Journal of Japan Association for Earthquake Engineering, Vol.9, No.4, 2009

THE REVIEW OF RECONSTRUCTION DESIGNS OF ZHANG HENG'S SEISMOSCOPE

Kuo-Hung HSIAO[1], Hong-Sen YAN[2]

[1] Postdoctoral researcher, Department of Mechanical Engineering, National Cheng Kung University, Tainan, Taiwan, kuohung1123@yahoo.com.tw
[2] Professor, Department of Mechanical Engineering, National Cheng Kung University, Tainan, Taiwan, hsyan@mail.ncku.edu.tw

ABSTRACT: This paper reviews the development of reconstruction designs of the lost Zhang Heng's seismoscope. Historical background of Zhang Heng's seismoscope including the biography of Zhang Heng and existing historical archives is presented. Available reconstruction designs, which are classified into external shape, suspended pendulum, direct contact, inverted pendulum, and authors' approach, are presented. Based on the proposed approach, all feasible design concepts that meet the science theories and techniques of the subject's time period can be recreated. And, this provides a logical foundation for the reconstruction designs of Zhang Heng's seismoscope before new evidences are found.

Key Words: Zhang Heng's seismoscope, Reconstruction design, Seismograph

INTRODUCTION

The methods and instruments of earthquake detection in ancient times are still quite mysterious to the modern people. From the documented literature, it has been approved that the earliest seismoscope namely "Hou Feng Di Dong Yi" (候風地動儀) was invented by Zhang Heng (張衡) (79-139 AD) in ancient China in 132AD (Fan 1977). Zhang's seismoscope is respected as a milestone invention since it can indicate not only the occurrence of an earthquake but also the direction to its source. Since there are no clear historical documents and physical remains, Zhang Heng's seismoscope is still a famous but mysterious instrument today.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 interesting research topic in the study of lost ancient machinery as well as history of seismology.

Reconstruction designs are to rebuild the original machines by applying ancient mechanical principles and technique skills. It is useful for reappearing the ancient inventions and realizing the achievements of previous generations. Many scholars tried to reconstruct Zhang Heng's seismoscope in the past decades. In the early stage, some exterior appearances of Zhang's seismoscope were proposed (Imamura 1942; Milne 1883; Wang 1963; Bolt 1978). Later, the interior mechanical structures with various operating functions were presented (Wang 1936; Feng et al. 2006 a, b; Sleeswyk and Sivin 1983; Imamura 1939; Wang 1963; Lee 1994; Imamura 1942; Yan and Hsiao 2007). And, it is believed that the design principle of Zhang's seismoscope and early modern seismograph are based on the principle of inertia.

The paper reviews the development of reconstruction designs of Zhang Heng's seismoscope including an innovative systematic approach (Yan 2007) for the reconstruction synthesis of possible interior mechanisms of the seismoscope by the authors.

ZHANG HENG THE MAN

Zhang Heng (張衡) (78-139 AD) was an extraordinary polymath in the Eastern Han Dynasty (25-220 AD), (Lu 2003). He was not only an astronomer royal but also a distinguished cartographer, mathematician, poet, painter, and inventor.

When Zhang was 17 to 23 years old (94-100 AD), he studied in Chang An, the capital city of the Western Han Dynasty, and Lo Yang, the capital city of the Eastern Han Dynasty. At 23 (100 AD), he accepted the invitation of Nanyang governor Bao De as a clerk to manage official documents in his hometown and assisted Bao in government affairs.

Between 31 to 34 years old (108-111 AD), Zhang stayed in his hometown and studied hard. He specialized in Yang Xiong's Tai Xuan Jing《太玄經》, which was a philosophical work on cosmic phenomena that discussed astronomy, calendar calculation and spherical heaven theory. He was called to the capital city to serve as a palace attendant at the age of 34 (111 AD). He became an assistant minister at 37 (114 AD). And at 38 (115 AD), he became a grand scribe responsible for observing astronomical phenomena, preparing calendars and managing time devices.

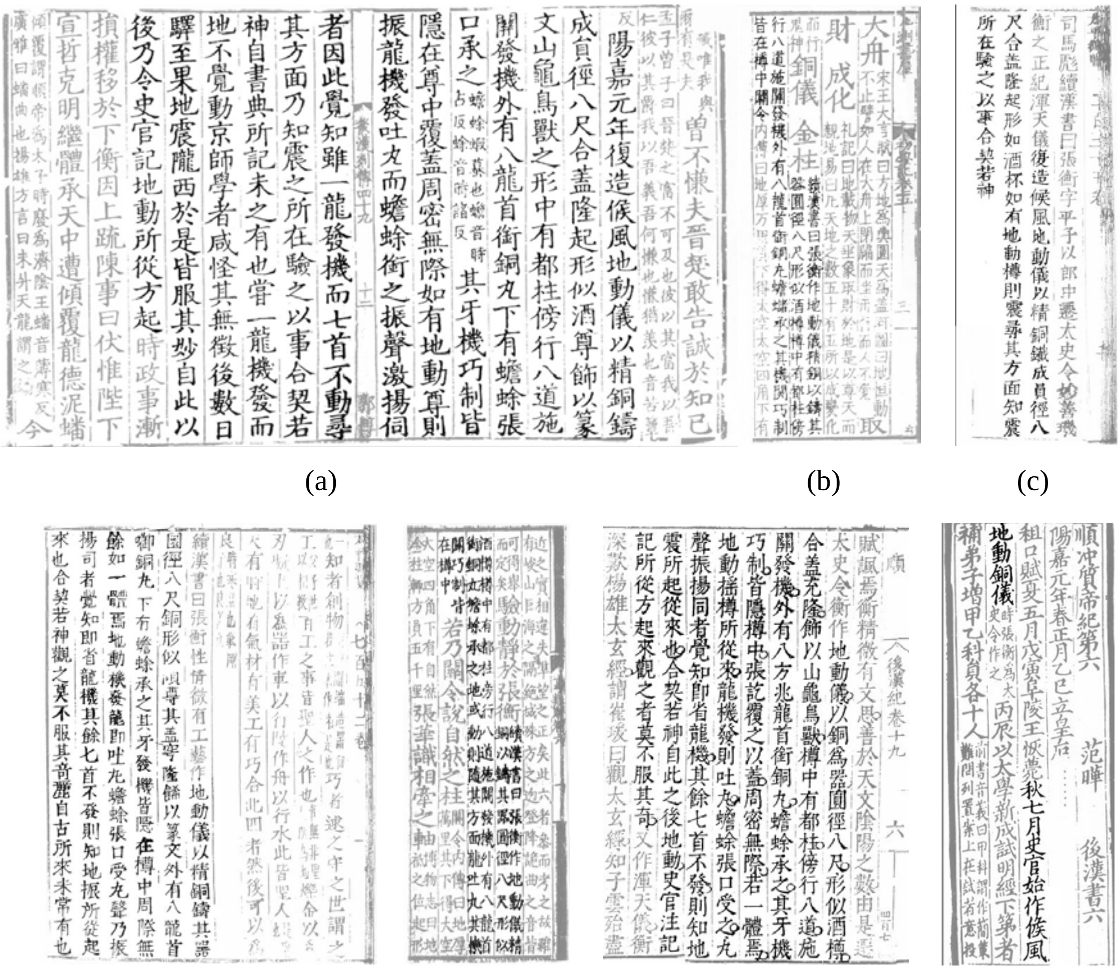
At 40 (117 AD), Zhang constructed the armillary sphere. At age 41, he published Ling Xian《靈憲》, which was a summary of astronomical theories at the time. The book contained discussions on the evolution of heaven and earth, the cosmos and the theory of planetary movements. It also contained accurate data on star observations and scientific explanations on the lunar eclipse. At 42 (119 AD), he wrote the Suan Wang Lun《算罔論》, a collection of works on the general theory of mathematics. 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 was between 3.1466 and 3.1622. At 49 (126 AD), Zhang again became a grand scribe.

At 55 (132 AD), Zhang invented the Di Dong Yi (地動儀), a device for detecting the direction of an earthquake. At 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 59 (136AD) and a minister at 61 (138 AD). He died at the age of 62 (139 AD) while serving as the minister.

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 summary, Zhang Heng can be respectfully referred to the Leonardo da Vinci of ancient China.

HISTORICAL RECORDS

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》(Fan 1977) is the only record about Zhang Heng's seismoscope, Fig. 1(a). In this archive, there are 196 Chinese characters regarding Zhang Heng's seismoscope. In 2006, six additional historical records were introduced including Xu Han Shu《續漢書》by Si Ma-biao (司馬彪), Hou Han Ji《後漢紀》by Yuan Hong (袁宏), and the Biography of Emperor Shun of the History of the Later Han Dynasty《後漢書·順帝紀》by Fan Ye (范曄) about Zhang Heng's seismoscope (Feng et al. 2006b). In these records, there are five earlier historical block-printed editions which had existed before the Biography of Zhang Heng in the History of the Later Han Dynasty by 70 to 150 years, such as Xu Han Shu《續漢書》, Figs. 1(b)-(e) and Hou Han Ji《後漢紀》, Fig. 1(f). Another record from the History of the Later Han Dynasty《後漢書》is shown in Fig. 1(g).



(a) (b) (c)

(d) (e) (f) (g)

Fig. 1 Historical records of Zhang Heng's seismoscope (Feng et al. 2006b)

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 parts mainly come from the Biography of Zhang Heng in the History of the Later Han Dynasty, such as the following descriptions:

1. During the first year of the Yang Jia period (132 AD), July in the autumn (in ancient Chinese calendar, July-September belongs to 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。)
2. The instrument was made of bronze with a diameter of eight chi (8 尺, 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 (都柱, a pillar) in the center of the interior and eight transmitting rods near the pillar. It carried out a switch ball and started the mechanism. There were eight dragons attached to the outside of the vessel, facing in the principal directions of the compass. A toad was below each dragon with open mouth toward the dragon. Each dragon's mouth contained a bronze ball. The intricate mechanism used was hidden inside the instrument. When the ground moved, the instrument shook and the ball located favorably to the direction of ground movement will drop out of the dragon's mouth and fall into the mouth of a bronze toad waiting below. The device also made a sound to inform the operator. And, each earthquake only made one ball drop. The direction faced

by the dragon whose ball was dropped would be the direction from which the shaking came. The device worked accurately and surprised the all viewers. From ancient times to the present, there was no record like it in the historical archives. (以精銅鑄其器，圓徑八尺，形似酒尊，其蓋窮隆，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。)

3. 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.

RECONSTRUCTION DESIGNS

Since the uncertain structure inside the seismoscope, some scholars had tried to reconstruct Zhang Heng's seismoscope in the past centuries. According to the characteristic and function, these reconstruction designs can be classified into five types, including external shape, suspended pendulum, direct contact, inverted pendulum, and authors' approach.

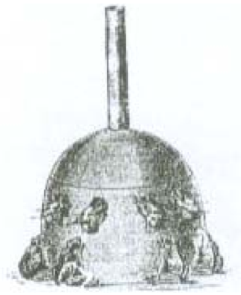
External shape

The first person to reconstruct Zhang Heng's seismoscope was I. Fukube, a Japanese scholar. He was also the first president of the Seismological Society of Japan, the first seismological society in the world found in 1880 AD. Based on the Biography of Zhang Heng in the History of the Later Han Dynasty, he drew the external of Zhang Heng's seismoscope in 1875, Fig. 2(a) (Imamura 1942). The dragons and the toads are in the appropriate positions and the shape of the vessel conforms to the historical records.

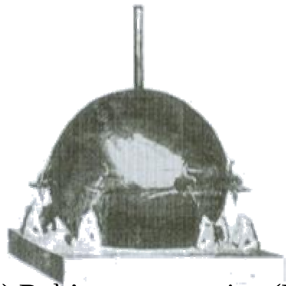
John Milne, often recognized as the Father of Modern Seismology, was a British geologist and mining engineer. Milne traveled from London, via Moscow, Beijing, and Shanghai to Tokyo in 1876. He was a professor at the Imperial College of Engineering in Tokyo from 1876 to 1895. He was not only the first vice-president of the Seismological Society of Japan in 1880 but also the first person who introduced the Biography of Zhang Heng in the History of the Later Han Dynasty to Western (Herbert-Gustar and Nott 1980). He designed the external of Zhang Heng's seismoscope in 1883, Fig. 2(b) (Milne 1883). His design shows a high pillar in the center of the vessel in order to suspend the long pendulum. However, the pillar of the design was too tall to conform to the historical records. Milne proposed that the principle of Zhang Heng's seismoscope is based on the principle of inertia. By the concept, he experimented on various types of pendulums including suspended, inverted and horizontal. For example, he experimented on a number of pendulums varying in the length from 1 to 36 feet suspended in his house and the building of the Engineering College for the purpose of verifying earthquake motion. Furthermore, he built the first practical seismograph and set up the seismograph in seismological stations all over the world.

The first Chinese to reconstruct Zhang Heng's seismoscope was Lu Yan-zhi (呂彥直), an architect (Wang 1963). In 1917, Lu just redrew the external of Milne's reconstruction design with more graceful painting. In 1931, Lee Shan-bang (李善邦), a Chinese seismologist, proposed the external of Zhang Heng's seismoscope (Wang 1963). However, he merely modified Hattori's external appearance of reconstruction design with a different painting method, Fig. 2(c).

In 1978, Bruce A. Bolt, an American seismologist, proposed a reconstruction design of Zhang Heng’s seismoscope based on Milne’s concept, Fig. 2(d) (Bolt 1978). And, the pillar was too tall to conform to the historical records.



(a) Fukube’s reconstruction (Imamura 1942)   (b) Milne’s reconstruction (Milne 1883)



(c) Lee’s reconstruction (Wang 1963)   (d) Bolt’s reconstruction (Bolt 1978)

Fig. 2 Reconstruction designs with external shape only

Suspended pendulum

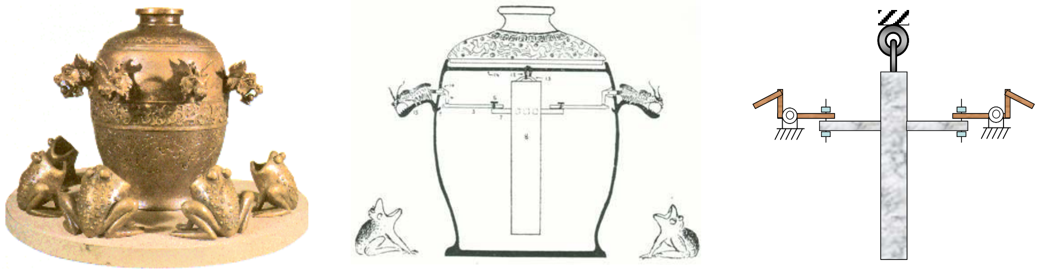
A suspended pendulum has two desirable characteristics as a sensing element. First, the suspended pendulum is largely isolated from the ground motion by its suspension design. Second, the mass of the pendulum has inertia, and tend to remain at rest. However, the main defect of suspended pendulum as a sensing element is the short free period and hard to detect the distant earthquake.

Wang Zhen-duo (王振鐸), a Chinese scholar, was the first person to reconstruct a real prototype of Zhang Heng’s seismoscope. In 1936, he presented a reconstruction design as shown in Fig. 3(a) (Wang 1936). In this design, the central pillar is a suspended pendulum to function as a sensing element. Once a seismic wave shakes the pendulum, the pendulum will press the nearby mechanism to release the ball from the dragon’s mouth. However, the shaking pendulum should press more than one linkage mechanism. By the means, more than one ball will fall into the toads, and therefore such a concept does not conform to the historical records.

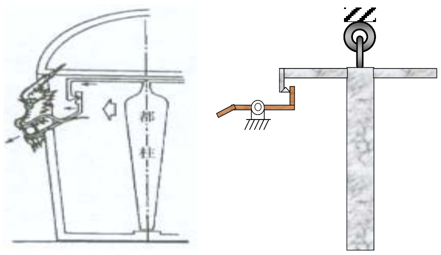
In 1981, Lee Shan-bang’s book proposed Lee’s second reconstruction design. He considered that the central pillar is a suspended pendulum to function as a sensing element, Fig. 3(b), and the toads are omitted (Feng et al. 2006b). However, the shaking pendulum should press more than one linkage mechanism. It has the same problem as the foregoing Wang’s model.

In 1983, Sleeswyk and Sivin presented an instrument such that the central pillar is a frame and the vessel is suspended from the central pillar, Fig. 3(c) (Sleeswyk and Sivin 1983). Once the seismic wave shakes the vessel, the vessel will press the central pillar and the ball on the top of the central pillar will roll into the corresponding dragon’s mouth. However, this model detects both cases of compressing and expanding waves. This means that the model can make response to the direction of the epicenter or opposite side of the epicenter.

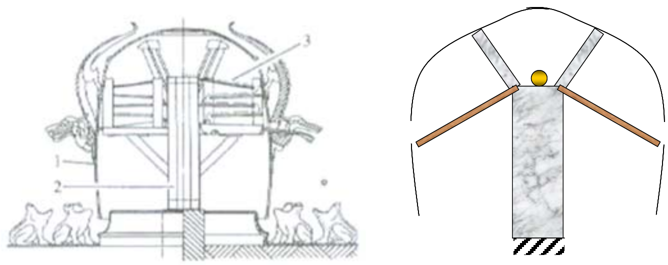
In 2006, Feng Rui (馮銳) and his colleague reported and reconstructed Zhang Heng’s seismoscope, Fig. 3(d) (Feng et al. 2006a). In this design, the central pillar is a suspended pendulum to function as the sensing element. The inner structure consists of five components: Zhu (柱, pendulum), Guan (關, ball 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 mechanism opens the corresponding dragon’s mouth and the ball falls into the toad below. This model detects both cases of compressing and expanding waves; nevertheless, it has the same problem as the foregoing Sleeswyk and Sivins’ model.



(a) Wang’s reconstruction (Wang 1936)



(b) Lee’s reconstruction (Feng et al. 2006b)



(c) Sleeswyk and Sivin’s reconstruction

(Sleeswykn and Sivin 1983)

(d) Feng’s reconstruction (Feng et al. 2006a)

Fig. 3 Reconstruction designs based on a suspended pendulum

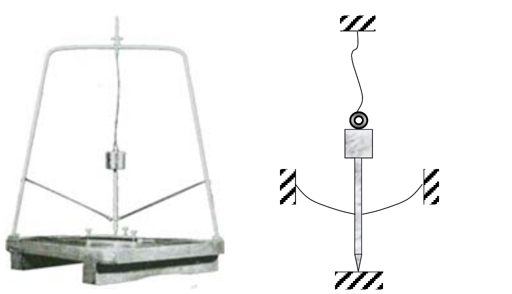
Direct contact

The direct contact is the simplest type of the sensing element. However, the detecting performance is the worst due to the friction and instability among the reconstruction designs.

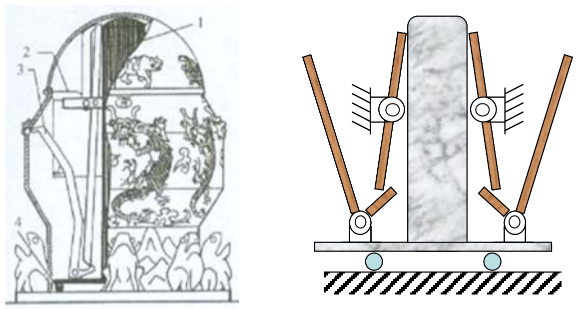
In 1939, A. Imamura, a Japanese seismologist, used an upright rod with its foot tapered to function as the sensing element, Fig. 4(a) (Imamura 1939). The top is tied to a thin cord with a hoop. A device is provided for correctly setting the pendulum which consists of a micrometer fixed on the top of a vertical metal frame crossing over the pendulum. A nut allows the micrometer to be slowly up and down without undergoing any rotations. Once a seismic wave comes, the pendulum loses its equilibrium and topples over to show the direction of the earthquake. This model detects both cases of compressing and expanding waves. It can make response to the direction of the epicenter or opposite side of the epicenter. The instable situation is another problem in detecting the epicenter.

In 1994, Lee Zhi-chao (李志超), another Chinese scholar, proposed a design of Zhang Heng’s seismoscope, Fig. 4(b) (Lee 1994). In such a design, the central pillar is a cylinder with eight small balls below. Once a shake comes, the central pillar can move in the inside plane of the instrument to press the nearby linkage mechanism. The ball in the vessel will fall after the mechanism functions. In this design, the central pillar should press more than one mechanism. By the means, more than one ball will fall into the toads, and therefore such a concept does not conform to the historical records.

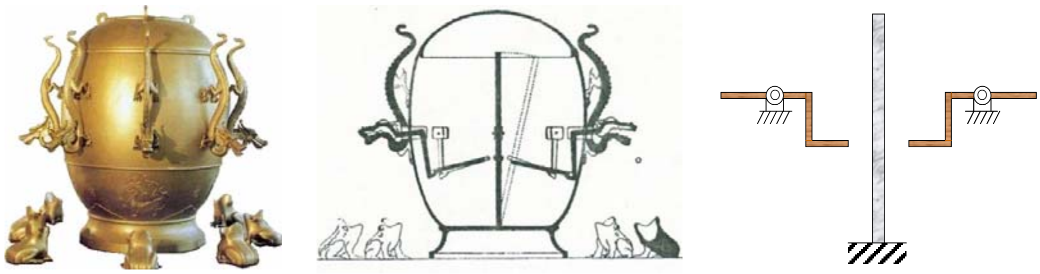
In 1963, Wang Zhen-duo presented another design of Zhang Heng’s seismoscope, Fig. 4(c) (Wang 1963), in which the central pillar is an upright rod to function as the sensing element. Once a shake comes, the rod loses its equilibrium and topples in one of eight channels to trigger the mechanism. Then the mechanism opens the corresponding dragon’s mouth and the ball in the dragon’s mouth falls in the toad below. This model detects both cases of compressing and expanding waves. It can make response to the direction of the epicenter or opposite side of the epicenter. And, the friction between the central pillar and ground is another problem in detecting the epicenter.



(a) Imamura’s reconstruction (Imamura 1939)



(b) Lee’s reconstruction (Lee 1994)



(c) Wang’s reconstruction (Wang 1963)

Fig. 4 Reconstruction designs based on direct contact

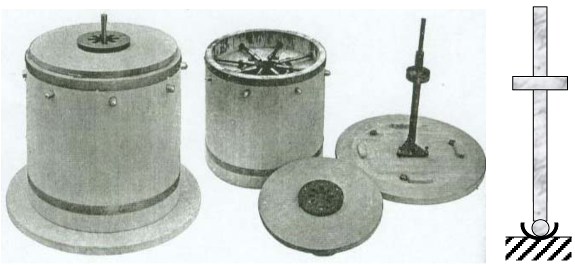
Inverted pendulum

Whereas a suspended pendulum is stable when hanging downward, an inverted pendulum is inherently unstable, and must be actively balanced in order to remain upright, either by applying a torque at the pivot point or by moving the pivot point horizontally.

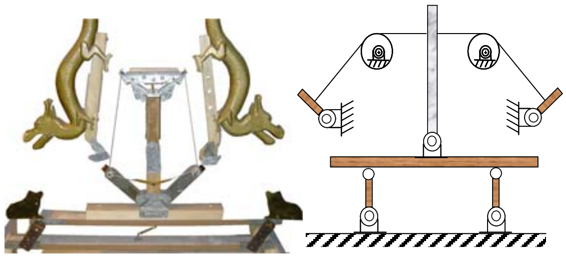
In 1937, T. Hagiwara, a Japanese seismologist, built an instrument with only an inverted pendulum to function as the sensing element, without the dragons and the toads, Fig. 5(a) (Imamura 1942). Once an earthquake occurs, the pendulum loses its equilibrium and topples in the center of a horizontal circular plate which is perforated with a circular hole at the center with eight equidistant slits. Then the pendulum goes into the nearest slit and pushes the slide to show the direction of the earthquake. Here, the pendulum should push more than one slide, and therefore such a concept does not conform to the historical records.

In 1991, Wang Jian (王湔), a Chinese scholar, designed and built another Zhang Heng's seismoscope, Fig. 5(b) (Feng et al. 2006b). The inverted pendulum is at the bottom of the instrument to function as a sensing element. The inverted pendulum detects the shake to drive the mechanism. The mechanism makes the center pendulum to topple over, and the ball in dragon's mouth falls by the toppling center pendulum. However, only 2 dimensions can be detected in this model.

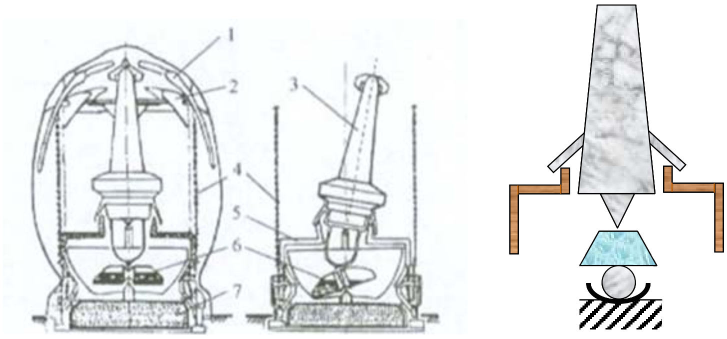
In 1994, Liang Shao-jun (梁紹軍), a Chinese industrialist, presented a design of Zhang Heng's seismoscope, Fig. 5(c) (Feng et al. 2006b). The mercury container is at the bottom of the instrument to function as a sensing element. Once a shake occurs, the mercury container topples over to force the central pillar driving the nearby mechanism. However, no historical records can be found in applying the mercury container to Zhang Heng's seismoscope.



(a) Hagiwara's reconstruction (Imamura 1942)



(b) Wang's reconstruction (Feng et al. 2006b)



(c) Liang's reconstruction (Feng et al 2006b)

Fig. 5 Reconstruction designs based on an inverted pendulum

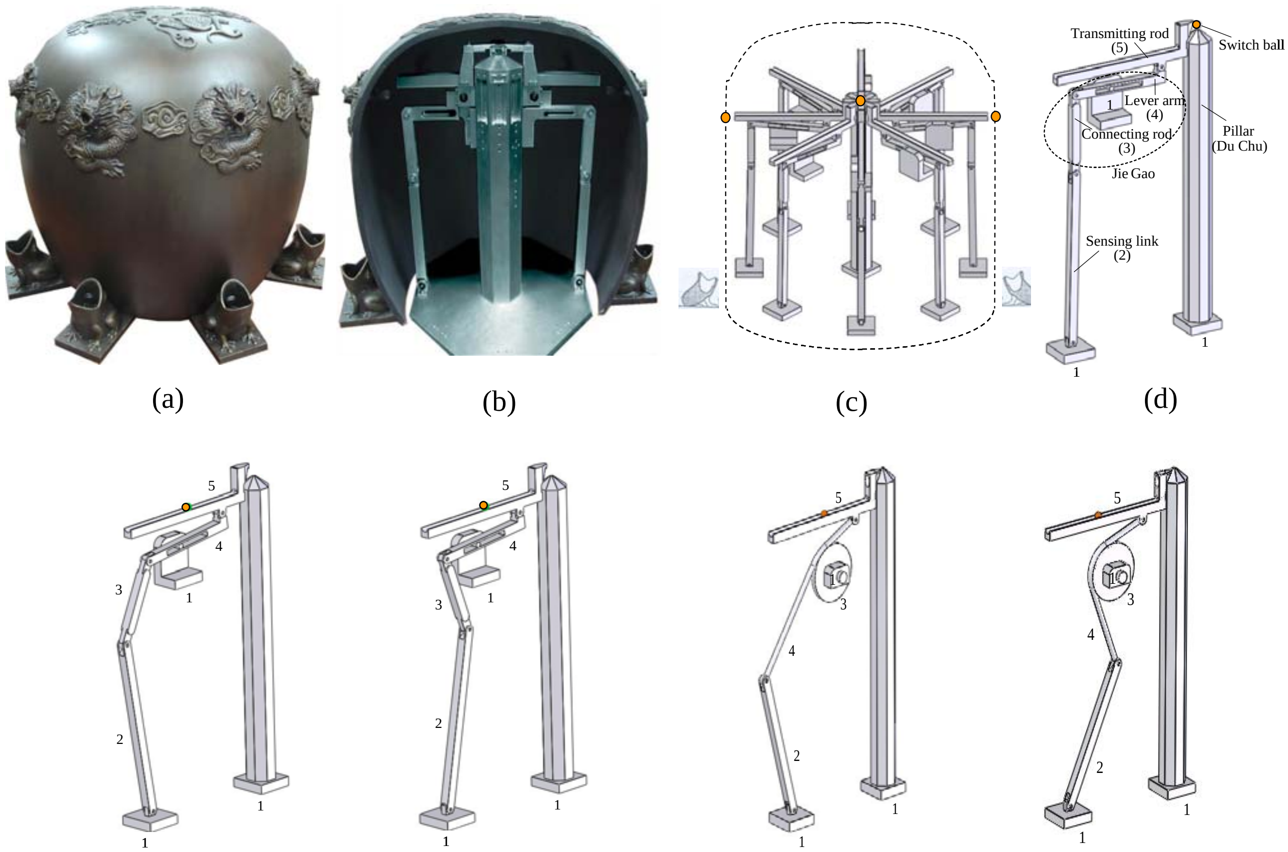
Authors' approach

In 2007, Yan and Hsiao proposed an approach to reconstruct possible interior mechanisms of Zhang Heng's seismoscope systematically (Yan and Hsiao 2007). Based on literature and seismology study, the design requirements and constraints of Zhang Heng's seismoscope are defined through the following three parts: study of historical archives, investigation of seismology, and analysis of ancient seismographs. Design requirements and constraints can be flexible and are varied for different expectations. They are normally identified based on technology reality and designers' decisions. Different design requirements and constraints derive different results.

Then, according to the concepts of generalization and specialization of mechanisms subject to the concluded design requirements and constraints, all feasible design concepts that are in accordance with the science theories and techniques of the subject's time period can be synthesized (Yan 2007).

The power source of Zhang Heng's seismoscope is seismic waves including P-wave, S-wave and surface waves. P-wave is the first-arriving wave from an earthquake. Its travel is the same as the direction of the earthquake and can produce either compressing or expanding ground motion. The main assuming wave in the instrument is P-wave. If Zhang Heng's seismoscope can detect the direction of P-wave, no matter whether it is compressing or expanding, the direction of the earthquake can be discovered by the instrument.

Fig. 6 shows the 3D solid models of two possible reconstruction designs of Zhang Heng's seismoscope with five members and six joints developed by the authors. Figs. 6(a) and (b) show the external shape and the part of the prototype of the interior mechanism, respectively. There are eight mechanisms in the principal directions of the instrument, Fig. 6(c). A switch ball is held with the eight transmitting rods (link 5) on the top of the pillar. The detail interior mechanism is shown in Fig. 6(d). The sensing link (link 2) detects the longitudinal wave of the earthquake, no matter whether it is compressing or expanding. When the wave is compressing, the sensing link 2 topples to the left, the magnifier makes the transmitting rod (link 5) rising. The switch ball loses its equilibrium and drops out of the pillar to move to the wall of the vessel by the transmitting rod. Through the collision between the balls, the ball in the wall will drop out and fall into the mouth of a toad below. The direction of the earthquake can be shown by the dropping ball, Fig. 6(e). Since only one switch ball on the top of the pillar, each earthquake only makes one ball drop. On the contrary, if the wave is expanding, the sensing link 2 topples to the right, Fig. 6(f). Figs. 6(g) and (h) show another possible interior mechanism with link and rope-and-pulley. Similarly, no mater it is compressing or expanding, the sensing link topples to pull the rope-and-pulley. The ball drops out of the pillar to move to the wall of the vessel.



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

(e) Compressing wave (f) Expanding wave (g) Compressing wave (h) Expanding wave

Fig. 6 Two possible reconstruction designs based on Yan's methodology

CONCLUSIONS

This work reviews the background of Zhang Heng's seismoscope including existing historical records and available reconstruction designs. An innovative systematical approach for reconstruction design of the lost Zhang Heng's seismoscope developed by the authors is also introduced. Through the study of historical archives, design requirements of Zhang Heng's seismoscope are concluded. Then, by applying the creative mechanism design methodology (generalization and specialization) subject to the concluded design requirements and constraints, all feasible design concepts of Zhang Heng's seismoscope are systematically reconstructed that meet the science theories and techniques of the subject's time period. Due to incomplete historical records, there are many possible designs for the inner structure of Zhang Heng's seismoscope. Based on authors' approach, various designs with different types and numbers of members and joints can be obtained. And, such an approach provides a logical means to study the lost seismoscope systematically.

ACKNOWLEDGMENT

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

REFERENCES

Bolt, B. A. (1978). *Earthquakes: A Primer*, W. H. Freeman and Co., New York, USA.

Fan, Y. (Eastern Jin Dynasty) (reprinted in 1977). *The History of the Later Han Dynasty* (in Chinese), Ding Wen Book Co., Taipei, Taiwan.

Feng, R., Tian, K., Shu, T., Wu, Y. X., Zhu, X. M., Li, X. D., and Sun, X. L. (2006a). "Scientific Reconstruction of Zhang Heng's Seismometer." *Studies in the History of Natural Sciences*, Vol. 25, Suppl., pp. 53-76.

Feng, R., Wu, Y. X., and Zhu, T. (2006b). "Research on the Historical Records and Reconstruction Models of Zhang Heng's Seismometer." *Studies in the History of Natural Sciences*, Vol. 25, Suppl., 34-52.

Herbert-Gustar, L. K. and Nott, P. A. (1980). *John Milne: Father of Modern Seismology*, Paul Norbury Publication Ltd, Tenterden, Kent, UK.

Imamura, A. (1939). "Tokyo and His Seismoscope." *Japanese Journal of Astronomy and Geophysics*, Vol. 16, No. 2-3, 37-41.

Imamura, A. (1942). *Zhi Na Wen Hua Cong* (in Japanese), Ming Qu Publishing House, Tokyo, Japan.

Lee, Z. C. (1994). *Tian Ren Gu Yi* (in Chinese), Elephant Press, Hefei, China.

Lu, J. Y. (2003). *History of Chinese Machinery* (in Chinese), Yue Yin Press, Taipei, Taiwan.

Milne, J. (1883). *Earthquakes and other Earth Movements*, Appleton, New York, USA.

Sleeswyk, A. W. and Sivin, V. (1983). "Dragons and Toads, the Chinese Seismoscope of A.D. 132." *Chinese Science*, Vol. 6, pp. 1-19.

Wang, Z. D. (1936). "Conjecture of Zheng Heng's Seismoscope." *Yenching University Journal of Chinese Studies* (in Chinese), Vol. 20, pp. 577-586.

Wang, Z. D. (1963). *Ke Ji Kao Gu Lun Cong* (in Chinese), Cultural Press, Beijing, China.

Yan, H. S. (2007). *Reconstruction Designs of Lost Ancient Chinese Machinery*, Springer, Netherlands.

Yan, H. S. and Hsiao, K. H. (2007). "Reconstruction Design of the Lost Seismoscope of Ancient China." *Mechanism and Machine Theory*, Vol. 42, No. 12, pp. 1601-1617.

(Submitted: September 24, 2008)
(Accepted: April 27, 2009)