made by animal hide. The lower end of the belt directly weighs down on the spindle rod. When the master wheel on the left side rotates, the friction between the belt and the spindle shaft will cause the spindle to rotate. The transmission of the reel is dependent on the relative motion between a pair of perpendicular wooden wheels and the sling. The friction from the upper end of the belt will cause the small rotary drum in the right bottom side rotating, and then the sling will cause the rotary drum on top rotating, too. The speed ratio of these two rotary drums will affect the speed of bast twisting. Using force transmission from two sections of sling, the spindle and reel are able to rotate at a specific speed.

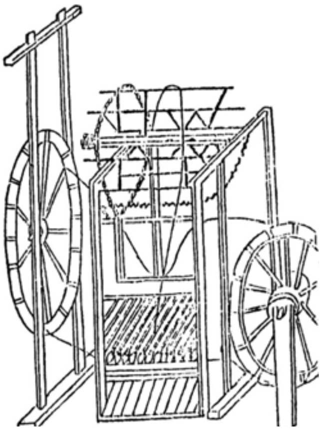


Figure 2-23　A large spinner [22]

Cow-driven Well-drilling Rope Wheel

A mechanism called the cow-driven well-drilling rope wheel was used in salt well mining in Si Chuan (四川) Province during the Ming Dynasty (明朝, 1368-1644 AD). This mechanism performs its functions relying on pulling movement and force transmission by using the sling. The book Tian Gong Kai Wu《天工開物》[21] states that “A Jie Gao, pulley block, and other tools were installed at the mouth of the well. A cow was tied and connected to the wheel. As the cow moves, the wheel turns and pulls the pulley block. Water was then drawn from the well.”『井上懸桔槔、轆轤諸具，置盤架牛，牛拽盤轉，轆轤絞纏，汲水而上。』, Figure 2-24. Therefore, the power used to rotate the big rope wheel is produced by the cows. One end of the rope passes through a stator and a pulley block and is tied to the drilling tool. The tool is lifted as the cow drives the big rope wheel.

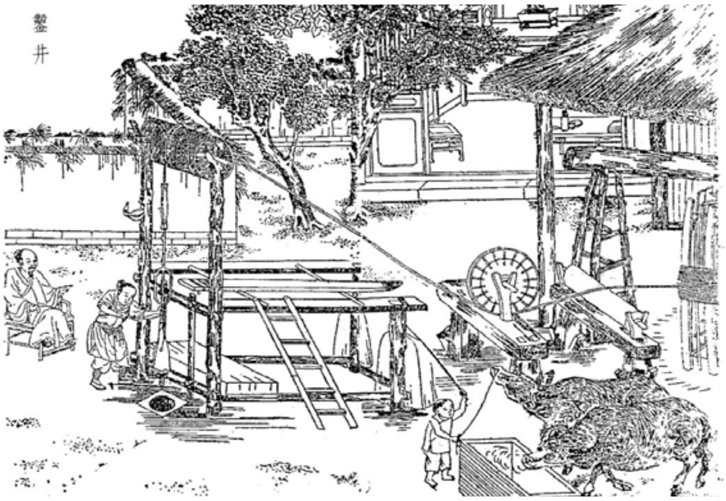


Figure 2-24　A cow-driven well-drilling rope wheel [21]

Sling-powered Grinding Machine

Ancient Chinese grinding machine for jade stones all used rope or belt for transmitting force and movement, Figure 2-25 [21]. The grinding wheel is placed on a horizontal axle, and both ends of the axle are attached to the bearings. Each side of the grinding wheel is with a rope or belt, whose upper portion is attached to the axle. The ropes or belts are coiled in a few circles around the axle on an opposite direction. The lower portion of the ropes is attached individually to two foot-paddles. Stepping alternately on the foot paddles causes the grinding wheel rotating back and forth. The jade stone is then brought to the grinding stone for processing.

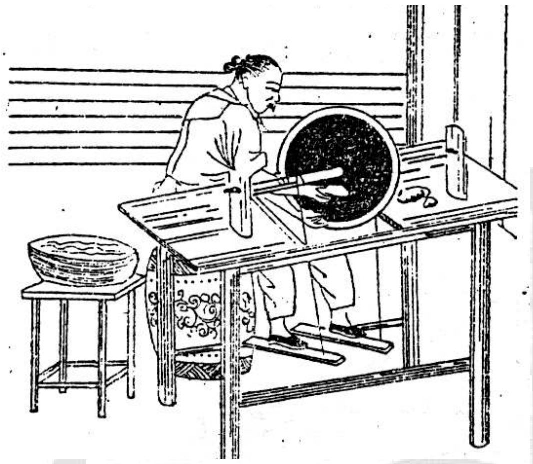


Figure 2-25 A sling-powered grinding machine [21]

2-5 Summary

The earliest seismoscope named Hou Feng Di Dong Yi (候風地動儀) was invented in ancient China by Zhang Heng (張衡) around the year 132 AD. This instrument was designed to indicate not only the occurrence of an earthquake but also the direction to its source. However, this instrument is with few literary records and without surviving hardware. There were 7 historical archives regarding Zhang Heng’s seismoscope including Xu Han Shu《續漢書》, Hou Han Ji《後漢紀》, and the History of the Later Han Dynasty《後漢書》. These historical records are precious, especially in the external appearance of Zhang Heng’s seismoscope. Nevertheless, the description of the inner structure was too brief for realizing the detecting mechanism. And, it is a major challenge to investigate and reconstruct Zhang Heng’s seismoscope.

In the past centuries, some scholars had tried to reconstruct and build Zhang Heng’s seismoscope. These reconstruction designs were useful for the external appearance of Zhang Heng’s seismoscope. Regarding to the detecting mechanism, most of them used a suspended pendulum or an inverted pendulum to function as a sensing element. Since the detecting mechanisms of these reconstruction designs are too simple, they are hard to achieve the high accuracy and sensitivity as described in historical records.

Ancient China had a very long history on the use of linkage mechanisms and rope-and-pulley mechanisms. But it is hard to trace their exact using dates via the literature and artifacts. The developments of machinery were from simple to complex. It also shows a close relationship of our daily life and machines, such as agricultural machines, weaving machines, and handicraft machines. This understanding should be put to good use in the reconstruction of Zhang Heng’s seismoscope.

Chapter 3 Investigation of Seismology

To most ancient and medieval people (and to some people even today), an earthquake is considered as an act of God, or some other supernatural power, visited on human being as punishment for misbehavior. Until the 19th century, due to the seismologists' efforts and the accurate earthquake instruments emerged, people gradually realized that the actual reason of the earthquake happened is the rock fracture.

Seismology is the study of earthquakes and associated phenomena, it includes a lot of subjects. In the study of seismology, two topics, seismic waves and the ground motion from the initial seismic wave will directly influence the design requirements of Zhang Heng's seismoscope. Hence, the developments of seismology, seismic waves, and first motion including fault-plane solution are discussed in this chapter.

3-1 Developments of Seismology

Seismology is the study of earthquakes, seismic sources, and wave propagation through the Earth. Early societies did not have the benefit of modern technology to gather information in understanding earthquake. They were limited to simple observation of what was occurring at Earth's surface when earthquake happened, and would combine this with guesses about Earth's interior to judge the reason of earthquake.

In the developments of seismology, it is divided into four periods: mythology period, direct observation period, golden period, and modern period, Table 3-1. Each period is conveniently marked by a very large earthquake [27].

Mythology Period

In the mythology period, earthquakes were viewed largely as "acts of God", or some other supernatural power, imposed on human being in retribution for misbehavior. There were some mythological causes in the world, such as, the squirming of a giant catfish beneath Japan, a frog (Mongolia), a hog (Celebes), or an ox (Chinese).

Table 3-1 Four periods of seismology

Period	Time (AD)	Event	Reasons
Mythology period	~1755		
Direct observation period	1755~1897	Lisbon earthquake (Portugal)	The role of rock fracture Seismographs
Golden period	1897~1960	Indian earthquake (India)	Seismic waves Elastic-rebound theory
Modern period	1960~	Chilean earthquake (Chile)	High-speed computer Ban nuclear explosion Plate tectonics

In 1755 AD, Lisbon was one of the most beautiful and largest cities in Europe. However, the Lisbon earthquake caused the deaths of over 60,000 people, an affected area of more than a million square miles, and the catastrophic groundswell. At this time, people started to think the earthquake as the natural phenomena, and the knowledge of the earthquake began to grow gradually but steadily as a result of careful observations.

Direct Observation Period

For nearly a century and a half after 1755 AD was the direct observation period. Underground winds and explosions were the preferred causes of earthquakes in this early period. People had advanced in the knowledge of the earthquake by two important reasons, the role of rock fracture and seismographs. Faulting as the principal cause of earthquakes was accepted gradually, and the idea gained acceptance as evidence collected during the 19th century. However, who first proposed this idea is not definitely known. Understanding of earthquakes was limited to what could be learned by visual observation. It was not until the development of sensitive seismographs toward the end of the 19th century that seismograms became sensitive enough to recognize the various types of pulses that are propagated. In this period, many seismologists were devoted to design and build the more accurate earthquake instruments. In 1875 AD, Filippo Cecchi built the first seismograph in Italy. However, the instrument was not sensitive enough. In 1880 AD, John Milne and his colleagues built the first practical seismograph in Japan. The developments of earthquake instruments will be discussed in Chapter 4.

Golden Period

Between 1897AD and 1960 AD, it was the golden period. Two significant reasons make seismology more complete, seismic waves and elastic rebound theory. Richard Oldham studied the seismograms of the Indian earthquake of 1897 AD, and was the first who correctly distinguished compressional wave (P wave), shear wave (S wave), and surface waves (Love and Rayleigh waves). This identification leaded seismology in a golden age lasting for over half a century. During this period, seismology was the principal tool for exploring Earth's interior. Although it was the interpretation of the seismograms that leaded in this new era of seismology, it was the development of improved seismographs that made it possible. In 1910 AD, Harry F. Reid published the elastic rebound theory through the study of the San Francisco earthquake in 1906 AD. He proposed that the whole crust of the earth is bent elastically under stresses applied in an unknown fashion until the breaking strength of the rocks was reached, at which point they fractured along the old, weak fault, rebounding to a new position. In Figure 3-1, in response to the action of tectonic forces, points A and B move in an opposite direction and bend the line across the fault [28]. Maximum rupture occurs at D and strained rocks on each side of the fault spring back to D_1 and D_2. The resultant sudden displacement was the source of the earthquake vibrations. Today, this idea is still the generally accepted theory of the origin of seismic waves.

Modern Period

Around 1960 AD, three reasons combined to revolutionize seismology again. The Chilean earthquake in 1960 AD can be used as a landmark for the start of the modern era of seismology. The first of these was the development of the high-speed digital computer, which made the solutions possible for treating a variety of problems unsolved before. The second reason arose from the need of a means to monitor a proposed ban on underground testing of nuclear explosions would be different from those of natural earthquakes. To carry out this, large sums of money were made seismic research available, and many scientists were attracted to seismology as a career.

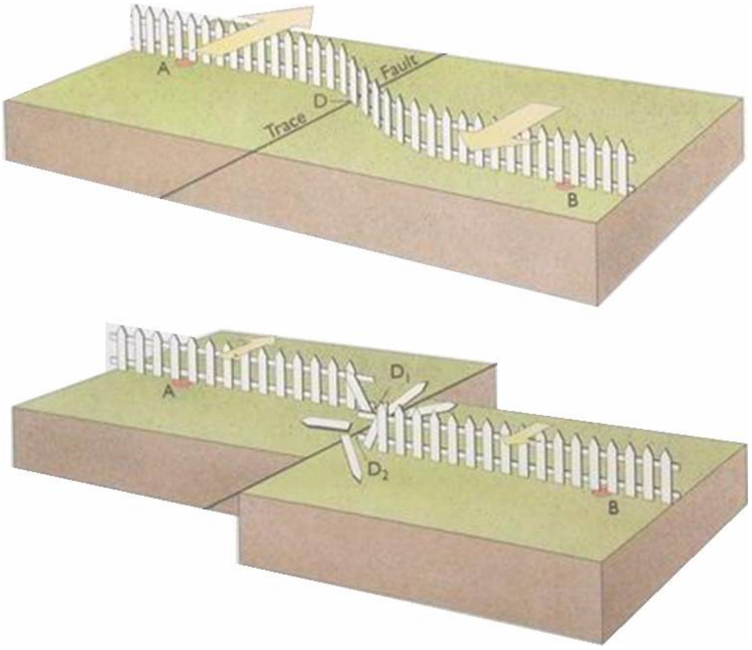


Figure 3-1 Marker lines drawn crossing a fault trace at the ground surface [28]

The Advanced Research Projects Agency (ARPA) of the United Stated Air Force became for a time the principal American agency involved in promoting seismology. ARPA wisely supported a variety of seismic researches, including many fundamental investigations as well as projects that were limited to unclear blast identification. One of ARPA's most important contributions was to provide over one hundred sets of modern, standardized seismographs to cooperate with many observatories distributed all over the world. The resulting seismograms were sent to a world data center from which any interested scientist can obtain copies. This had two effects. Firstly, seismograms could be obtained promptly for any earthquake of interest by contacting a single agency. Previously, one had to write each observatory separately and wait, sometimes for months, to see how much data would be forthcoming. Secondly, and more importantly, the recording instruments were alike in their characteristics, making it easier to compare the ground motions at various locations. The combination of easily obtained good data, funds for carrying out research, and a flood of young investigators resulted in rapid advances in seismic knowledge.

The third development was the rapid acceptance of the theory of plate tectonics after the publication of the papers authored by Robert S. Dietz and Harry H. Hess in 1962-1963 AD [29]. The idea of a mobile Earth's surface consisting of rock plates driven by convection called the plate tectonics. Tectonics refers to the study of the deformation of

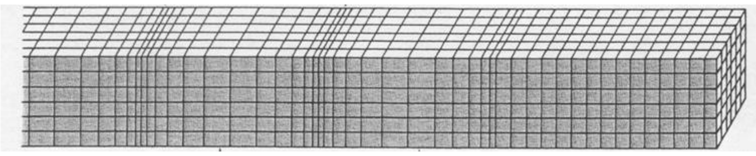
Earth's crust and of the forces responsible for that deformation. The result promotes that a comprehensive model to simulate earth as a heat engine became available by which where and when the earthquakes occur can be explained. It led to rapid advances in not only seismology but throughout the geological sciences.

In the past decades followed by these developments, the nature of seismic research changed. Many data became available, and these data were processed by computers. In advance, data are now fed directly from the seismograph to the computer. Now, the seismic implications of multiple models of earth structure or behavior are developed by computer and are compared with actual observations to select the most likely model. The new understanding of earth processes based on plate tectonics theory has led as to reasonably evaluate earthquake hazard and even to make predictions of earthquakes possible. Eventually, earthquake prediction becomes a national goal for several countries including the United States and Japan.

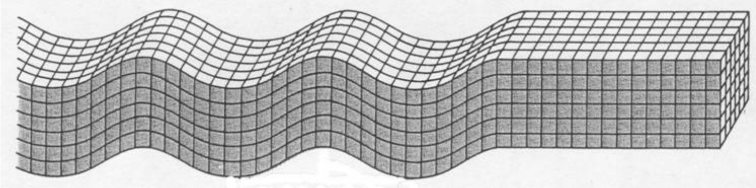
3-2 Seismic Waves

Most earthquakes are caused by the release of elastic strain accompanying sudden displacements on faults from which seismic waves are generated. Seismograph is an instrument that records the ground motion from this release of energy. The resulting seismograms provide information about the earthquake process itself and about the earth materials the elastic seismic waves pass through [28-33]. It is known that rocks, like other solid materials, can behave elastically. They can respond as a rubber band if it is stretched. Once the stretching force is released, the rubber band returns to its original shape. When a wave which represents energy and force, travels through rock, the rock deforms elastically by only a small amount. Thus, the seismic record of this event can be produced. And, the wiggle on a seismogram can be studied by applying elastic wave theory.

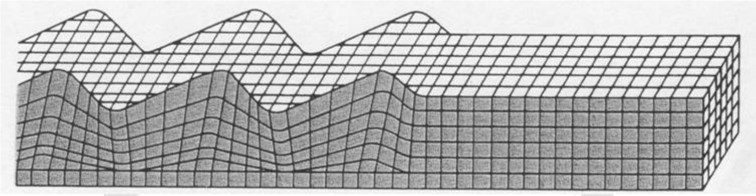
Elastic wave theory predicts that in homogeneous solids two types of waves can be transmitted. One is a compressional wave namely P wave that compresses and expands the elastic solid in the direction of travel of the wave, Figure 3-2(a). The direction of P wave travel is the same as the direction of the earthquake. The compressional wave is followed by slower waves named S wave, which pushes material from side to side, out of the



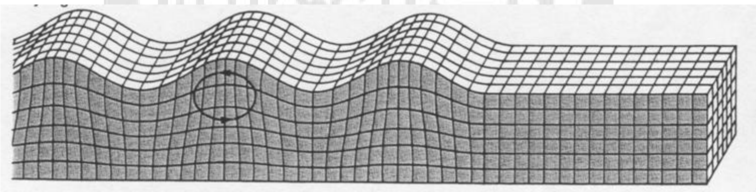
(a) P wave



(b) S wave



(c) Love wave



(d) Rayleigh wave

Figure 3-2 Four types of earthquake waves [28]

direction of the wave path, Figure 3-2(b). These two waves were recognized on seismograms by seismologists as the primary compressional waves, and the slower traveling secondary waves.

P wave is like sound wave that is simply compressional wave traveling through the air. This fact explains why observers hear low rumbling sounds associated with earthquakes. When P wave reaches Earth’s surface, some of the energy enters the air above the ground and becomes a sound wave. As the wave enters the air, the velocity drops because velocity of seismic wave is governed by the properties of the material it is traveling through. The decrease in density of material results in the decrease in velocity. For example, P wave traveling through rocks near the surface may have an average velocity of about 4.5 kilometers per second. But in the air, the equivalent sound wave will be traveling at the speed of sound, or about 0.3 kilometers per second.

S wave velocity is likewise affected by the density and elasticity of material the wave travels through. S wave distorts the medium through which it passes by changing the shape of the material. As the wave passes, elastic rebound restores the shape of the material. The stronger the rock, the more quickly the restoration occurs, and the faster the wave moves. Liquids have no strength, so S wave will not propagate in liquids or gases.

Waves traveling along Earth’s surface had been predicted before the advent of seismographs. The British mathematicians A. E. H. Love and Lord Rayleigh had predicted the existence of surface waves through application and development of elastic-wave theory. The conditions for the existence of the Love wave are more restrictive. Love wave can only be generated where layered rocks exist and where the surface layer is lower velocity material than that beneath it, Figure 3-2(c). Since Love waves generated by earthquakes are observed on seismograms, this is proof that the interior of Earth has layers separated by distinct boundaries. The Love wave displaces material like the S wave, moving rock material from side to side perpendicular to the wave path. However, the Love wave is horizontally polarized, that is, rock material is displaced only parallel to Earth’s surface. In the other hands, Rayleigh wave can be generated along Earth’s surface and moves rock material in an elliptical pattern with both vertical and horizontal components of motion, Figure 3-2(d). In generally, the amplitudes of surface waves are larger than body waves. The calamities of earthquakes are usually caused by the releasing energies of surface waves.

During 1890s seismographs had been designed that could routinely detect and record waves from larger distant earthquakes. Owing to the efforts of John Milne, seismograph stations had been established by 1900 AD on all continents except Antarctica. There were 16 stations regularly to send records to England where the data from this worldwide network were being catalogued and evaluated. The collection of the data allowed the construction of a basic earthquake location tool, namely the travel time chart. This chart is a plot of the travel time of seismic waves against distance from the earthquake. Milne plotted the time of arrival of the phase of the maximum amplitude at each station against the distance of the station from the known epicenter. The known epicenter location was usually determined from felt reports of observers.

In 1900 AD, Richard Oldham was the first to plot and correctly identify the P wave and S wave. Figure 3-3 shows several seismograms of the same earthquake as recorded by

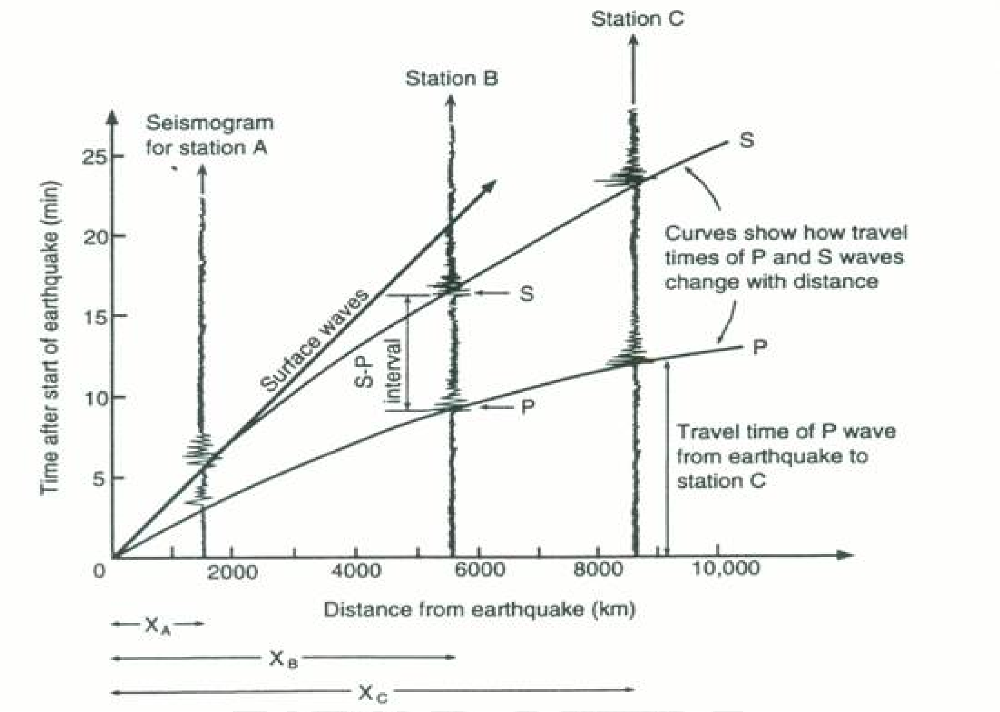


Figure 3-3 Travel time chart [31]

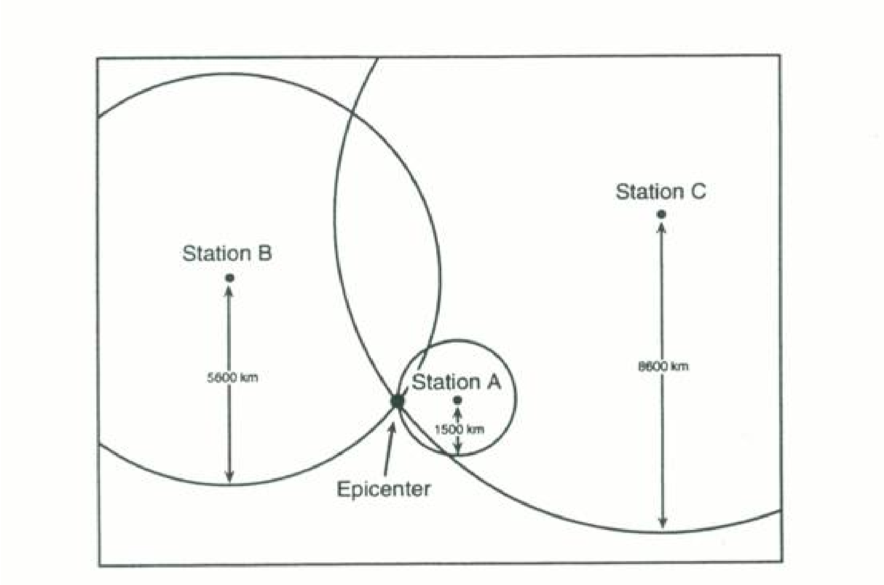
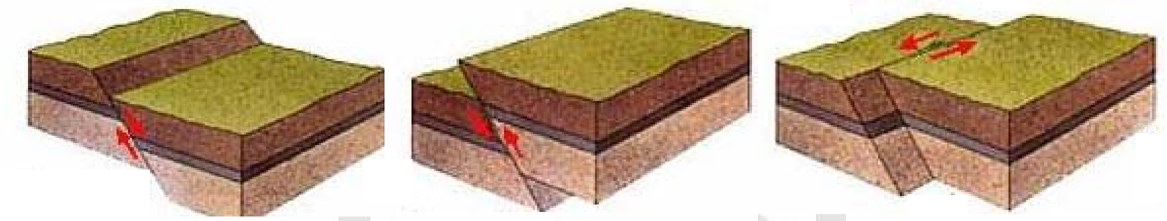


Figure 3-4 Determined epicenter by three stations [31]

seismographs located at A, B, and C [31]. Through the use of the travel time chart and records from at least three stations, it became possible to locate earthquakes by a method similar to triangulation in surveying. The time interval between the passage of the P wave and that of the S wave allows the calculation of the distance between the seismograph and the earthquake, because the speed of P wave and S wave are known. Figure 3-4 shows on a map as the radius of a circle with seismograph at the center [31]. The earthquake is located where the three circles intersect.

3-3 Fault-plane Solution

Most of the earthquakes are related to movement along faults. A fault is a shear fracture. The rock on one or both sides of the fracture surface will have slipped along it. There are three basic types of faults, such as, normal due to tension, reverse due to pressure, and strike-slip fault due to shear, Figure 3-5.



Normal fault Reverse fault Strike-slip fault

Figure 3-5 Three types of faults [28]

The key breakthrough in understanding earthquake had been the realization by the beginning of the 20th century that a cause-and-effect relation existed between faults and earthquakes. This relationship was further documented and detailed by development of the elastic rebound theory as a result of the 1906 AD San Francisco earthquake. The San Francisco earthquake had been natural laboratories for the study of the earthquake process. Thousands of earthquakes occur throughout the world each year that could provide large information for the earthquake process, but they are usually too deep below Earth’s surface for direct observation. A tool was needed that would allow such events to be analyzed. By 1920s, it was becoming clear that such a tool might have its basis in the earthquake seismogram itself.

An important aspect of analysis of earthquake records was the first arrival of the P wave. The motion of the ground from the initial P wave arrival is known as the first motion. Ideally, for an explosion, the ground motion would be up in response to the outward pulse of the compressive shock wave [32], Figure 3-6. However, for an earthquake, Earth’s surface can be either up or down as indicated by movement of a vertical component seismometer. That is, Earth’s surface is forced to move up and away from the earthquake focus or move down and close to the earthquake focus.

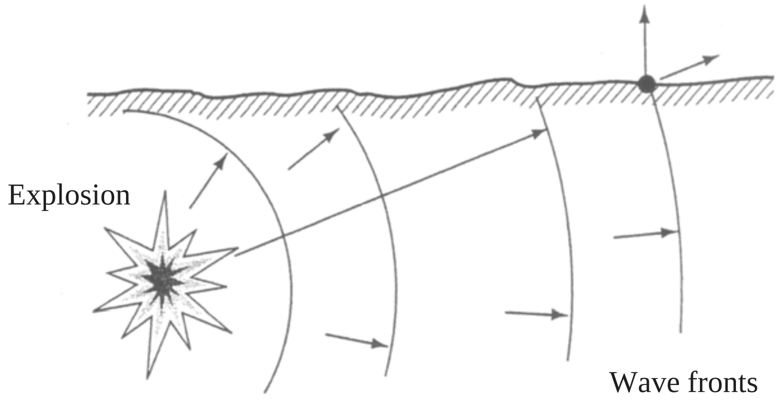


Figure 3-6 Wave fronts of explosion [32]

The seismograph can be distinguished between a wave where the first motion is a compression and a wave where the first motion is an expansion. Seismologists recognized that lines could be drawn on a map of local earthquakes separating regions of upward and downward first motion of the ground. The first motion can be separated into quadrants or quarter spaces by two lines on a map. In Figure 3-7, if the seismograph is in the southeast or northwest quadrant with respect to the source, the first motion of a P wave would be a compression, in which the record signal would be an upward displacement. However, if the seismograph is in southwest or northeast quadrant, the first motion would be an expansion, in which the record signal would be a downward displacement.

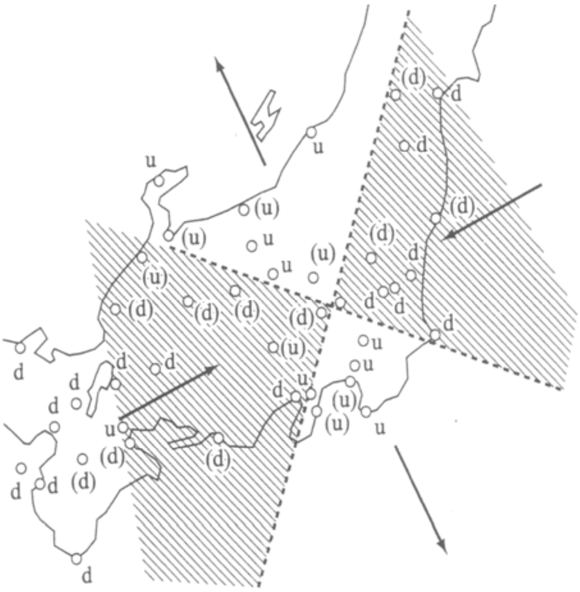


Figure 3-7 Map showing local earthquake separating regions [32]

The first motion plot of P wave arrivals on a map is a clue to explore the type of fault of an earthquake. Through comparing the quadrantal first motion pattern with the already existing concept, earthquakes and faults are related. Clearly a fault can be represented as a line on a map. So it is extremely possible that one of the two perpendicular lines defines the quadrants and represents the trace of the fault of the earthquake.

However, there are two problems with such map plots. First, which line represents the fault plane? This is an inherent problem in this type of analysis. The first motion data cannot determine which line represents the fault plane. Second, is it only valid for local/regional earthquakes where focus-to-station distances are relatively small? This problem comes because seismic wave paths curve within the Earth. This produces a distortion of the source first-motion pattern at Earth's surface. If fault planes are chosen for distant earthquakes, the locations of theses lines at the surface would differ from the correct projected traces.

The challenge was to try to eliminate the problem of the curved seismic wavepath. An easier visualized projection technique is called the stereographic projection. The technique has the effect of eliminating curved wavepaths. The stereographic projection is carried out by considering only the region around the focus. It is possible by centering the plot in the source region rather than at Earth's surface. Instead of a map, the plot device is a sphere centered on the focus and is known as the focal sphere. The first ground motion of P-wave at each station is plotted on the sphere’s surface. This stereographic technique is a projection of the ground motion back along the wavepath to the focal sphere. The direction of the first motion does not change between the focus and Earth’s surface.

Since the arrivals of P wave at stations from distant earthquakes represent the wavepaths that leave the focus traveling downward, only the lower half or hemisphere of the focal sphere is necessary to be plotted, Figure 3-8. This is transformed into a more manageable and useful two-dimensional representation of the hemisphere by the stereographic projection technique as mentioned above. With this transformation, points and lines are projected onto a two-dimensional plot surface tangent to the bottom of the hemisphere.

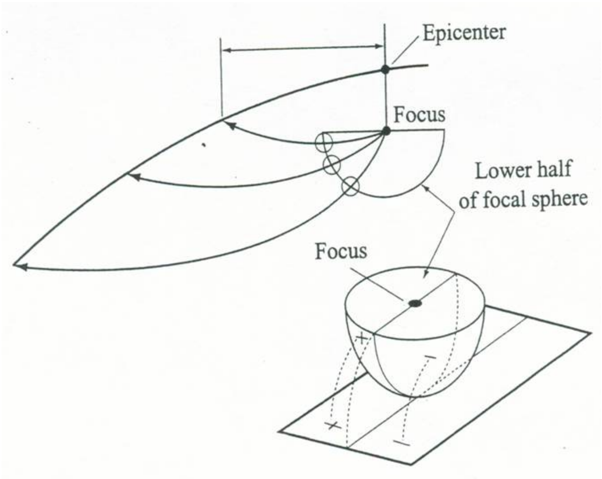


Figure 3-8 Two-dimensional plots of first motion and nodal planes [32]

Because the focus of the earthquake lies at the center of the focal sphere, all wavepaths must also originate over there, and the two perpendicular planes, known as the nodal planes including one fault plane, also center on the focus. All planes in the corresponding stereographic projection are represented as great circle lines or traces. This is similar to the lines of geographic longitude on Earth’s globe, which are also the surface traces/lines that represent the intersection with the planes of the Earth that pass through the center of Earth.

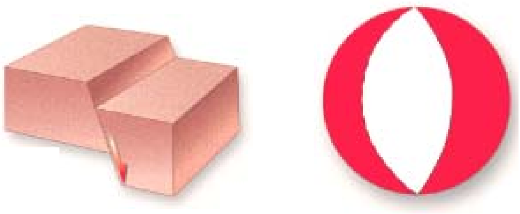
The interpretation of the stereographic plot is straightforward. On the two-dimensional projection, surface is seen the plot of points (station motions) and lines that represent nodal planes. The points are the intersection of P wave paths with the surface of the hemisphere. Each point is represented by a symbol indicting either up (compression) or downward (expansion) movement of the ground, which corresponds, respectively, to outward or inward movement of the focal region.

The lines in the projection of the surface of the focal sphere are the great-circle traces of the intersection of nodal planes with the sphere surface. One of these planes must be the fault plane, the other the so-called auxiliary plane, which is perpendicular to the fault plane, the stereographic projection of the focal region including the points of compression and expansion. And the nodal planes are known as the fault-plane solution.

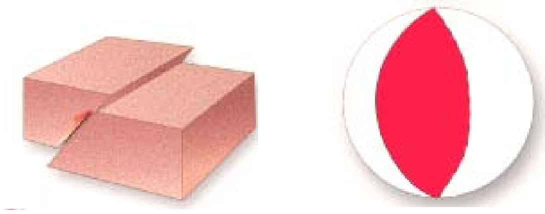
An alternate representation of the fault-plane solution is the “beach ball” display. Instead of representing each station’s motion at a point on the focal sphere, the quadrants created by the two perpendicular nodal planes are represented [28]. By convention, the compressional quadrant is usually colored or shaded in, and the dilatational quadrant is left blank. This makes for a more visually effective diagram, especially when large numbers of stations are used in a solution, or when large numbers of fault-plane solutions must be displayed in a diagram.

Three kinds of beach balls will be resulted if the fault motion is either pure dip slip, or pure strike slip. These three beach balls would then correspond to the three basic kind of faulting: normal, reverse (or thrust), and strike slip, Figure 3-9. Note that for normal faulting the central quadrant is unshaded. For the reverse or thrust fault beach ball, the opposite is true: The central quadrant is shaded. The strike slip beach ball pattern is seen as a distinctive checkerboard pattern. If slip is not exactly in the dip or strike directions, but at some angle in between, then a more complex-looking beach ball will result with both normal, reverse, and strike slip components.

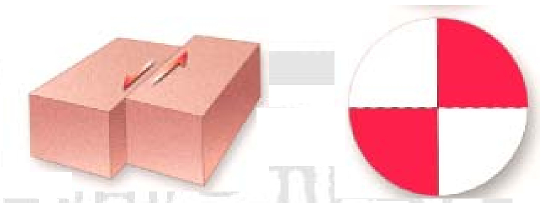
The fault-plane solution technique has been a powerful tool since its inception in the 1920s in understanding earthquakes and faulting. The technique has been checked against earthquakes in which fault-slip directions and fault-plane orientations could be deduced by independent means, such as in cases where faults break the surface and displace the ground. Good solutions based on high-quality data are direct indicators of fault type and fault orientation.



(a) Normal fault



(b) Reverse fault



(c) Strike slip fault

Figure 3-9 Three kinds of beach balls [33]

3-4 Summary

The development of seismology can be divided into four periods, the mythology period, direct observation period, golden period, and modern period. Each period is conveniently marked by a very large earthquake. Based on the seismologists' efforts and the accurate earthquake instruments, people gradually realize that the actual cause of earthquakes is not the supernatural power but faults.

An earthquake can generate seismic waves. There are three kinds of seismic waves, i.e., P wave, S wave, and Surface waves. P wave is the first-arriving wave from an earthquake. 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, which pushes material from side to side out of the direction of the wave path.

Based on the study of seismology, an important keynote for investigating the type of fault can be concluded that the first motion of each earthquake can force the ground motion to move away from or close to epicenter depended on the different locations. Accordingly, as this work intends to reconstruct Zhang Heng’s seismoscope as sensitive as described in the historical records, the instrument must be able to detect the first motion of P wave whether it is compressive or expansive.

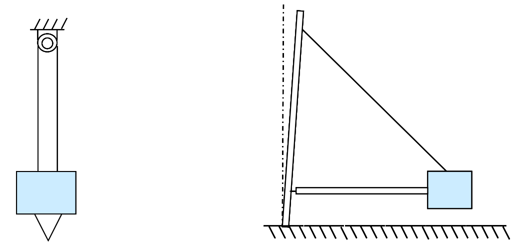
Chapter 4 Development of Ancient Earthquake Instruments

The instrument that produces a chronologic record of ground motion during an earthquake is called a seismograph. The development of measuring and recording instruments to the ground movements during a distant earthquake in ancient times was a truly great intellectual achievement. Many attempts had been made to create earthquake instruments over 1700 years before the true seismographs were developed. In the 18th century, people found the proposals which recorded the times and the character of ground motion of occurred in earthquakes. The most important advance was made in the late 19th century, with the invention of instruments which gave records representing earthquake ground motion as a continuous function of time.

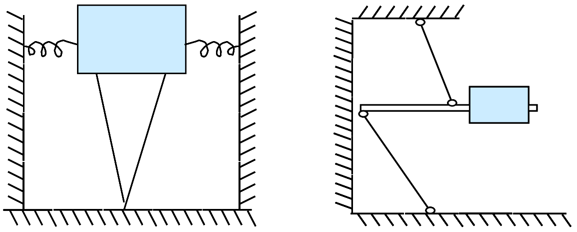
This chapter studies the mechanical structures embedded in ancient seismometers first. The development of ancient earthquake instruments is then focused. Finally, a comparison among ancient seismographs with their recording systems is concluded.

4-1 Ancient Seismometers

A basic seismograph comprises of a seismometer, a recording system, and a timing system. The greatest difficulty in the development of a seismograph was in the design of a seismometer. An early seismometer consisted of three basic components: a sensing member, a magnifier, and a long arm. The advance step in the development of seismometers was the use of a pendulum system as a sensing member that responded to ground motion and not moved with the ground. The sensing member in the seismograph records ground motion that results from seismic waves. The resulting seismograms provide information about the earthquake process itself and about the earth materials the seismic waves pass through. A complete earthquake record includes three-dimensional picture of ground motion, two horizontal seismometers, one oriented north-south and the other east-west, as well as a vertical seismometer. There were four types of sensing member designs in ancient horizontal seismometers, such as common, Milne, Wiechert, and Galitzin pendulums [34, 35], as shown in Figure 4-1.



(a) Common (b) Milne



(c) Wiechert (d) Galitzin

Figure 4-1 Types of the sensing member of ancient horizontal seismometers [35]

A common pendulum has a number of desirable characteristics as a potential seismometer [32]. Two design principles make this a workable seismometer. First, the common pendulum is largely isolated from the ground motion by its suspension design. Second, the mass of the pendulum has inertia, and tends to remain at rest. These two basic principles were utilized in the design of early seismometers. However, the relative motion caused by a distant earthquake would be very small, and various modifications have been made to increase the sensitivity. At first experiments were made with longer pendulums.

A pendulum will oscillate freely when the period of ground movement is close to the period of the pendulum. The free period of a pendulum is directly related to pendulum length by the following formula:

$$T = 2\pi(L/g)^{1/2} \tag{4.1}$$

Where, T is free period of the pendulum in seconds, L is pendulum length, and g is acceleration of gravity (9.8 m/sec^2).

In Equation (4.1), if pendulum length increases, the light side, the period, must also increase. As pendulum length increases, the system responds to longer period ground movement. A grandfather clock typically has a pendulum length of 1 meter so that its period is 2 seconds. Large earthquakes can produce ground movement with a cycle of motion period of 20 seconds. The equation can be solved for corresponding length (L), putting in 20 seconds for T, as follows:

$$L = T^2 g / 4\pi^2 \tag{4.2}$$

$$= (20s)^2 (9.8m/sec^2) / 4(3.14)^2 = 99 \text{ meters}$$

Although long pendulums were used by some Italian scientists in the early days of instrumental seismology, a pendulum of 99 meters long is not very practical. Fortunately, a new design was devised to solve this problem, the horizontal pendulum. The basic principle of the horizontal pendulum is similar to a swinging gate in the fence, Figure 4-2. If the gate post is tiled off vertical, the gate describes an arc that has not only a horizontal component of movement, but also a vertical one. This arc has a very slight curvature, which suggests that it is equivalent to a vertical suspension pendulum with a very long rod length, and thus a very long period. The long period of a vertical suspension pendulum can be achieved with the horizontal suspension design. The extra mass is to remain the pendulum stable and keep the pendulum to its original position after being displaced. When the support follows the earth movement, the seismic waves set up relative movement between the frame and the pendulum. A horizontal pendulum is shown in Figure 4-1(b), the suspension is by a single wire to the arm carrying the extra mass, and the end of this arm nearer the axis has a pivot bearing.

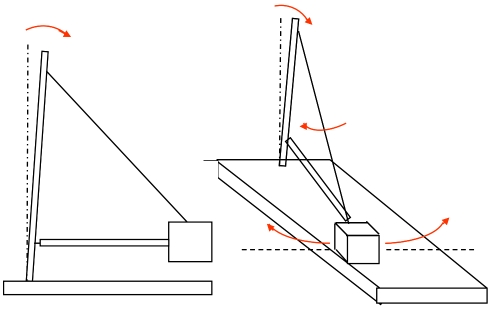


Figure 4-2 Basic principle of the horizontal pendulum [32]

An inverted-pendulum is shown in Figure 4-1(c). The extra mass carried by an upright rod is hinged to the base through two flat springs at right angles to each other, and is free to move in any horizontal direction. The instability of this arrangement can be overcome by connecting the extra mass to the frame by small springs. In the Galitzin type, shown in Figure 4-1(d), the rod carrying the extra mass is supported from the frame by two wires. The wires are arranged such that both are pulled taut by the extra mass.

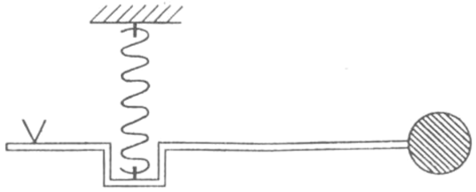
During the 19th century many attempts were made to design an instrument for measuring the vertical movement of the ground. In some of these the mass was carried at the end of a strong horizontal spring projecting from a wall, in some it was suspended from a coiled spring, and in others it floated in a vessel of liquid. None of these instruments were satisfactory on account of the difficulty of obtaining a sufficiently long free period. The problem was solved in 1880 AD by Thomas Gray, who constructed an instrument in which the extra mass is fixed to one end of a lever with the spring attached [34], as shown in Figure 4-3(a), between the fulcrum and the extra mass. To increase the stability of the instrument, Gray attached to the outer end of the bar a hermetically sealed tube containing mercury, which when the bar was depressed ran outwards and increased the load in such a manner as to compensate for the decreased leverage.

In 1881AD, Ewing devised another method of compensation, by attaching the spring below the axis of the lever, Figure 4-3(b); with this arrangement when the spring lengthens, or when the moment of the mass is reduced, the point of attachment moves towards the fulcrum, and vice versa when the spring shortens. These principles have been incorporated in the design of the Galitzin vertical seismometer, Figure 4-3(c). In this instrument the mass is fitted into a triangular support which is hinged to the main framework by crossed springs and carried by the coiled spring.

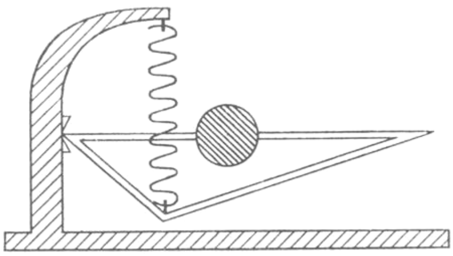
The combined use of horizontal and vertical seismometers has resulted in a complete picture of ground motion directions. Standard practices in earthquake observatories use two horizontal seismometers; one oriented north-south and the other east-west, as well as a vertical seismometer.

One negative characteristic of a pendulum system used as an earthquake sensor is resonance. For a seismometer, the wildly swinging pendulum means that we are only recording the resonant vibration of the system itself, rather than the true motion of the ground. To eliminate the resonance, it is possible to control the pendulum swing, a process called damping. Early seismometers had a paddle fastened to the pendulum, which would be immersed in a container of a viscous fluid. When the pendulum moved, the drag of the paddle through the fluid would mechanically damp the system, eliminating wild swinging of the pendulum.

(a) Gray



(b) Ewing



(c) Galitzin

Figure 4-3 Types of the sensing member of ancient vertical seismometers [34]

4-2 Development of ancient Earthquake Instruments

Early earthquake instruments called seismoscopes were primarily intended to indicate that an earthquake had happened but did not produce a permanent record of it. The first seismoscope invented is Hou Feng Di Dong Yi (候風地動儀) made in ancient China by Zhang Heng（張衡）around the year 132 AD [05, 10]. The instrument was cast with bronze. Its outer appearance was like a jar with an inner diameter of 2 meters. This instrument was designed to indicate not only the occurrence of an earthquake but also the direction to its source. It is believed that Zhang Heng’s seismoscope is based on the principle of inertia.

A seismoscope designed by J. de la Haute Feuille in 1703 contained a central reservoir from which mercury would spill into cups around the periphery if the ground moved [36], Figure 4-4. This seems the first record about earthquake detecting instrument in Europe. Andrea Bina in 1751 proposed a common or clock-type pendulum that was suspended over a tray of sand, so that the pendulum bob could trace a record of ground motion in the sand [37], Figure 4-5. Although the device was built, it is not known if it ever recorded an earthquake. The first well-documented pendulum seismometer must be credited to a British scientist, James Forbes. The basis of his sensing member was an inverted pendulum [36], Figure 4-6. It consisted of a vertical metal rod having a mass C moveable upon it. By adjusting the stiffness of the wire, the free period of the pendulum might be altered. A pencil L placed on the prolongation of the metal rod wrote a record on a stationary, paper-lined, spherical dome. Forbes was the first to describe mathematically the behavior of a seismic instrument in an "earthquake".

A more accurate seismoscope was built in 1855 by Luigi Palmieri in Italy [38]. An electrical circuit was closed when the mercury moved, stopping a clock to indicate the time of the earthquake. A pencil pressed on a rotating drum whenever the electrical circuit was complete, providing a measure of the duration of the shaking, as shown in Figure 4-7. Using the electrical seismic system was unique for its time. This remarkable system possessed enough sensitivity to detect earthquakes imperceptible to human beings. Because of its success in detecting earthquakes, the Palmieri's seismoscope was widely adopted. It remained the premier seismic instrument until it was replaced by improved pendulum seismometers and seismograph systems near the end of the 19th century.

Figure 4-4 J. de la Haute Feuille's seismoscope [37]

Figure 4-5   Andrea Bina’s seismoscope [37]

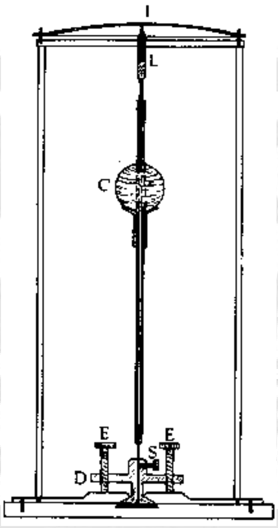


Figure 4-6   James Forbes’s seismoscope [36]

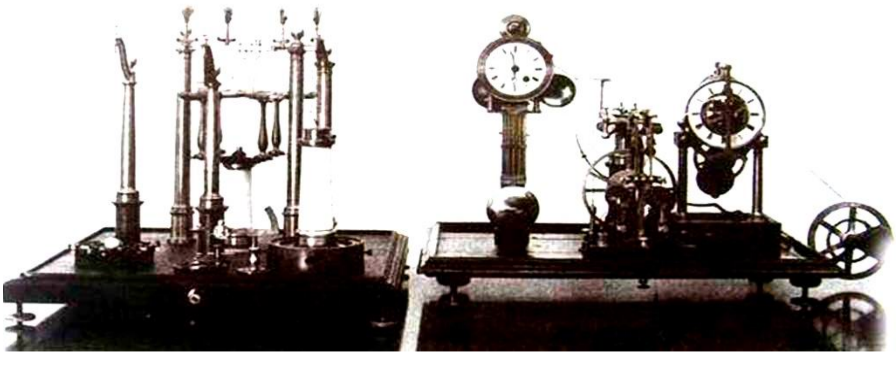


Figure 4-7   Luigi Palmieri’s seismoscope [38]

The first seismograph was built by Filippo Cecchi in Italy in 1875 [36]. Cecchi's seismograph used two common pendulums to measure horizontal motions, one swinging north-south and the other east-west, an orientation still almost always used today. The pendulum motions were magnified three times before being recorded by a rope-and-pulley, Figure 4-8. Cecchi also recorded the vertical component of motion by using a mass suspended by a spiral spring. And, he arranged a seismoscope to start a clock and to start into motion the recording surface at the time of an earthquake. The magnification of Cecchi's seismograph was too small to record any but the strongest shakes. However, the three essential features of all useful seismographs were incorporated in this instrument. It produced a seismogram whose trace deflection was proportional to the amplitude of ground motion. The motions were amplified so that small movements could be studied, and the exact time of the event was recorded.

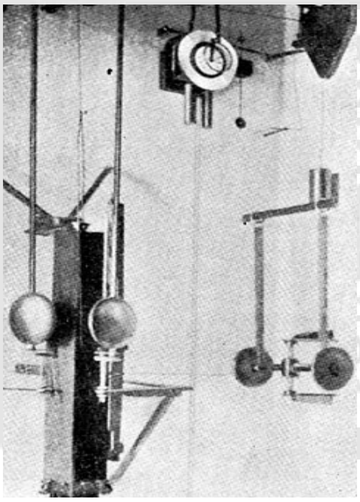


Figure 4-8 Filippo Cecchi's seismograph [38]

The most significant person in developing a practical seismograph was John Milne. In 1876 AD he joined the faculty of the Imperial College of Engineering in Tokyo. There, in association with Thomas Gray and J. Alfred Ewing, they experimented with a variety of pendulum instruments for recording ground motions. The British in Japan made many observations with their instruments and must be credited with first demonstrating the value to seismology of seismographic devices. John Milne in 1894 AD used the horizontal pendulum as a sensing link, as shown in Figure 4-9 [09, 36]. Instead of having light reflected onto photographic paper with a mirror fastened to the pendulum, Milne had light shine onto the paper through the intersection of two mutually-perpendicular slits. One of the slits was fastened to the pier. The other slit was fastened to the pendulum and moved with the pendulum, thus causing the spot of light to move on the paper.

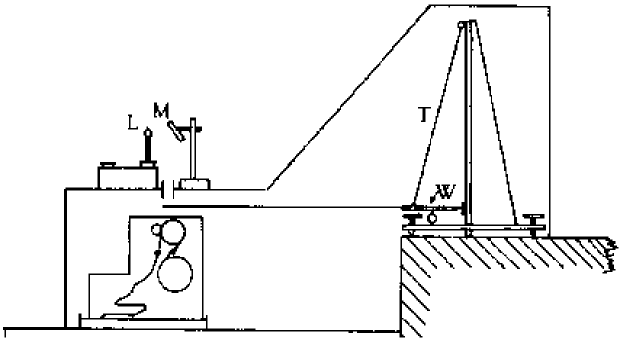


Figure 4-9 John Milne's seismograph [36]

A most dramatic increase of seismological activity in Europe followed the confirmation in 1889 AD that waves from large earthquakes could be detected by sensitive instruments located halfway around the world from the earthquakes' epicenters. The first known recordings of a distant earthquake, which were identified as such, were made in 1889 AD [28, 36]. The instruments were horizontal pendulums, designed by Ernst von Rebeur-Paschwitz to measure slight changes in the direction of the vertical. Two of these pendulums, located in Potsdam and Wilhelmshaven, recorded a large earthquake on April 17, 1889 AD. Figure 4-10 shows one of the first known recordings of a distant earthquake. The earthquake had been felt in Japan about an hour before it was recorded in Germany.

Figure 4-10 First known recordings of a distant earthquake. [28]

Von Rebeur's instrument consisted of a rigid frame, rotating about two bearings A and B, each consisting of a point pressing into a socket, Figure 4-11. To the frame was attached a mirror M, which reflected light from a lamp, through a cylindrical lens, to a rotating drum which was covered with photographic paper. The drum turned 11 millimeters in an hour. Von Rebeur's pendulum was only 10 centimeters long, and carried a mass of only 42 grams. It was usually used with a period of from 12 to 17 seconds and a static magnification of 100. Time was obtained with a second fixed light trace which wrote on the same photographic paper. Every hour, this second trace was eclipsed for five minutes.

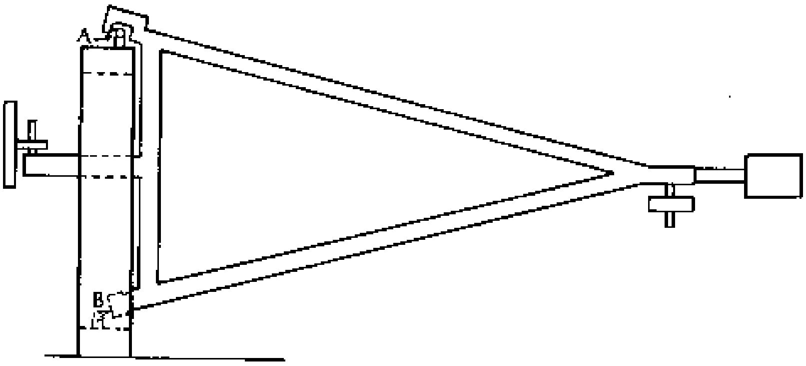


Figure 4-11 Von Rebeur’s seismograph [36]

Emil Wiechert used the inverted pendulum with a viscous damping as a sensing link in 1898 AD [36]. This was an important advance in seismograph design. The accuracy of the seismograph was greatly improved by a viscous damping. The pendulum weight was over a ton. Because of the large inertial mass, Wiechert’s instrument was affected very little by the friction of the stylus on the recording paper. The pendulum was connected to two thrust arms set in directions at right angles. Each thrust arm was connected to a lever which carried a stylus for recording, Figure 4-12. Wiechert’s seismograph recorded a wide spectrum of seismic signals, accurately reproducing ground motions.

Early seismometers and seismograph systems were termed mechanical because they consisted of clever combinations of springs, levers, rods, and masses. Their primary drawback was that they were not very sensitive and could not record distant earthquakes well at all. Some magnification of ground motion could be achieved by means of increasing pendulum length, or adding rods to magnify the arc of a pen swing.

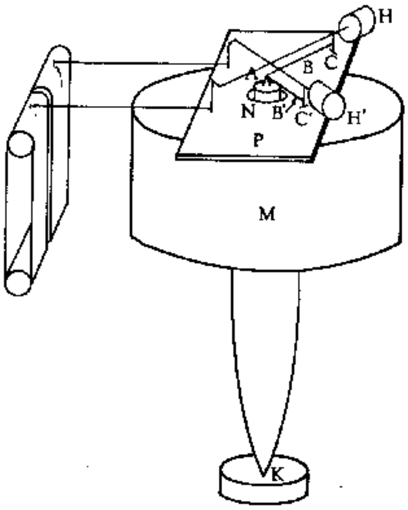


Figure 4-12 Emil Wiechert's seismograph [36]

Despite improvements, the most successful mechanical seismograph system designs were never able to magnify ground motion more than about 2800 times. This may sound like a lot, but a distant earthquake may not move the ground as much as one hundred millionth of a centimeter. So a magnification of up to 2800 times would not allow detection by the early mechanical systems for many worldwide earthquakes occurring each year. A greater sensitivity was necessary for adequate detection. Such sensitivity would not come from mechanical seismograph systems, but from an entirely new kind of system, the electromagnetic seismograph.

The electromagnetic seismograph was a tremendous advance because the resulting instrument could magnify ground motion hundreds of thousands of times. This invention was the result of work by a Russian aristocrat, Prince B.B. Galitzin, who was a physicist turned seismologist. In 1906 AD Galitzin introduced the new method depending on the principle that when a coil of wire moves across a magnetic field electric currents were set up in the wire [09]. Several coils, joined in series and connected to a sensitive galvanometer, were carried by the pendulum and moved between the poles of strong magnets. As the pendulum moved the current flowing through the galvanometer was proportional to the angular velocity of the pendulum. The deflections of the galvanometer mirror were recorded photographically. A set of three Galitzin pendulums is shown in Figure 4-13; the pendulums are suspended in the manner shown in Figures 4-1(d) and 4-3(c). The vertical pendulum is placed between the two horizontal pendulums, and three pendulums are set up at right angles to each other.

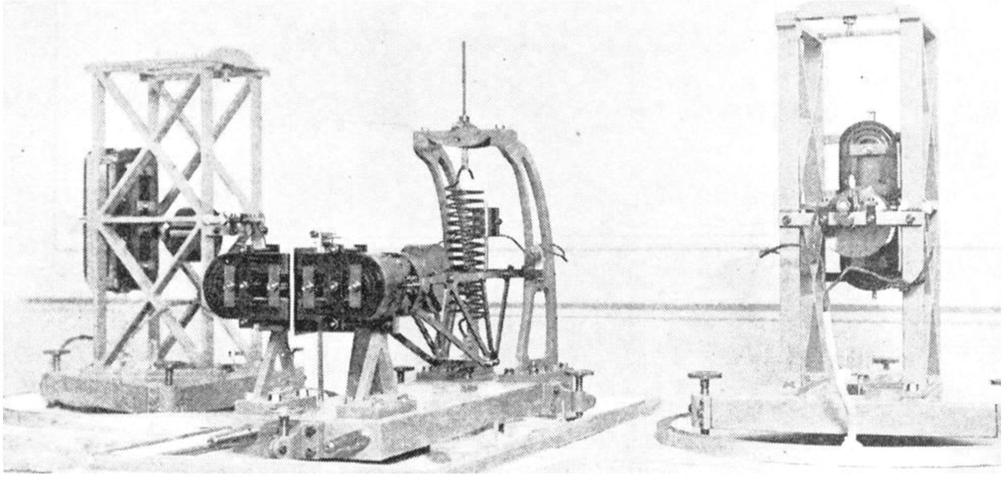


Figure 4-13 Boris Galitzin's seismograph [09]

The application of the electromagnetic principle remains the basis for most modern seismograph systems. An important addition to this is the development of digital recording systems in recent years. A digital recording system is achieved by converting voltages into discrete numbers that represent motion by periodically sampling and recording ground motions as numbers. This can be done automatically and has the advantage that the data are in a much more useful format. Digital data sets representing earthquake ground motion can produce more familiar-looking paper seismogram records directly, or the numbers can be manipulated by computers to select, for example, only certain wave periods, or time intervals, for analysis purposes.

4-3 Comparisons

Devices whose purpose is primarily to determine that an earthquake has happened are called seismoscopes. Early seismograph systems consisted of three major components, named, a seismometer, a clock, and a recording system. The clock provides absolute time. A number of different ways have been devised to put time parks on a seismic record. Early crude mechanical approaches involved a timed physical deflection of the pen on the record. Modern timing systems consist of crystal-controlled clocks calibrated to Universal coordinated Time, which in turn are part of an electrical circuit. The electrical circuit will generate a current at the beginning of each time interval and this current pulse is transformed into a pen deflection with a device consisting of a coil and a magnet, termed galvanometer. As will be seen, time marks indicating absolute time are critical for calculating earthquake locations, wave velocities, and the time of occurrence of earthquakes. Different methods have been used to record earthquake ground motion, such as mechanical, direct optical, and galvanometric registrations.

The pendulum of a seismograph which records mechanically is connected by levers or by a long arm to a scribing point which rests on a smoked sheet of paper. The mechanical registration has one great advantage, for the records are visible while the seismograph is in operation. However, there is an uncertain amount of friction at the pivots of the magnifying levers, and between the scriber and the sheet. The friction between the indicator and the recording surface exerts a greater force on the pendulum accordinly as the mechanical magnification increases. The primary drawback of the mechanical registration is not very sensitive. There exists a limit of magnification, above which the inertia of the pendulum cannot overcome the frictional forces between the indicator and the recording surface.

In direct optical registration, a beam of light is reflected from a mirror usually connected to the pendulum, and focused on to a moving sheet of photographic paper. The light beam serves as a long weightless pointer. The advantage of photographic recording is the complete absence of friction in magnifying and recording the relative motion of the pendulum and the Earth. The sources of friction in direct optical registrations are the points where the pendulum arm is pivoted. The effect of this friction on the dynamic behavior of the pendulum is independent of the magnification of the instrument. Therefore, the moment of inertia of the moving system is less than the devices with mechanical members. However, there are disadvantages to photographic registration as compared with mechanical registration. Photographic records are not as sharp as smoked paper records. Rapid, high amplitude oscillations are not recorded on photographic papers. Otherwise, due to the expensive photographic paper, photographic registrations were operated in slower speeds and hard to record waveforms accurately and in detail.

The advantages of the galvanometric registration are that it gives a very high magnification, it achieves a great sensitivity, the instrument is not affected by titling, and it is possible to have the pendulum system and the recording device in different rooms. With the application of the galvanometric registration, it is possible to detect the worldwide earthquakes occurring each year.

4-4 Summary

The greatest challenge in the development of seismographs was in the design of a seismometer. The first important step in the development of ancient seismometers was the use of an inertial system. The value of various types of pendulums for earthquake sensing instruments was realized early, probably as early as 132 AD in ancient China by Zhang Heng. A successful seismograph of low sensitivity was invented by Cecchi in 1875. Nevertheless, British scientists working in Japan in the 1880's must be credited for developing the seismograph as a practical research instrument. The accuracy of the seismograph was greatly improved in 1898 when Wiechert introduced a very large pendulum with a viscous damping.

Three methods were used to record earthquake motions in ancient seismographs, such as, mechanical, direct optical, and galvanometric registrations. Mechanical registration thus continued to be widely used in seismographs. In fact, those by using heavy masses and reducing friction to a minimum, mechanically recording seismographs were built which rivaled the photographically recording instruments in sensitivity. Applying the principles of electricity and magnetism to basic seismometer design, the galvanometric registrations give a very high magnification.

The primary drawback of mechanical seismographs was not very sensitive and could not record distant earthquakes. A greater sensitivity was necessary for a distant earthquake. And, the mechanical seismographs of the 1800s were superseded by electromagnetic seismographs in the early 1900s. Electromagnetic seismographs convert pendulum motions into electric voltages. The electric current resulting from the voltage can be amplified thousands of times to dramatically increase seismograph sensitivity. This basic design application underlies modern seismograph systems.

Based on the study of ancient earthquake instruments, an important keynote for designing an earthquake detecting instrument can be concluded that a complete seismograph is consisted of three directions including two horizontal seismometers, one oriented north-south and the other east-west, as well as a vertical seismometer. Since this work intends to reconstruct Zhang Heng’s seismoscope as accurate as the historical records, it should have eight devices inside the Zhang Heng’s seismoscope to detect eight principal directions.

Chapter 5 Reconstruction Design of Zhang Heng's Seismoscope

Researches on literature show that the earliest seismoscope named "Di Dong Yi" (地動儀) was invented by Zhang Heng (張衡) in ancient China. This device is with literary records but without surviving hardware. However, the records for the interior are too simple to understand the real structure of the mechanism inside the seismoscope.

This chapter proposes a reconstruction design approach for the lost Zhang Heng's seismoscope. Based on the literature review, the design requirements of Zhang Heng's seismoscope are defined and concluded. Then, according to the concepts of generalization and specialization subject to the concluded design requirements, all feasible design concepts that are in accordance with the science theories and techniques of the subject's time period are recreated.

5-1 Design Requirements

The reconstruction of ancient machines requires exhaustive literature study to clearly recognize and define the problem in order to develop design requirements. It is also important to be familiar with the available science and technology of the subject time period. Based on literature and seismology study, the design requirements of Zhang Heng's seismoscope are defined through the following three parts: study of historical archives, investigation of seismology, and analysis of ancient seismographs [39], Figure 5-1.

Study of Historical Archives

There are three components in the study of historical archives: Biography of Zhang Heng in the History of the Later Han Dynasty, history of ancient Chinese machinery, and existing reconstruction designs.

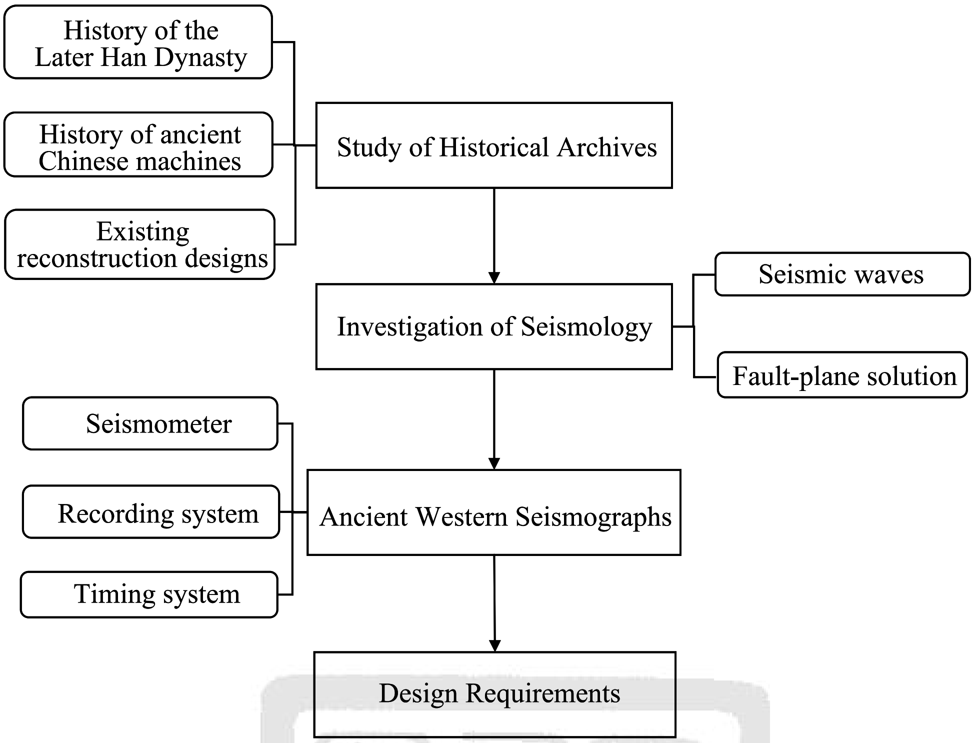


Figure 5-1 Design requirements of Zhang Heng's seismoscope

Although there are totally seven historical records regarding Zhang Heng's seismoscope, the Biography of Zhang Heng in the History of the Later Han Dynasty《後漢書・張衡傳》is the most important and complete one. The records describe clearly that there is one pillar (*du zhu*) in the center of interior and there are eight transmitting rods near the pillar. And, this is the first design requirement.

The transmitting rod is a channel to transport some thing. However, no detail descriptions about the transmitting rod can be found in historical records. Here, it is defined that there is a switch ball on the top of the pillar. When an earthquake occurs, the switch ball can move on the transmitting rod. And, this is the second design requirement.

Through the study of the history of ancient Chinese machinery, the developments of linkage mechanisms were very matured and full of various applications, especially in agricultural machines, weaving machines, and handicraft machines. The most elaborate use of linkages in ancient China was in textile machinery, in which levers and links were united with treadles to form complicated linkage mechanisms. The Jie Gao (a lever mechanism) was a device based on the principle of levers to draw water. A bucket for lowering into the well was attached to a hook on a vertical long rod connected to one end of the horizontal rod, while a rock was tied to the other end of the horizontal rod to balance the weight. The lever arm is supported near its centre, weighted with a stone at one end, and loaded by a bucket at the other end, Figure 2-2(a). The corresponding lever mechanism (Jie Gao) consists of a connecting rod and a lever arm, Figure 2-2(b).

Furthermore, the origin of rope-and-pulley appears in ancient China very early. The levers and links were united with rope-and-pulleys to form intricate machinery. The applications of linkage mechanisms and rope-and-pulley mechanisms were popular in daily life in ancient China.

Through the investigation of existing reconstruction designs, it is valuable to understand the development of the reconstruction of Zhang Heng's seismoscope. Although the existing reconstruction designs are not so sensitive and accurate, they are helpful to realize the design principle and outer appearance of Zhang Heng's seismoscope.

Investigation of Seismology

Seismology includes a lot of subjects. Seismic waves and fault-plane solution directly influence the design requirements of Zhang Heng's seismoscope [27-33]. Seismic waves including P wave, S wave, and Surface waves that are generated by earthquakes. 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. It forces particles of material in its path to move from side-to-side, perpendicular to the wavepath. Surface waves are the last-arriving waves that travel along Earth's surface.

An important aspect of the design requirements 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. 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. And, this is the third design requirement.

Analysis of Ancient Seismographs

Through the analysis of ancient Western seismographs, it can realize the developments and design principles of seismographs [34-38]. Early seismoscopes were primarily intended to indicate that an earthquake had occurred. The first device was built by Filippo Cecchi in Italy in 1875 AD. Cecchi's seismograph used two simple pendulums to measure horizontal motions, one swinging north-south and the other east-west, an orientation still almost always used today. The most significant person in developing a practical seismograph was John Milne. In 1876 AD he joined the faculty of the Imperial College of Engineering in Tokyo. There, in association with Thomas Gray and J. Alfred Ewing, they experimented with a variety of pendulum instruments for recording ground motions.

Early seismograph consists of three basic components: a seismometer, a timing system, and a recording system. The greatest challenge in the development of seismographs was in the design of the seismometer. A seismometer consists of three basic components: a sensing element, a magnifier, and a long arm. A sensing element responds to ground motion. The motions are magnified before being recorded by a magnifier. 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 an earthquake, the ground moves simultaneously in three dimensions: for example, east-west, north-south, and up-down. A single device records only one of these three components of motion. According to the foregoing, it is defined that there are eight devices in Zhang Heng's seismoscope to detect eight principal directions. Each device has the detecting mechanism as a seismometer inside and a recording system outside. And, this is the fourth design requirement.

According to historical records, each recording system of Zhang Heng's seismoscope definitely includes a dragon, a ball, and a toad in the outside. But in the view of the function, the real dragon is not necessary in the recording system. The function of the dragon is to hold the ball. The real dragons are replaced by painting the dragons on the surface of the compass. The balls can be contained in the wall of the vessel. In the developments of seismographs, one or more lever mechanisms were generally used in the early magnifiers of the ancient Western seismometers. The most popular lever mechanism in ancient China is Jie Gao, i.e., a lever mechanism as shown in Figure 2-2. Therefore, we define that each detecting mechanism has a pillar as the ground link, a sensing link to respond to ground shake, a lever mechanism (Jie Gao, including a connecting rod and a lever arm) as a magnifier, and a transmitting rod at least. It is a planar mechanism with one degree of freedom. And, this is the fifth design requirement. The transmitting rod connects the seismometer and the recording system, much like the long arm in ancient Western seismograph.

5-2 Reconstruction Design

According to the historical records, the outer appearance of Zhang Heng's seismoscope is clear. The reconstruction design presented here focuses on the detecting mechanism. The procedure for the reconstruction of design concepts of possible detecting mechanisms of Zhang Heng's seismoscope [39-44], is shown in Figure 5-2. It consists of the following four steps:

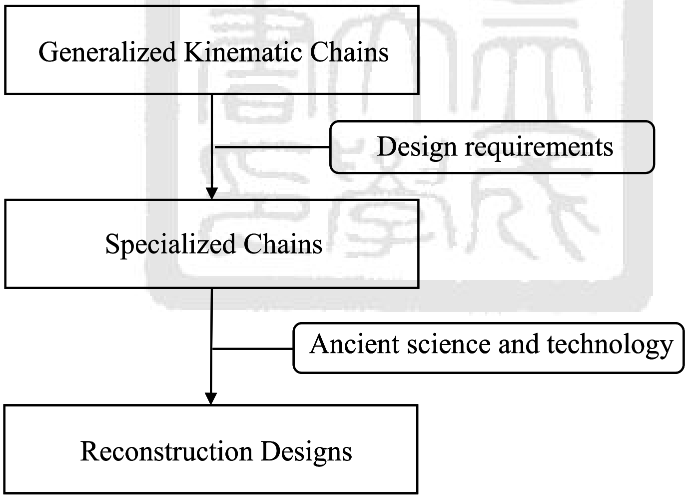


Figure 5-2 Process of reconstruction design

Step 1. Design requirements

Based on the above concluded design requirements, it is defined that one complete detecting mechanism should include a ground link, a sensing link, a connecting rod, a lever arm, and a transmitting rod. The design is at least a planar five-bar mechanism with six joints including one pin-in-slot joint (J_J), one prismatic joint (J_P), and four revolute joints (J_R). And, this is the simplest structure to carry out the third design requirement. In summary, the design requirements of Zhang Heng's seismoscope are:

1. It has one central pillar (*du zhu*) as the frame in the center of the interior, and it has eight transmitting rods as channels near the pillar.

2. The switch ball which can move on the transmitting rod is held with the eight transmitting rods on the top of the pillar.

3. Zhang Heng's seismoscope must detect the first motion of P wave; no matter it is compressing or expanding.

4. There are eight devices in the eight principal directions of Zhang Heng's seismoscope. Each device has the detecting mechanism as a seismometer and a recording system.

5. Each detecting mechanism has at least a ground link, a sensing link, a connecting rod, a lever arm, and a transmitting rod. It is a planar mechanism with one degree of freedom.

   (a) The pillar in the center of the interior is the ground link. The switch ball is on the top of the ground link.

   (b) The sensing link detects 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.

   (c) The magnifier consists of a connecting rod and a lever arm at least. Since the joint between the lever arm and the ground link is a pin-in-slot joint, the lever arm can slide and rotate around the pin. The feature of the pin-in-slot joint enables the lever arm to move to the direction of earthquake. The purpose of such design is to make sure that the movement of the lever arm can follow its corresponding sensing link, no matter where the sensing link topples.

   (d) The function of the transmitting rod is to connect the seismometer and the recording system. When the lever arm moves, it pulls the transmitting rod up. 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 found by the dropping ball.

6. It is a planar mechanism with one degree of freedom.

Step 2. Generalized kinematic chains

The second step is to obtain or identify the atlas of generalized kinematic chains with the required numbers of links and joints subject to defined design requirements by applying the algorithm of number synthesis [41]. A generalized kinematic chain consists of generalized links connected by generalized joints. It is connected, closed, without any bridge-link, and with simple generalized joints only. A generalized link is a link with generalized joints; it can be a binary link, ternary link, quaternary link, etc. A generalized joint is a joint in general; it can be a revolute joint, prismatic joint, spherical joint, helical joint, or others. A generalized joint with two incident members is called a simple generalized joint, and a generalized joint with more than two incident members is called a multiple generalized joint.

Step 3. Specialized chains

The third step is to have the atlas of specialized chains with assigned types of links and joints subject to the concluded design requirements and constraints for each generalized kinematic chain obtained in Step 2. The process of assigning specific types of links and joints in the available atlas of generalized kinematic chains, subject to certain design requirements and constrains, is called specialization [41, 43]. And, a generalized kinematic chain after specialization is a specialized chain. Based on the process of specialization, all possible specialized chains can be identified according to the following sub-steps:

1. For each generalized kinematic chain, identify the ground link.

2. For each case obtained in sub-step 1, identify the sensing link.

3. For each case obtained in sub-step 2, identify the transmitting rod.

4. For each case obtained in sub-step 3, identify the connecting rod.

5. For each case obtained in sub-step 4, identify the lever arm.

Specialized chains are identified subject to the following design requirements and constraints. The design constrains are defined based on the concluded characteristics of the detecting mechanism.

Ground link – (link K_F)

1. In each generalized kinematic chain, there must be one ground link (link K_F) as the frame.
2. The ground link must be a multiple link.

Sensing link (link 2)

1. The sensing link (link 2) is adjacent to the ground link (link K_F) with a revolute joint (J_R).
2. It must be a binary link.

Transmitting rod (link 5, the channel of the switch ball)

1. The transmitting rod (link 5) is adjacent to the ground link (link K_F) with a prismatic joint (J_P).
2. It must be a binary link.

Magnifier (link 3 and link 4)

1. The connecting rod (link 3) must be a binary link.
2. It (link 3 or link 4) must be adjacent to link K_F.

Step 4. Reconstruction designs

The last step is to obtain the atlas of reconstruction designs from the atlas of specialized chains, according to the motion and function requirements of the ancient machinery, and by utilizing the mechanical evolution and variation theory to perform a mechanism equivalent transform [42, 44]. Ancient science theories and technologies of the subject's time period are applied to find out appropriate and feasible mechanisms that can be considered as reconstruction designs.

5-3 Summary

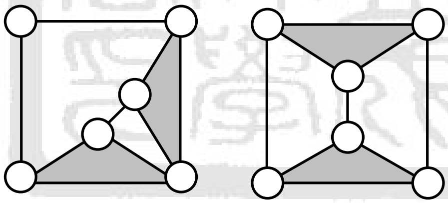
Through the study of ancient Chinese historical archives, the investigation of seismology, and the analysis of ancient Western seismographs, the design requirements of Zhang Heng’s seismoscope are defined and concluded. Then, according to the concepts of generalization and specialization subject to the concluded design requirements, all feasible designs that are in accordance with the science theories and techniques of the subject’s time period can be recreated.

Chapter 6 Examples of Reconstruction Design

According to the proposed approach in Chapter 5, four design examples based on different design requirements and constraints are provided. Linkage and rope-and-pulley mechanisms are used to form the detecting mechanism of Zhang Heng's seismoscope. By applying the approach, all feasible and appropriate reconstruction designs that are consistent with the science theories and technologies of the subject's time period are recreated.

6-1 Example 1: Linkage Mechanisms and with Five Members

In this case (Example 1), there are two generalized kinematic chains with five members and six joints as shown in Figure 6-1. All possible feasible specialized chains are identified through the following steps.



(a) (b)

Figure 6-1 Atlas of generalized kinematic chains with five members and six joints

<u>Ground link</u> (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 Figure 6-1(a), the assignment of the ground link K_F generates one non-isomorphic result, Figure 6-2(a_1).
2. For the generalized kinematic chain shown in Figure 6-1(b), the assignment of the ground link K_F generates one non-isomorphic result, Figure 6-2(a_2).

Therefore, two specialized chains with one identified ground link K_F are available as shown in Figures 6-2(a_1) and (a_2).

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 case shown in Figure 6-2(a_1), the assignment of the sensing link 2 generates two results, Figures 6-2(b_1) and (b_2).
2. For the case shown in Figure 6-2(a_2), the assignment of the sensing link 2 generates one non-isomorphic result, Figure 6-2(b_3).

Therefore, three specialized chains with identified ground link K_F and sensing link 2 are available as shown in Figures 6-2(b_1)-(b_3).

Transmitting rod (link 5)

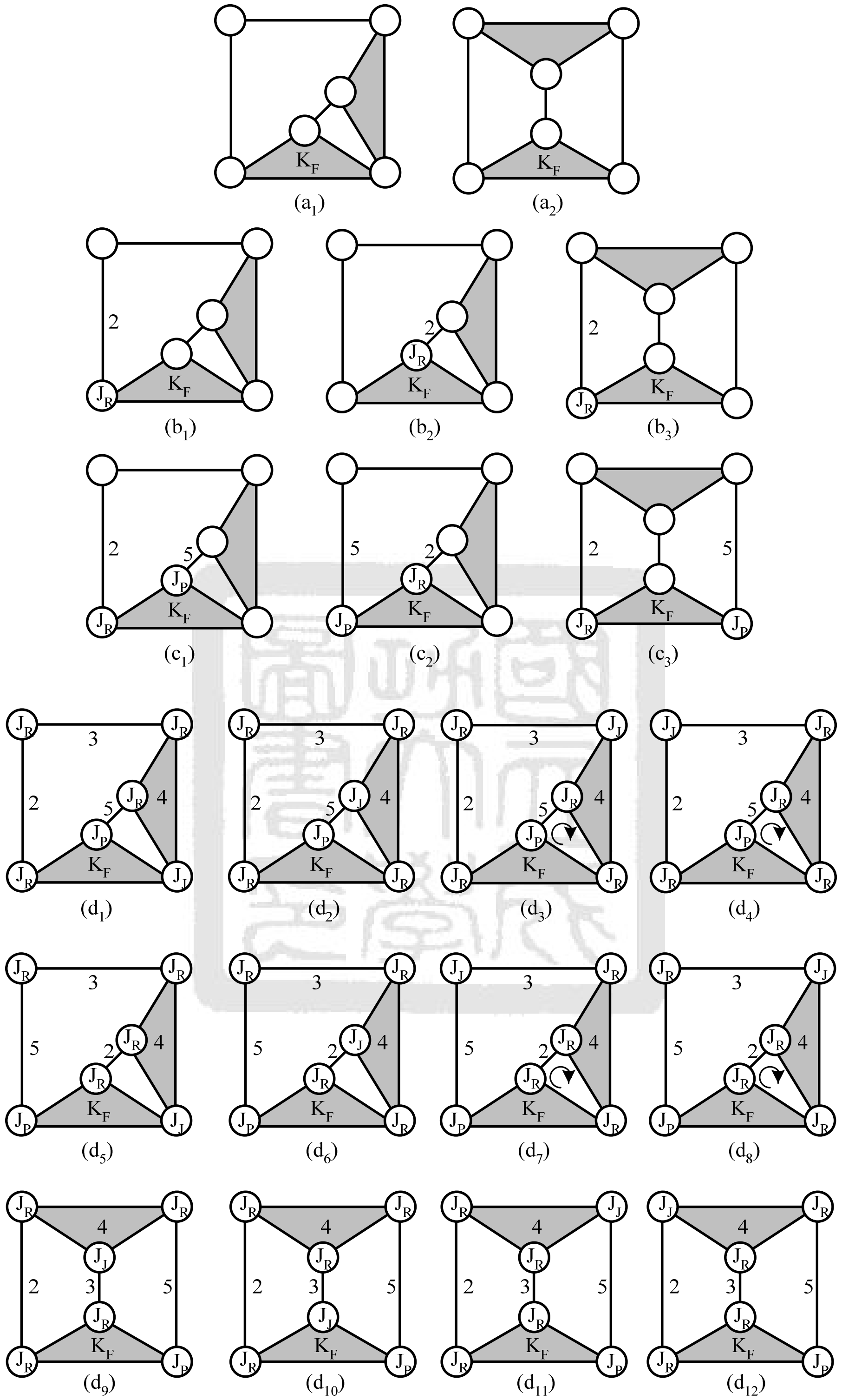
Since there must be a binary link as the transmitting rod 5 that is adjacent to the ground link K_F with a prismatic joint J_P, the transmitting rod can be identified as follows:

1. For the case shown in Figure 6-2(b_1), the assignment of the transmitting rod 5 generates one result, Figure 6-2(c_1).
2. For the case shown in Figure 6-2(b_2), the assignment of the transmitting rod 5 generates one result, Figure 6-2(c_2).
3. For the case shown in Figure 6-2(b_3), the assignment of the transmitting rod 5 generates one non-isomorphic result, Figure 6-2(c_3).

Therefore, three specialized chains with identified ground link K_F, sensing link 2, and transmitting rod 5 are available as shown in Figures 6-2(c_1)-(c_3).

Magnifier (link 3 and link 4)

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



(a$_1$) (a$_2$)

(b$_1$) (b$_2$) (b$_3$)

(c$_1$) (c$_2$) (c$_3$)

(d$_1$) (d$_2$) (d$_3$) (d$_4$)

(d$_5$) (d$_6$) (d$_7$) (d$_8$)

(d$_9$) (d$_{10}$) (d$_{11}$) (d$_{12}$)

Figure 6-2 Atlas of specialized chains (Example 1)

1. For the case shown in Figure 6-2(c_1), the assignment of the connecting rod 3, the lever arm 4, the pin-in-slot joint J_J, and the remaining revolute joints J_R generate four results, Figures 6-2(d_1)-(d_4).

2. For the case shown in Figure 6-2(c_2), the assignment of the connecting rod 3, the lever arm 4, the pin-in-slot joint J_J, and the remaining revolute joints J_R generate four results, Figures 6-2(d_5)-(d_8).

3. For the case shown in Figure 6-2(c_3), the assignment of the connecting rod 3, the lever arm 4, the pin-in-slot joint J_J, and the remaining revolute joints J_R generate four results, Figures 6-2(d_9)-(d_{12}).

Therefore, twelve non-isomorphic specialized chains with identified ground link K_F, sensing link 2, transmitting rod 5, connecting rod 3, and lever arm 4 are available as shown in Figures 6-2(d_1)-(d_{12}). Removing those with rigid chains including Figures 6-2(d_3), (d_4), (d_7), and (d_8), eight feasible specialized chains are available as shown in Figures 6-2(d_1), (d_2), (d_5), (d_6), and (d_9)-(d_{12}).

Here, the motion and function requirements of mechanisms are taken into account and keep the types of links and joints unchanged. Then, the detecting mechanism of the corresponding eight feasible specialized chains in Figures 6-2(d_1), (d_2), (d_5), (d_6), and (d_9)-(d_{12}) are represented as shown in Figures 6-3(a)-(h), respectively. The structure of Jie Gao in ancient China is that the connecting rod (link 3) is adjacent to the lever arm (link 4) with a revolute joint and the lever arm is adjacent to the ground link (link K_F) with a pin-in-slot joint. Since the design shown in Figure 6-3(a) has the structure of Jie Gao, Figure 6-3(a) is a good possibility as the detecting mechanism of Zhang Heng's seismoscope among the concepts with five members and six joints.

Figure 6-4 shows the movement process of Zhang Heng's seismoscope. Figure 6-5 shows the 3D solid model of a reconstruction design of Zhang Heng's seismoscope. There are eight devices in the principal directions of the instrument, Figure 6-5(a). A switch ball is held with the eight transmitting rods (link 5) on the top of the pillar. A complete detecting mechanism, based on Figure 6-3(a), is shown in Figure 6-5(b). 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, Figure 6-5(c). On the contrary, if the first motion is expanding, the sensing link 2 topples in the right, Figure 6-5(d).

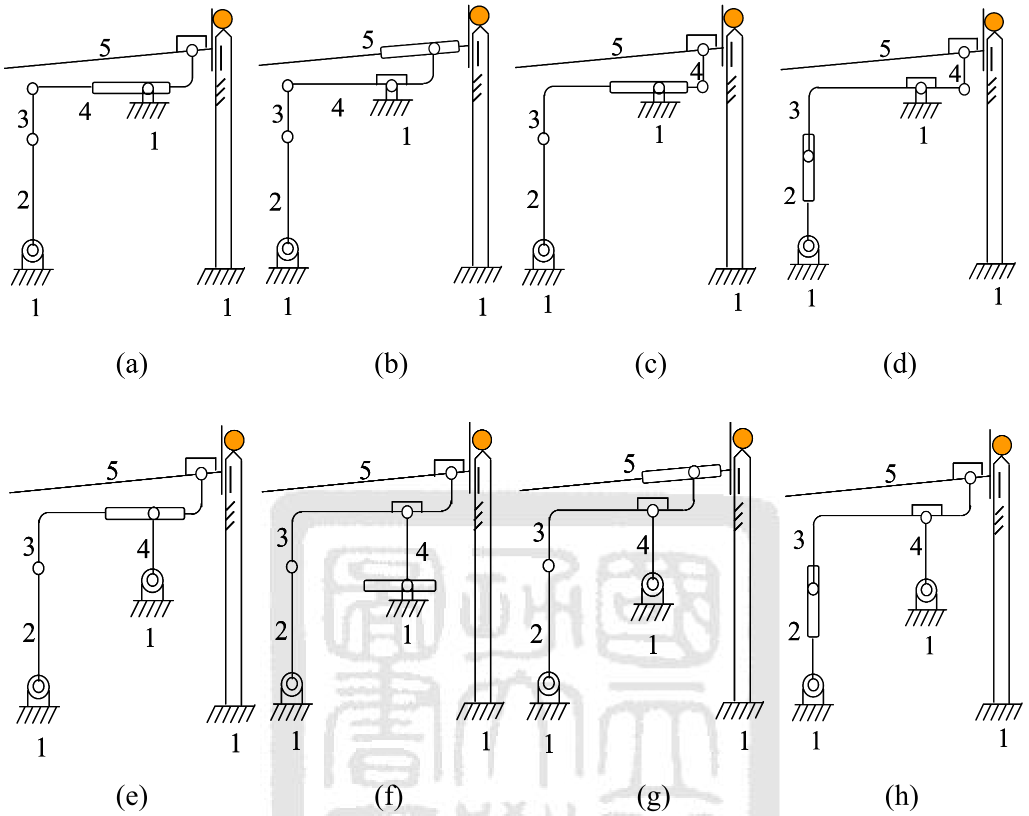


Figure 6-3　Detecting mechanisms (Example 1)

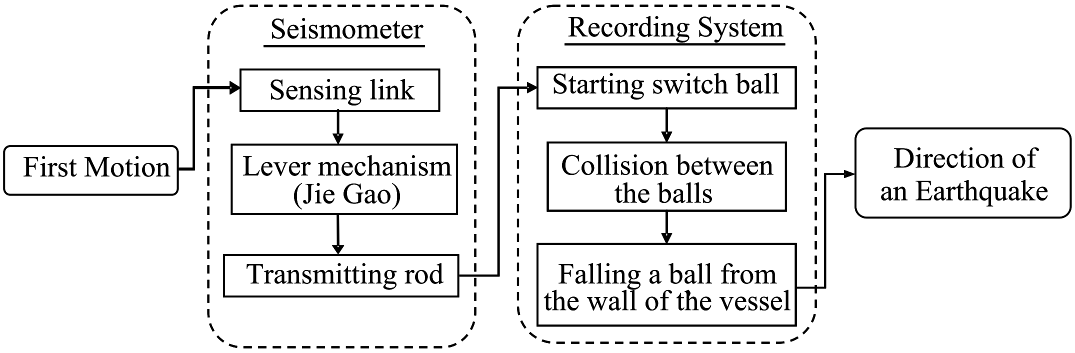
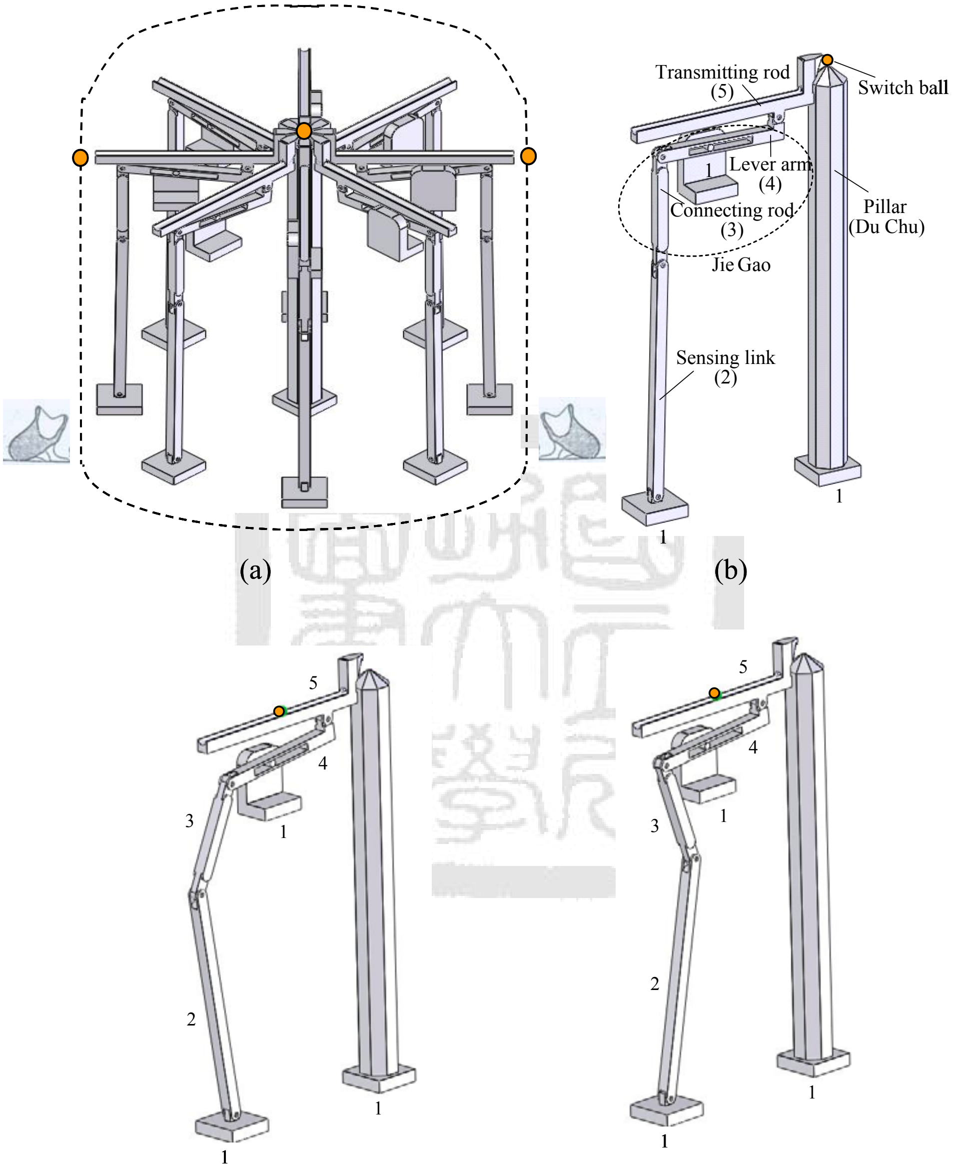


Figure 6-4　Movement process of Zhang Heng's seismoscope



(c) Sensing link 2 topples in the left by compressing wave

(d) Sensing link 2 topples in the right by expanding wave

Figure 6-5 A reconstruction design of Zhang Heng's seismoscope (Example 1)

6-2 Example 2: Linkage Mechanisms and with Six Members

In this case (Example 2), the detecting linkage mechanisms with six members and eight joints can be synthesized by following the same approach as described in Example 1. The design requirements and constrains that are different from the (5, 6) detecting mechanisms in Example 1 are:

1. The magnifier includes link 3, link 4, and link 5.
2. The ground link (link K_F) must be a quaternary link.
3. The (6, 8) detecting mechanism consists of a ground link (link K_F), a sensing link (link 2), a connecting rod (link 3), two lever arms (link 4 and link 5), a transmitting rod (link 6), a prismatic joint (J_P), two pin-in-slot joints (J_J), and five revolute joints (J_R).
4. Two pin-in-slot joints (J_J) must not be incident with the same link simultaneously.

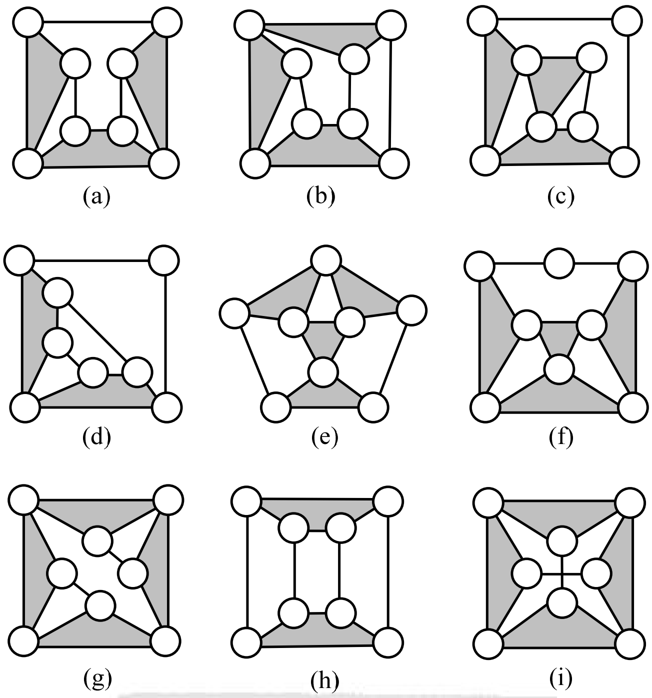
There are nine generalized kinematic chains with six members and eight joints as shown in Figure 6-6, and all possible specialized chains are identified through the following steps.

Since the detecting 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 generalized kinematic chain should have only three binary links. Therefore, only those three generalized kinematic chains shown in Figures 6-6(a)-(c) are qualified for the process of specialization.

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 generalization kinematic chain shown in Figure 6-6(a), the assignment of the ground link K_F generates one result, Figure 6-7(a).
2. For the generalization kinematic chain shown in Figure 6-6(b), the assignment of the ground link K_F generates one result, Figure 6-7(b).



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

Figure 6-6 Atlas of generalized kinematic chains with six members and eight joints

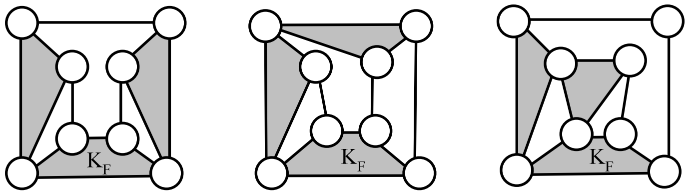
3. For the generalization kinematic chain shown in Figure 6-6(c), the assignment of the ground link K_F generates one result, Figure 6-7(c).

Therefore, three specialized chains with one identified ground link K_F are available as shown in Figures 6-7(a)-(c).

<u>Sensing link</u> (link 2)

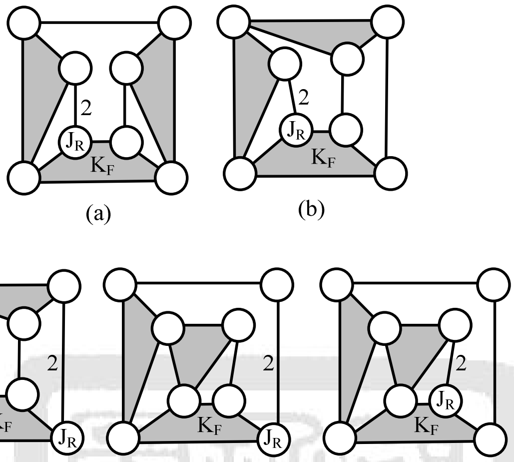
Since there must be a binary link as the sensing link 2 that is adjacent to the ground link K_F with a revolute joint J_R, the sensing link can be identified as follows:

1. For the case shown in Figure 6-7(a), the assignment of the sensing link 2 generates one non-isomorphic result, Figure 6-8(a).
2. For the case shown in Figure 6-7(b), the assignment of the sensing link 2 generates two non-isomorphic results, Figures 6-8(b) and (c).
3. For the case shown in Figure 6-7(c), the assignment of the sensing link 2 generates two results, Figures 6-8(d) and (e).



(a) (b) (c)

Figure 6-7 Atlas of (6, 8) specialized chains with identified ground link K_F (Example 2)



(a) (b)

(c) (d) (e)

Figure 6-8 Atlas of (6, 8) specialized chains with identified ground link K_F and sensing link 2 (Example 2)

Therefore, five specialized chains with identified ground link K_F and sensing link 2 are available as shown in Figures 6-8(a)-(e).

<u>Transmitting rod</u> (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 case shown in Figure 6-8(a), the assignment of the transmitting rod 6 generates one result, Figure 6-9(a).

2. For the case shown in Figure 6-8(b), the assignment of the transmitting rod 6 generates one non-isomorphic result, Figure 6-9(b).

3. For the case shown in Figure 6-8(c), the assignment of the transmitting rod 6 generates two results, Figures 6-9(c) and (d).

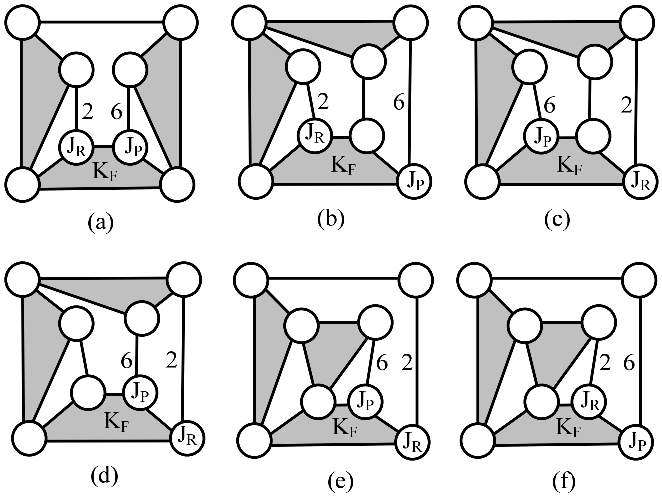


Figure 6-9 Atlas of (6, 8) specialized chains with identified ground link K_F, sensing link 2, and transmitting rod 6 (Example 2)

4. For the case shown in Figure 6-8 (d), the assignment of the transmitting rod 6 generates one result, Figure 6-9(e).

5. For the case shown in Figure 6-8(e), the assignment of the transmitting rod 6 generates one result, Figure 6-9(f).

Therefore, six specialized chains with identified ground link K_F, sensing link 2, and transmitting rod 6 are available as shown in Figures 6-9(a)-(f).

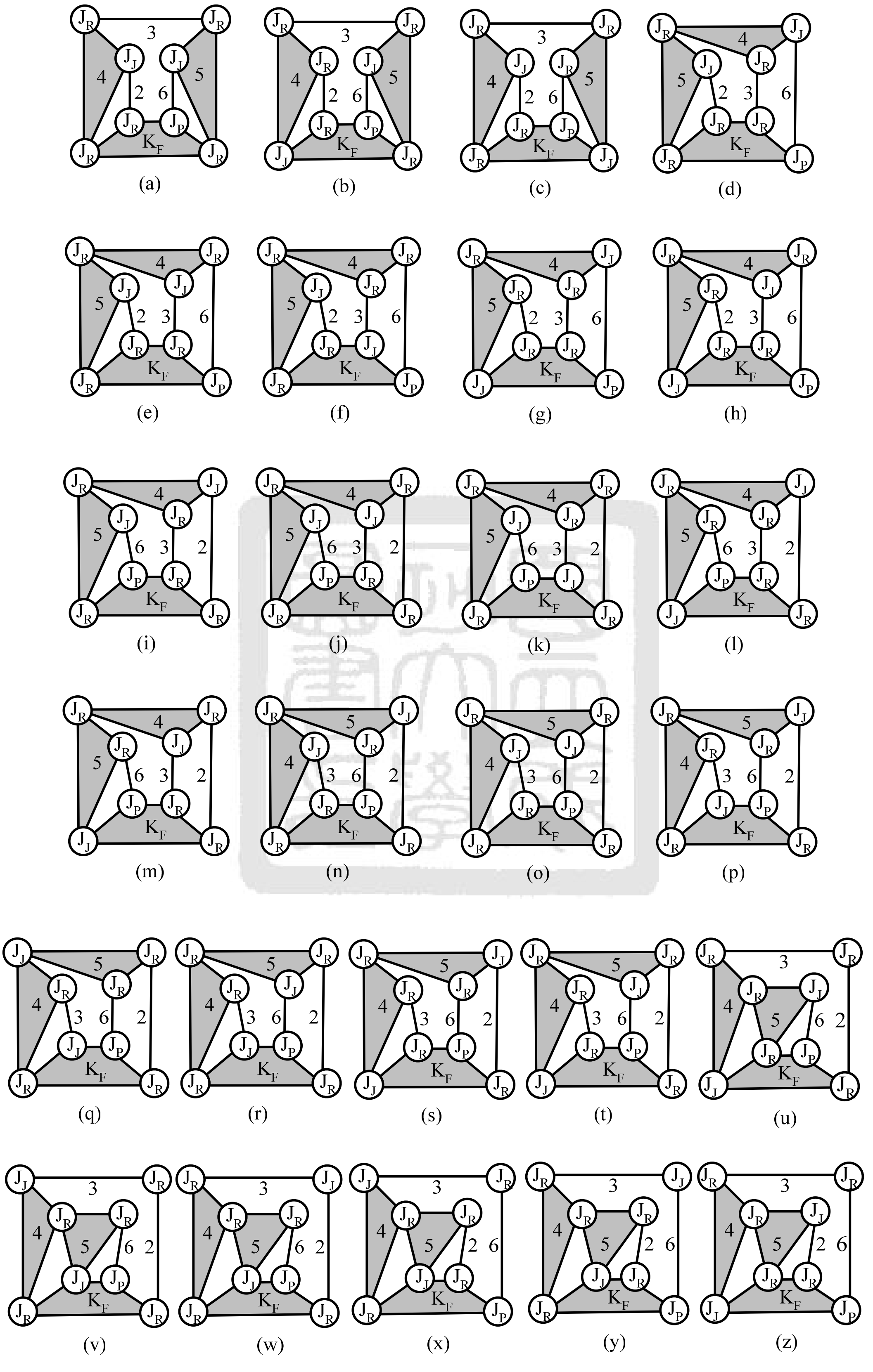
<u>Magnifier</u> (link 3, link 4, and link 5)

Since there must be a binary link as the connecting rod 3, the connecting rod and two lever arms 4 and 5 can be identified as follows:

1. For the case shown in Figure 6-9(a), the assignment of the connecting rod 3, two lever arms 4 and 5, two pin-in-slot joints J_J, and the remaining revolute joints J_R generate three feasible results, Figures 6-10(a)-(c).

2. For the case shown in Figure 6-9(b), the assignment of the connecting rod 3, two lever arms 4 and 5, two pin-in-slot joints J_J, and the remaining revolute joints J_R generate five feasible results, Figures 6-10(d)-(h).

3. For the case shown in Figure 6-9(c), the assignment of the connecting rod 3, two lever arms 4 and 5, two pin-in-slot joints J_J, and the remaining revolute joints J_R generate five feasible results, Figures 6-10(i)-(m).



(a) (b) (c) (d)

(e) (f) (g) (h)

(i) (j) (k) (l)

(m) (n) (o) (p)

(q) (r) (s) (t) (u)

(v) (w) (x) (y) (z)

Figure 6-10 Atlas of specialized chains (Example 2)

4. For the case shown in Figure 6-9(d), the assignment of the connecting rod 3, two lever arms 4 and 5, two pin-in-slot joints J_J, and the remaining revolute joints J_R generate seven feasible results, Figures 6-10(n)-(t).

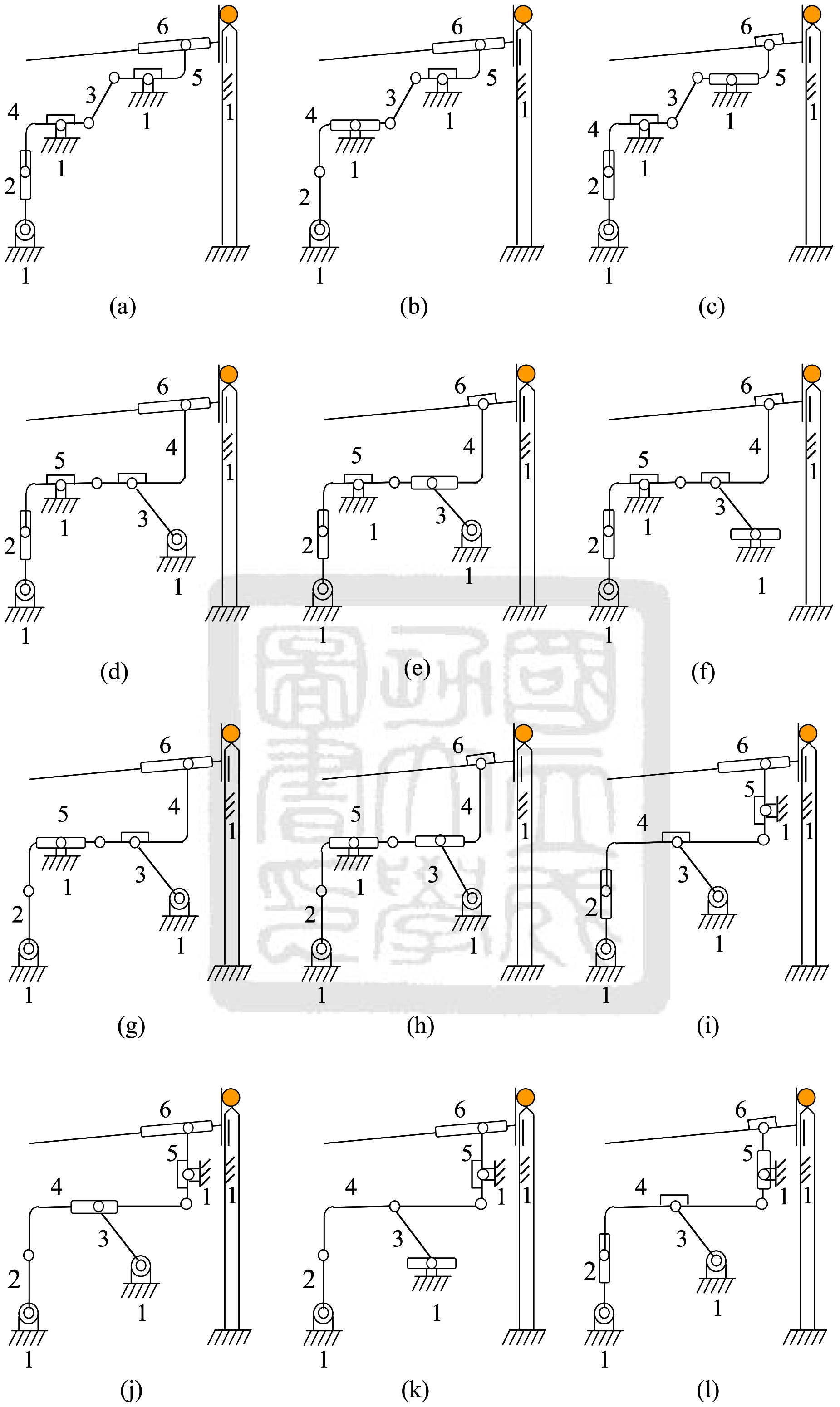
5. For the case shown in Figure 6-9(e), the assignment of the connecting rod 3, two lever arms 4 and 5, two pin-in-slot joints J_J, and the remaining revolute joints J_R generate three feasible results, Figures 6-10(u)-(w).

6. For the case shown in Figure 6-9(f), the assignment of the connecting rod 3, two lever arms 4 and 5, two pin-in-slot joints J_J, and the remaining revolute joints J_R generate three feasible results, Figures 6-10(x)-(z).

Therefore, twenty six specialized chains with identified ground link K_F, sensing link 2, transmitting rod 6, connecting rod 3, and two lever arms 4 and 5 are available as shown in Figures 6-10(a)-(z).

Through particularizing the twenty six feasible specialized chains in Figure 6-10, the corresponding twenty six detecting mechanisms are obtained as shown in Figures 6-11(a)-(z). Since the design shown in Figure 6-11(u) has the structure of Jie Gao, Figure 6-11(u) is a good possibility as the detecting mechanism of Zhang Heng's seismoscope among the concepts six members and eight joints.

Figure 6-12 shows the 3D solid model of a detecting mechanism with six members and eight joints. A complete detecting mechanism is shown in Figure 6-12(a) based on the design shown in Figure 6-11(u). When the first motion is compressing, the sensing link 2 topples in the left, Figure 6-12(b). On the contrary, if the first motion is expanding, the sensing link 2 topples in the right, Figure 6-12(c).



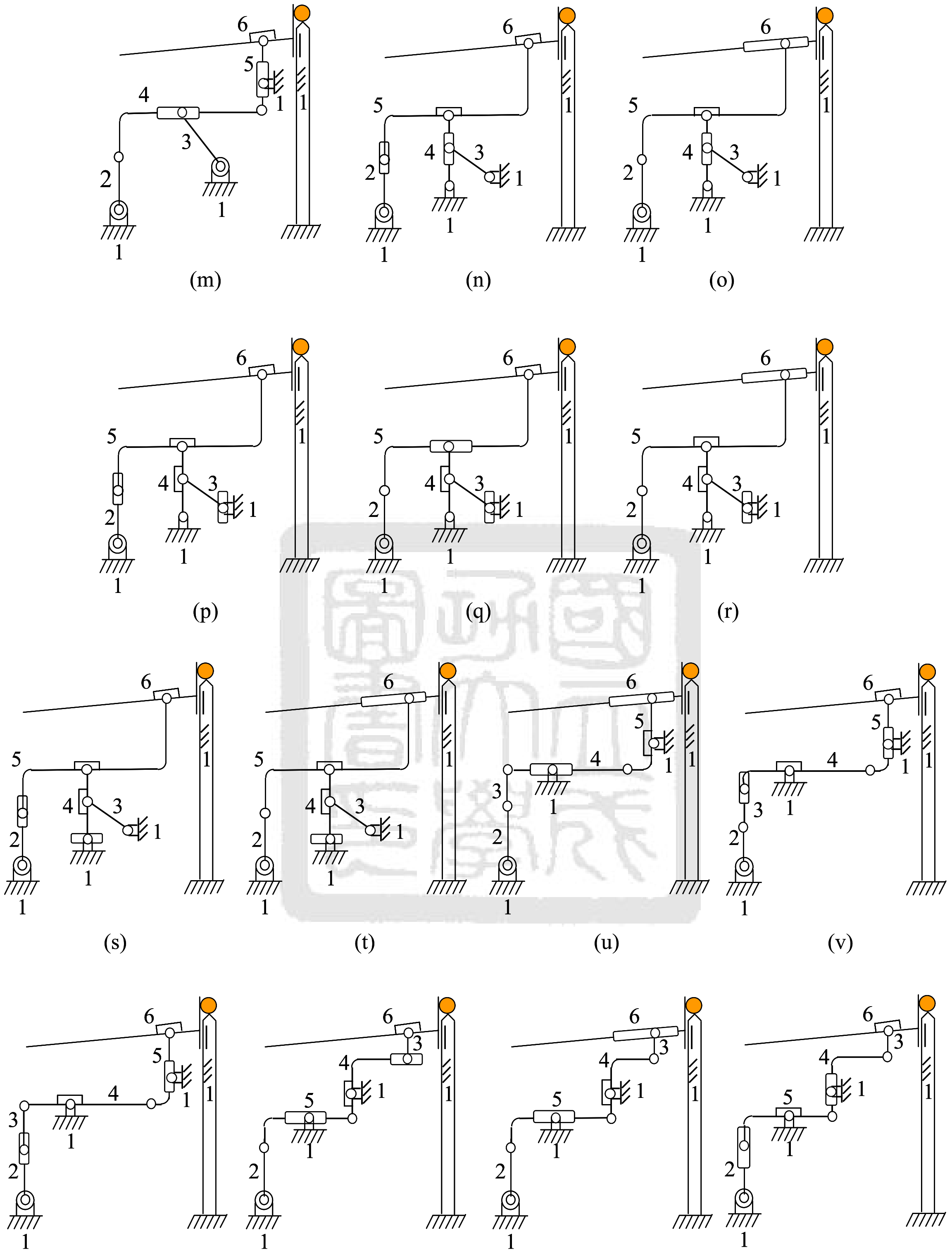
(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

(j) (k) (l)

Figure 6-11 Detecting mechanisms (Example 2)



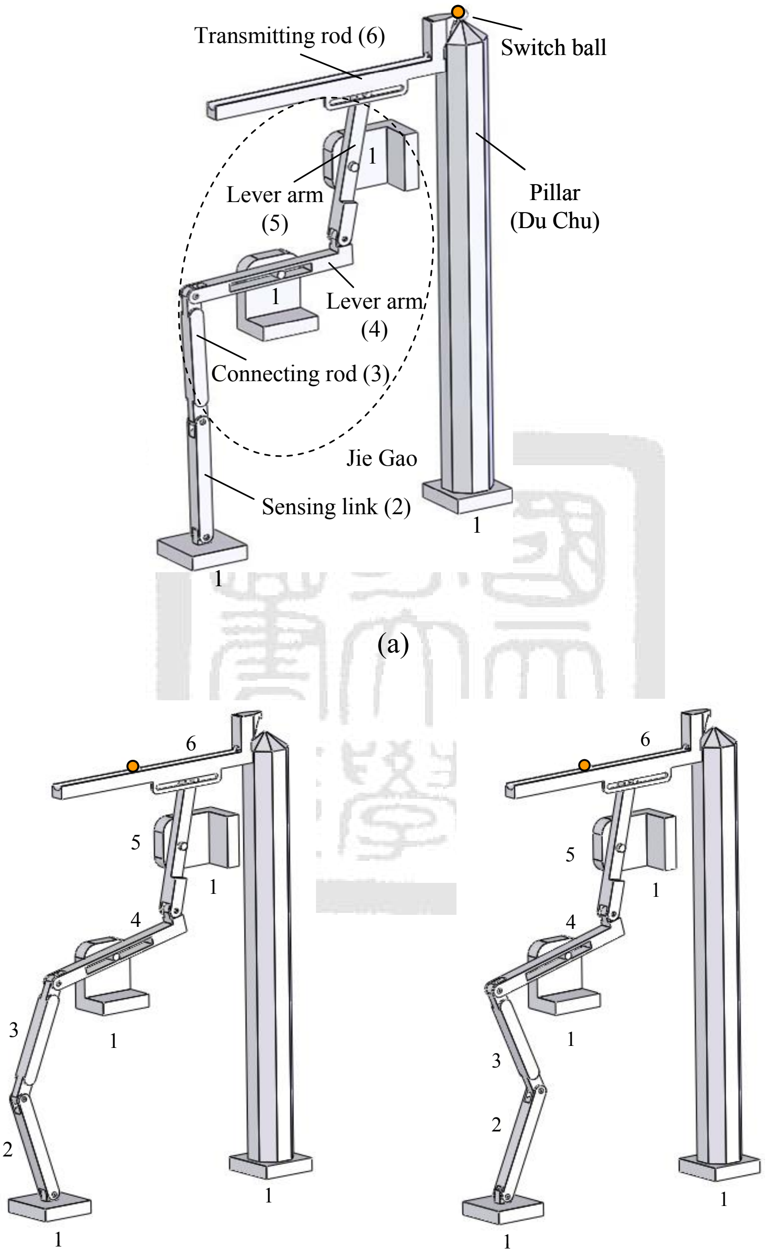
(m) (n) (o)

(p) (q) (r)

(s) (t) (u) (v)

(w) (x) (y) (z)

Figure 6-11　(Continued)



(a)

(b) Sensing link 2 topples in the left by compressing wave

(c) Sensing link 2 topples in the right by expanding wave

Figure 6-12 A reconstruction design of Zhang Heng’s seismoscope (Example 2)

6-3 Example 3: Rope-and-pulley Mechanisms and with Five Members

In this case (Example 3), the detecting mechanisms with a rope-and-pulley and with five members and six joints can be synthesized by following the same approach as described in Example 1. This design consists of a ground link (link K_F), a sensing link (link 2), a pulley (link 3), a rope (link 4), a transmitting rod (link 5), a prismatic joint (J_P), a wrapping joint (J_W), and four revolute joints (J_R).

Specialized chains are identified subject to the following design requirements and constraints:

Ground link

1. In each generalized kinematic chain, there must be one ground link as the frame (K_F).
2. The ground link must be a multiple link.

Sensing link

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

Transmitting rod

1. The transmitting rod, channel of the switch ball, is adjacent to the ground link with a prismatic joint (J_P).
2. It must be a binary link.

Pulley

1. The pulley is adjacent to the ground link with a revolute joint (J_R).
2. It must be a binary link.

Rope

1. The rope is adjacent to the pulley with a wrapping joint (J_W).

2. It must be a ternary link.

There are two generalized kinematic chains with five members and six joints as shown in Figure 6-1.

Since the detecting mechanisms with five members and six joints must have a sensing link, a transmitting rod, and a pulley, a feasible generalized kinematic chain should have three binary links that are adjacent to the ground link K_F. Therefore, only generalized kinematic chain shown in Figure 6-1(b) is qualified for the process of specialization.

<u>Ground link</u> (link K_F)

Since there must be a multiple link as the frame, for the generalized kinematic chain shown in Figure 6-1(b), the assignment of the ground link K_F generates one result, Figure 6-13(a).

<u>Sensing link</u> (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, for the case shown in Figure 6-13(a), the assignment of the sensing link 2 generates one non-isomorphic result, Figures 13(b).

<u>Transmitting rod</u> (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, for the case shown in Figure 6-13(b), the assignment of the transmitting rod 6 generates one non-isomorphic result, Figure 6-13(c).

<u>Pulley</u> (link 3)

Since there must be a binary link as the pulley 3 that is adjacent to the ground link K_F with a revolute joint J_R, for the case shown in Figure 6-13(c), the assignment of the pulley 3 generates one result, Figure 6-13(d).

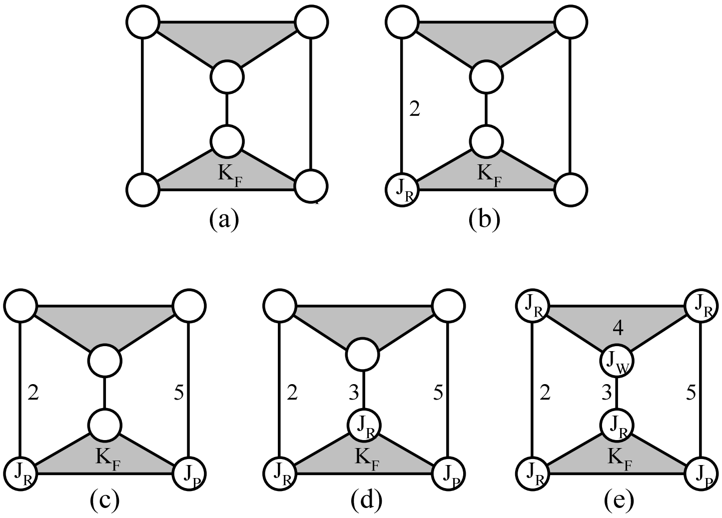


Figure 6-13 Atlas of Specialized chains (Example 3)

Rope (link 4)

Since there must be a ternary link as the rope 4 that is adjacent to the pulley 3 with a wrapping joint J_W, for the case shown in Figure 6-13(d), the assignment of the rope 4 and remaining revolute joint J_R generates one result, Figure 6-13(e).

Figures 6-14 show the corresponding feasible specialized chain shown in Figure 6-13(e). Figure 6-15 shows the 3D solid model of a detecting mechanism with five members and six joints. There are eight devices in the principal directions of the instrument, Figure 6-15(a). A complete detecting mechanism is shown in Figure 6-15(b) based on the design shown in Figure 6-14. When the first motion is compressing, the sensing link 2 topples in the left, Figure 6-15(c). On the contrary, if the first motion is expanding, the sensing link 2 topples in the right, Figure 6-15(d).

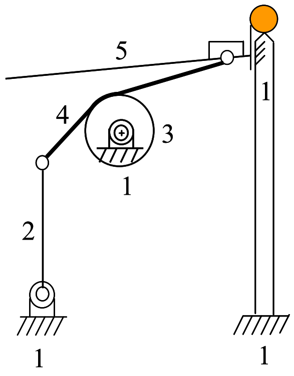
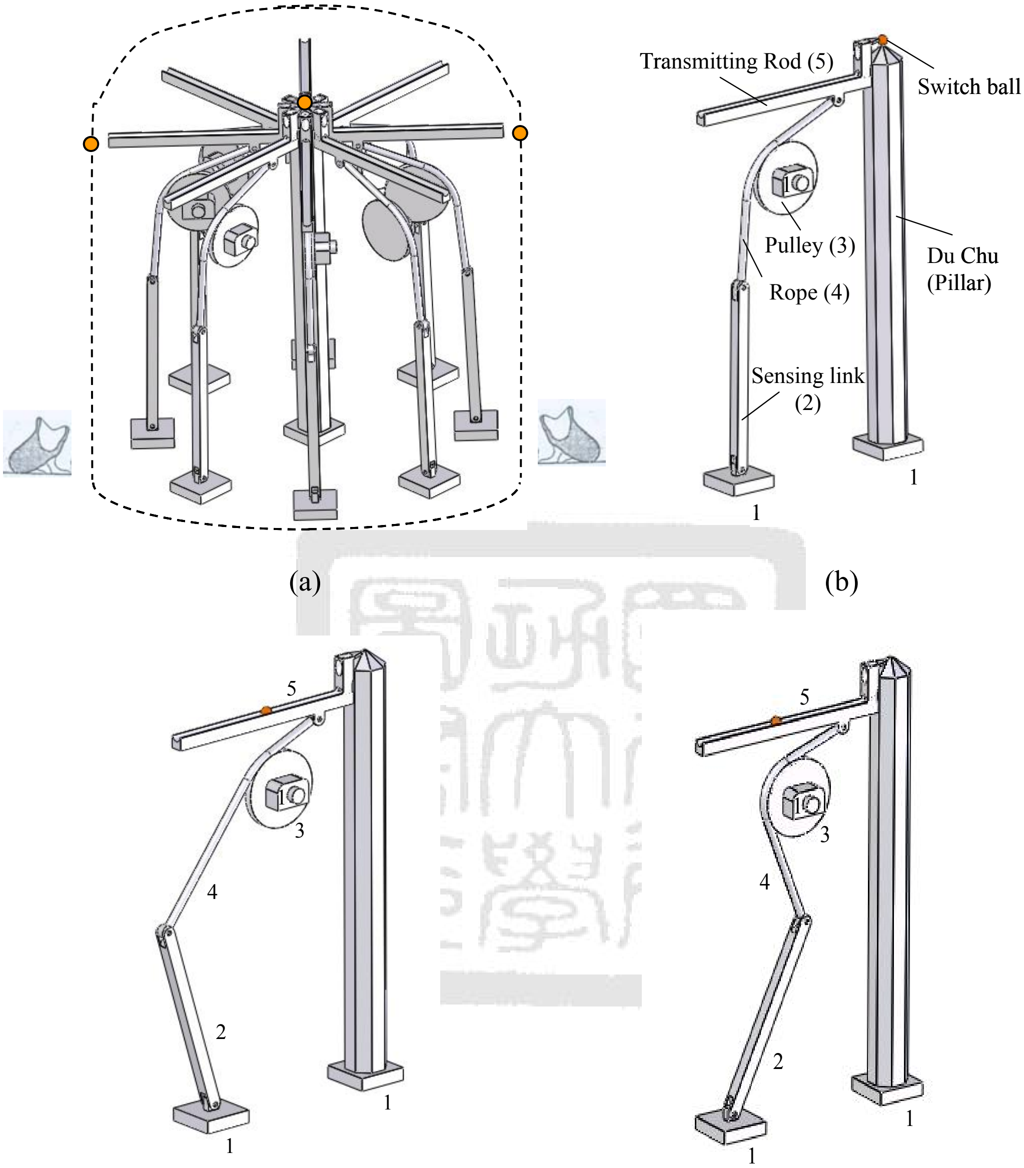


Figure 6-14 A detecting mechanism (Example 3)



(c) Sensing link 2 topples in the left by compressing wave

(d) Sensing link 2 topples in the right by expanding wave

Figure 6-15 A reconstruction design of Zhang Heng's seismoscope (Example 3)

6-4 Example 4: Rope-and-pulley Mechanisms and with Six Members

In this case (Example 4), the detecting mechanisms with a rope-and-pulley and with six members and eight joints can be synthesized by following the same approach as described in Example 2. This design consists of a ground link (link K_F), a sensing link (link 2), a pulley (link 3), a rope (link 4), a lever arm (link 5), a transmitting rod (link 6), a prismatic joint (J_P), a wrapping joint (J_W), a pin-in-slot joint (J_J), and five revolute joints (J_R).

Specialized chains are identified subject to the following design requirements and constraints:

Ground link

1. In each generalized kinematic chain, there must be one ground link as the frame (K_F).
2. The ground link must be a quaternary link.

Sensing link

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

Transmitting rod

1. The transmitting rod, channel of the switch ball, is adjacent to the ground link with a prismatic joint (J_P).
2. It must be a binary link.

Pulley

1. The pulley is adjacent to the ground link with a revolute joint (J_R).
2. It must be a binary link.

Rope

1. The rope is adjacent to the pulley with a wrapping joint (J_W).
2. It must be a ternary link.
3. The pin-in-slot joint (J_J) must not be incident to the rope.

There are nine generalized kinematic chains with six members and eight joints as shown in Figure 6-6.

Since the detecting mechanisms with six members and eight joints must have a sensing link, a transmitting rod, and a pulley, a feasible generalized kinematic chain should have only three binary links that are adjacent to the ground link K_F. And, there must be a ternary link as the rope. Therefore, only the generalized kinematic chain shown in Figure 6-6(b) is qualified for the process of specialization.

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 Figure 6-6(b), the assignment of the ground link K_F generates one result, Figure 6-16(a).

Therefore, one specialized chain with one identified ground link K_F is available as shown in Figure 6-16(a).

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 case shown in Figure 6-16(a), the assignment of the sensing link 2 generates two non-isomorphic results, Figures 6-16(b) and (c).

Therefore, two specialized chains with identified ground link K_F and sensing link 2 are available as shown in Figures 6-16(b) and (c).

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 case shown in Figure 6-16(b), the assignment of the transmitting rod 6 generates one non-isomorphic result, Figure 6-16(d).
2. For the case shown in Figure 6-16(c), the assignment of the transmitting rod 6 generates two results, Figures 6-16(e) and (f).

Therefore, three specialized chains with identified ground link K_F, sensing link 2, and transmitting rod 6 are available as shown in Figures 6-16(d)-(f).

Pulley (link 3)

Since there must be a binary link as the pulley 3 that is adjacent to the ground link K_F with a revolute joint J_R, the pulley can be identified as follows:

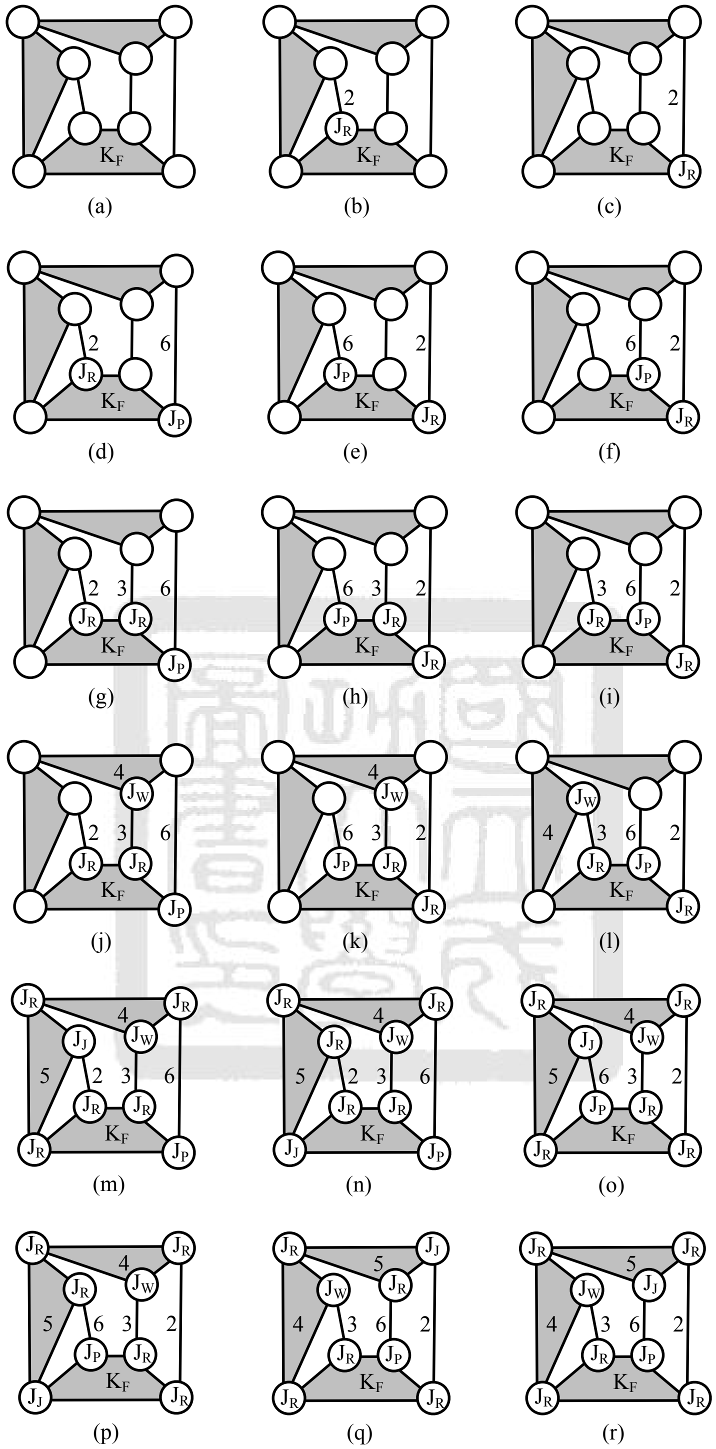
1. For the case shown in Figure 6-16(d), the assignment of the pulley 3 generates one result, Figure 6-16(g).
2. For the case shown in Figure 6-16(e), the assignment of the pulley 3 generates one result, Figure 6-16(h).
3. For the case shown in Figure 6-16(f), the assignment of the pulley 3 generates one result, Figure 6-16(i).

Therefore, three specialized chains with identified ground link K_F, sensing link 2, transmitting rod 6, and pulley 3 are available as shown in Figures 6-16(g)-(i).

Rope (link 4)

Since there must be a ternary link as the rope 4 that is adjacent to the pulley 3 with a wrapping joint J_W, the rope can be identified as follows:

1. For the case shown in Figure 6-16(g), the assignment of the rope 4 generates one result, Figure 6-16(j).



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

(j) (k) (l)

(m) (n) (o)

(p) (q) (r)

Figure 6-16 Atlas of specialized chains (Example 4)

2. For the case shown in Figure 6-16(h), the assignment of the rope 4 generates one result, Figure 6-16(k).

3. For the case shown in Figure 6-16(i), the assignment of the rope 4 generates one result, Figure 6-16(l).

Therefore, three specialized chains with identified ground link K_F, sensing link 2, transmitting rod 6, pulley 3 and rope 4 are available as shown in Figures 6-16(j)-(l).

<u>Lever arm</u> (link 5)

Since there must be a lever arm, the lever arm can be identified as follows:

1. For the case shown in Figure 6-16(j), the assignment of the lever arm 5, the pin-in-slot joint J_J, and the remaining revolute joints J_R generates two results, Figures 6-16(m) and (n).

2. For the case shown in Figure 6-16(k), the assignment of the lever arm 5, the pin-in-slot joint J_J, and the remaining revolute joints J_R generates two results, Figures 6-16(o) and (p).

3. For the case shown in Figure 6-16(l), the assignment of the lever arm 5, the pin-in-slot joint J_J, and the remaining revolute joints J_R generates two results, Figures 6-16(q) and (r).

Therefore, six feasible specialized chains with identified ground link K_F, sensing link 2, transmitting rod 6, pulley 3, rope 4, and lever arm 5 are available as shown in Figures 6-16(m)-(r).

Figures 6-17(a)-(f) show the corresponding six detecting mechanisms after particularization for the six feasible specialized chains shown in Figures 6-16(m)-(r). Figure 6-18 shows the 3D solid model of a detecting mechanism with six members and eight joints. And, a complete detecting mechanism is shown in Figure 6-18(a) based on the design shown in Figure 6-17(c). When the first motion is compressing, the sensing link 2 topples in the left, Figure 6-18(b). On the contrary, if the first motion is expanding, the sensing link 2 topples in the right, Figure 6-18(c).

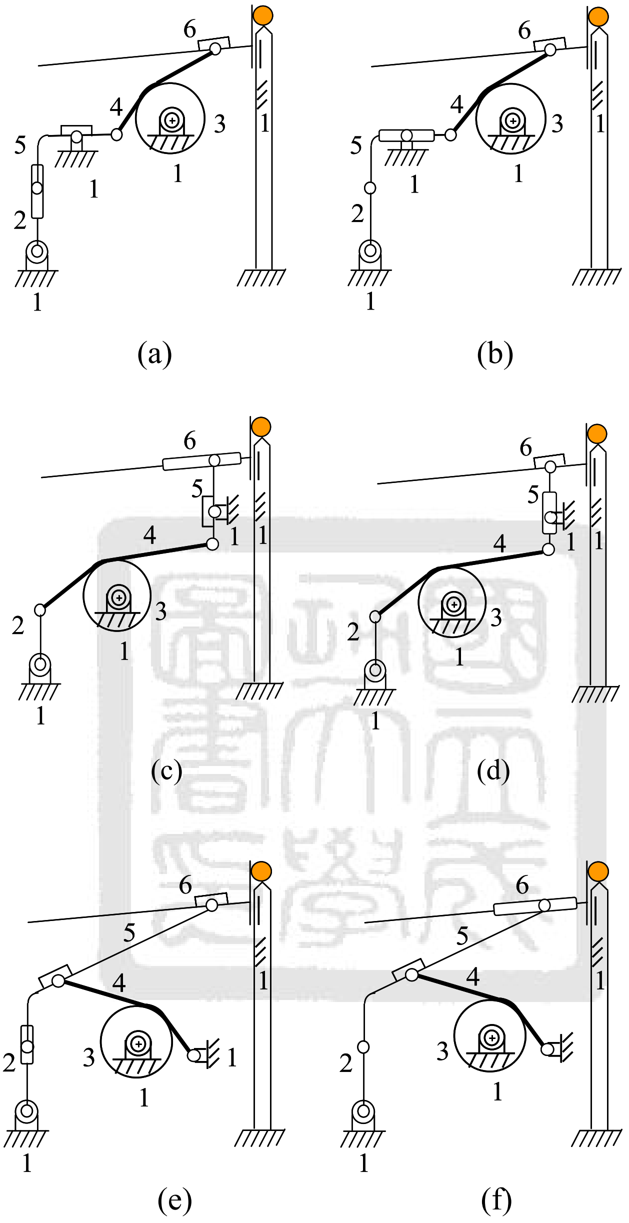
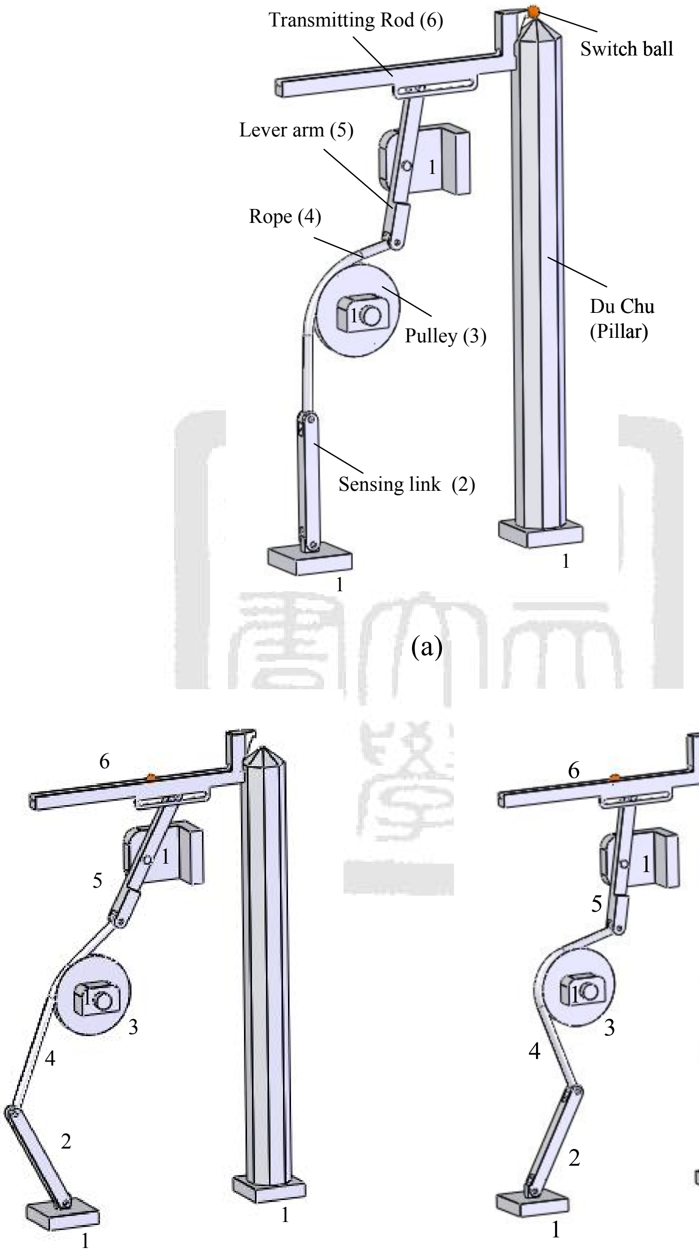


Figure 6-17 Detecting mechanisms (Example 4)



(a)

(b) Sensing link 2 topples in the left by compressing wave

(c) Sensing link 2 topples in the right by expanding wave

Figure 6-18 A reconstruction design of Zhang Heng's seismoscope (Example 4)

6-5 Summary

Based on the proposed approach for reconstruction design of Zhang Heng's seismoscope subject to the different design requirements and constraints, we systematically reconstruct all feasible design concepts of Zhang Heng's seismoscope that meet the science theories and techniques of the subject's time period. The detecting linkage mechanisms of Zhang Heng's seismoscope with five members and six joints (5, 6) designs and with six members and eight joints (6, 8) designs are synthesized. As the results, the linkage mechanisms with (5, 6) and (6, 8) designs have 8 and 26 feasible designs, respectively. As well as the rope-and-pulley mechanisms of Zhang Heng's seismoscope with (5, 6) and (6, 8) designs are are derived with 1 and 6 feasible designs, respectively.

Various designs with different types and numbers of members and joints can be obtained by following the proposed approach. Logically, one of the reconstruction designs is possible to be the inner mechanism of Zhang Heng's seismoscope. Furthermore, the result of this work provides a logical and feasible solutions and approach for the reconstruction design of Zhang Heng's seismoscope before new and solid evidences are found.

Chapter 7 Prototyping

In this Chapter, a two-dimensional prototype of the detecting mechanism of Zhang Heng's seismoscope with five members is built to verify the feasibility of its function. Detail sizes and shapes of links are designed. A computer simulation and animation for the detecting mechanism of Zhang Heng's seismoscope is set up. And, a prototype of the detecting mechanism is built.

7-1 Detail Design of Links

According to the historical archives, the diameter of Zhang Heng's seismoscope is 8 chi (尺), and this is the only clue for the size of Zhang Heng's seismoscope. In Han Dynasty, one chi (尺) is equal to 23 cm [15], that is, the diameter of Zhang Heng's seismoscope is 184 cm. The ratio of the diameter and height of the jar is around 1:1.4 in Han Dynasty [16]. The external of Zhang Heng's seismoscope is like a jar. That is, the diameter of Zhang Heng's seismoscope is 258 cm.

The concept with five members and six joints in Figure 6-3(a) is adopted to build the prototype of the detecting mechanism. Based on the concluded size and the design requirements of Zhang Heng's seismoscope, detail dimensions of links are designed as shown in Figure 7-1 with the unit in millimeters. The ratio of this prototype to the authentic object is around 1:5.

7-2 Computer Simulation

Through computer simulation, the function of the detecting mechanism can be checked, and it is a suitable mean to demonstrate the motion of links. On the basis of the detail dimensions of links, the simulation of the detecting mechanism with five members is built through the following steps:

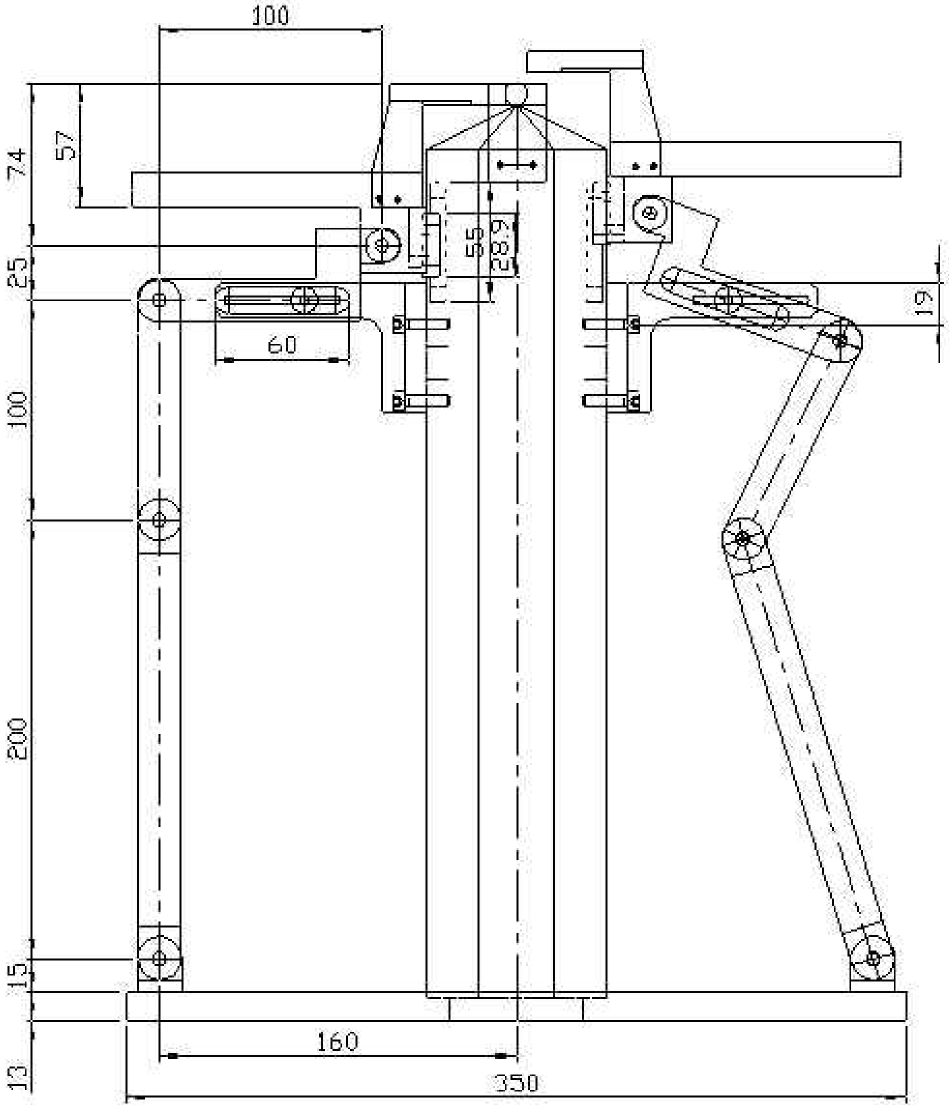


Figure 7-1 Detail dimensions of links

1. The model of the detecting mechanism is built by using the software, SolidWorks 2005, Figure 7-2.

Figure 7-2 Model of the detecting mechanism

2. The initial external of Zhang Heng’s seismoscope is built by using the software, 3D Max, Figure 7-3.

Figure 7-3 Initial external of Zhang Heng’s seismoscope

3. The initial external of Zhang Heng’s seismoscope and the model of the detecting mechanisms are decorated with art design by using the software, Adobe Photoshop.

4. The animation for simulation of Zhang Heng’s seismoscope is carried out as shown in Figure 7-4 for several successive pictures. Figure 7-4(a) shows the external of Zhang Heng’s seismoscope. Figure 7-4(b) shows the inner arrangement of the detecting mechanism of Zhang Heng’s seismoscope. When the P wave is expanding from the right, the sensing link of the right detecting mechanism topples

(a) (b)

(c) (d)

(e) (f)

Figure 7-4 Simulation of Zhang Heng's seismoscope first, the corresponding transmitting rod lifts, and the switch ball moves in the corresponding transmitting rod, Figures 7-4(c)-(d). Figure 7-4(e) shows that the switch ball impacts the ball in the wall. After the collision between the balls, the ball in the wall falls in the toad, Figure 7-4(f). The direction of the occurring earthquake can be discovered by the falling ball in the toad.

7-3 Prototype

A two-dimensional prototype of the detecting mechanism is fabricated and shown in Figure 7-5. Figure 7-5(a) shows the situation for detecting the earthquake. When the first motion is an expanding wave from the right, the sensing link topples in the left, Figure 7-5(b). On the contrary, if the first motion is a compressing wave from the right, the sensing link topples in the right, Figure 7-5(c).

Observing the motion of the detecting mechanism, it works out smoothly and sensitively. Experimenting on the detecting mechanism, it indeed can detect the direction of an additional test shake. And, the proposed concept of the detecting mechanism is proved to be feasible.

(a)

(b) (c)

Figure 7-5 A two-dimensional prototype of the detecting mechanism

Chapter 8 Conclusions and Suggestions

The earliest earthquake instrument was invented by Zhang Heng (張衡) in ancient China in 132 AD. This work is dedicated to reconstruct the detecting mechanism of Zhang Heng's seismoscope systematically. Firstly, an exhausted literature search and study including historical archives and seismology are performed. Based on literature review, the design requirements of Zhang Heng's seismoscope are defined and concluded. By applying the concept of generalization and specialization of mechanisms subject to the concluded design requirements, a systematic approach for reconstruction design of the detecting mechanism of Zhang Heng's seismoscope is provided by which all feasible design concepts that meet the science and technology background of the subject's time period are recreated.

The contributions of this work are concluded as follows:

1. The developments of Zhang Heng's seismoscope, including biography of Zhang Heng, historical records, and existing reconstruction designs are introduced. Seven historical archives are studied and more than fifteen reconstruction designs of Zhang Heng's seismoscope are investigated.

2. The developments of seismology are reviewed. It can be concluded that Zhang Heng's seismoscope should be designed to detect the initial ground motion of P wave whether it is compressive or expansive.

3. The developments of ancient earthquake instruments, including seismometer, seismoscope, and seismograph, are presented. It reveals that an important step in developing ancient seismometers was the use of an inertial system. This principle is applied to the reconstruction design of Zhang Heng's seismoscope and modern seismographs.

4. A reconstruction design approach for Zhang Heng's seismoscope is proposed. Through the studies of ancient Chinese historical archives, the investigation of seismology, and the analysis of ancient Western seismographs, the design requirements of Zhang Heng's seismoscope are defined and concluded. Then, according to the concepts of generalization and specialization of mechanisms

subject to the concluded design requirements, all feasible design concepts of Zhang Heng's seismoscope that meet the science theories and techniques of the subject's time period are systematically recreated.

5. Four design examples based on different design requirements and constraints are illustrated. Two linkage examples, one with five members and six joints and the other with six members and eight joints, of the detecting mechanism of Zhang Heng's seismoscope are derived with 8 and 26 feasible designs, respectively. Besides, two rope-and-pulley examples with five members and six joints and the other with six members and eight joints are derived with 1 and 6 feasible designs, respectively.

6. The computer simulation and prototype with five members and six joints is built to demonstrate the motion of the detecting mechanism. Observing and experimenting on the prototype, it indeed can detect the direction of the additional test shake. The proposed concept of the detecting mechanism of Zhang Heng's seismoscope is workable.

7. The approach developed in this work provides a logical foundation for reconstructing Zhang Heng's seismoscope. Before new and solid evidences are found, it is believed that one of above the reconstruction designs is possible to be the detecting mechanism of Zhang Heng's seismoscope.

In addition, there are several relevant works that are worth for future study:

1. The main function of the switch ball is to make only one ball drop from dragon's mouth in each earthquake. However, no detail descriptions about the switch ball can be found in historical records. A new concept in the detecting mechanism to function as a switch ball is needed to be investigated.

2. In this work, the linkage and rope-and-pulley mechanisms are used to form the detecting mechanism of Zhang Heng's seismoscope. However, there may be other mechanical elements to agree with Zhang Heng's instrument, such as cam and gear mechanisms, etc. Other mechanisms may be adopted in the future study of Zhang Heng's seismoscope.

3. The sensitivity of the detecting mechanism of Zhang Heng’s seismoscope does not be analyzed in this work. Therefore, how to deal with the mathematical model of the sensitivity might be studied in the future.

4. Through the real test in the seismological station, the accuracy and sensitivity of the detecting mechanism can be experimented in physically. It is also useful to set up the mathematical model of the sensitivity of the detecting mechanism.

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