The Effect of Driving Method and Crank Arrangements on the Performance of a Reconstructed Ancient Chinese Wooden Horse Carriage

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The purpose of this study is to investigate the effect of driving method and crank arrangements on the performance of a reconstructed ancient Chinese wooden horse carriage. The results demonstrate better transmission efficiency when the driving torque of wooden horse carriage acts on the crank shaft. The analysis of crank arrangements shows that the phase angle between front and rear legs on the same side should be 0 deg or 90 deg and the one between the legs on the different sides should be 180 deg. These results are beneficial to the future reconstruction of the ancient Chinese wooden horse carriage. [DOI: 10.1115/1.4024233]

Keywords: crank arrangement, wooden horse carriage, walking machine, equation of motion

1 Introduction

A walking machine or a legged vehicle is one that moves itself and keeps itself balanced as it moves from one place to another by legs. Different from traditional wheeled vehicles, it moves with legs using contact and noncontact finite motions relative to the ground. The study on walking machines started in the late 19th century. In 1893, Rygg [1] obtained a U.S. patent for a mechanical horse. It consisted of linkages and gears and was driven by manpower, but there was no evidence showing that this design could remain stable while walking.

Studies and publications on the modern walking machines appeared only in the last 100 years. However, according to an ancient Chinese record, "Lun Heng" by Wang Chong in the Eastern Han Dynasty (AD 23–220), a legendary walking machine named "wooden horse carriage" might have been created by Lu Ban during the period of ancient China's Era of Spring and Autumn around 500 BC [2]. This invention was considered a novelty and could only be found in literary records without surviving objects.

It is unfortunate that most ancient inventors were unable to adequately document their inventions and safely preserve them. Therefore, the reconstruction of ancient machinery is to rebuild the machinery by applying available ancient mechanical principles, engineering, and technological skills to an original machine. A systematic procedure of reconstruction investigation is helpful when people try to rebuild the lost designs. Very few scholars had studied the lost Chinese walking machines, but till the last decades, scholars believed that the wooden horse carriage of Lu Ban was an enigmatic ancient invention. In the mid of 1980 s, Wang Chien of Urumqi in Province Xinjiang of China, built a wooden horse carriage based on his ingenious experience in a sense of practicality [2]. This design is composed of a walking mechanism with four legs and a carriage to balance itself while in motion. Each leg of the walking mechanism is an eight-bar linkage mechanism with identical structures. Based on the methodology for the reconstruction synthesis of lost mechanisms, Yan [3,4] started to reconstruct various designs of this lost machine. One of the feasible designs, a planar 8-bar linkage as the leg mechanism, was further developed into various mechanical horse carriages. This walking machine realistically mimicked the walking manners of a horse with only one degree-of-freedom (DOF) and without any control device.

When designing a walking machine, its dynamic response is the key element that must be considered. It affects the stability of locomotion. Existing references have synthesized the feasible structures of walking mechanism, studied the foot trajectory and stance leg sequence of selected designs, and then calculated the driving force and mechanical advantage. For a rigid mechanical system with a single DOF, its equation of motion can be expressed as a second-order nonlinear differential equation [5,6]. Generally speaking, most mechanisms have a single DOF and their dynamic response can be expressed as a single equation of motion that can easily be solved by numerical methods [7]. And, this study is to further investigate the effect of driving method and crank arrangements on the motion performance of the walking machine, including dynamic responses of the wooden horse carriage, stance leg sequence, and pitch angle.

2 Assembly of Wooden Horse Carriage

Based on the reconstruction research regarding Lu-Ban's wooden horse carriage, a walking machine consists of two parts: the quadruped walking mechanism and the carriage, Fig. 1. The walking mechanism generates leg movement, while the carriage is to maintain balance during the motion. This walking mechanism consists of four identical leg mechanisms. The front and rear legs on the right and left sides are oriented in reverse directions.

Many applications in engines, pumps, and compressors involve the use of multiple mechanisms, which are synchronized to provide smoother flow of fluid or transmission of power than that can be accomplished in a single-cylinder device. Besides, through a proper crank arrangement of individual mechanisms, the performance can be improved as well. For investigating the effect of crank arrangements on the performance of wooden horse carriage, three designs are proposed as shown in Table 1. The symbols RF, LF, RR, and LR in Table 1 indicate the right front, left front, right rear and left rear legs, respectively. Type A is the existing reconstructed design in which there is no phase angle between the cranks of front and rear legs on the same side and 180 deg between the legs on the different sides. Type B is a new design in which there is 90 deg between the front and rear legs on the same side and 180 deg between the legs on the different sides. Type C is another new design in which there is 180 deg between the front and rear legs on the same side and 90 deg between the legs on the different sides.

3 Generalized Equation of Motion

According to the mobility criterion for planar mechanisms, the walking machine is a single-DOF mechanical system. Because all members of the walking machine are rigid members, its motion can be represented by a second-order nonlinear differential equation [5] as follows:

$$I(\theta)\ddot{\theta}(t) + C(\theta)\dot{\theta}^2(t) = M(\theta) \quad (1)$$

Contributed by the Mechanisms and Robotics Committee of ASME for publication in the Journal of Mechanical Design. Manuscript received October 2, 2012; final manuscript received March 21, 2013; published online May 9, 2013. Assoc. Editor: Oscar Altuzarra.

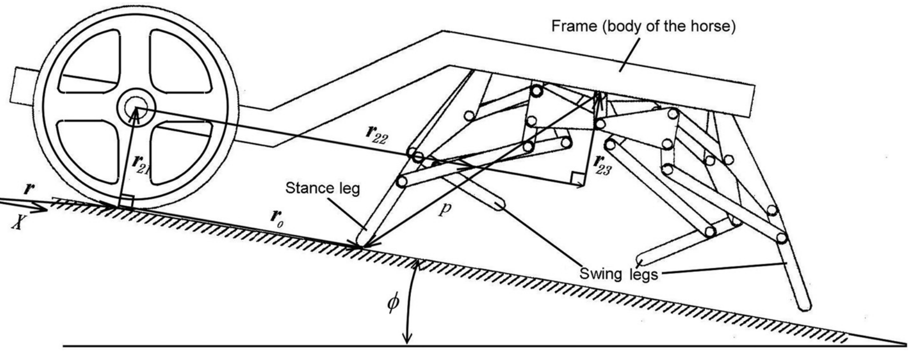

Fig. 1 Wooden horse carriage

Table 1 Crank arrangements

Type	A	B	C
Phase angle	RF RR (top); LF LR (bottom)	RF (top); LR (left); RR (right); LF (bottom)	RF (top); LR (left); LF (right); RR (bottom)

which is known as the generalized equation of motion in which θ is the angular displacement of the input link, $I(\theta)$ is the generalized inertia, $C(\theta) = 1/2\ d[I(\theta)]/d\theta$, and $M(\theta)$ is the generalized moment.

If a mechanism is formed by n links, $I(\theta)$ and $C(\theta)$ in Eq. (1) can be represented as follows:

$$I(\theta) = \sum_{i=1}^{n} \left[m_i (h_{gix}^2 + h_{giy}^2) + J_i h_i^2 \right] \tag{2}$$

$$C(\theta) = \sum_{i=1}^{n} \left[m_i (h_{gix} h'_{gix} + h_{giy} h'_{giy}) + J_i h_i h'_i \right] \tag{3}$$

where m_i is the mass of link i, J_i is the mass moment of inertia of link i, h_i is the kinematic coefficient of link i relative to the input link, and h_{gix} and h_{giy} are the kinematic coefficients of the centre of gravity of link i in X and Y axis, respectively, relative to the input link. The details with regard to deriving the kinematic coefficients of each link and its center of gravity, and the position analysis can be referred to Ref. [7]. Besides, when the driving torque is applied on the crank shaft, the generalized moment, $M(\theta)$, for the wooden horse carriage during downhill is

$$M(\theta) = T(1 - h_1) + \sum_{i=1}^{4} \sum_{j=1}^{8} m_j g (h_{gjx} \sin\phi - h_{gjy} \cos\phi) - C_d \dot{\theta} \tag{4}$$

And when the driving torque is applied on the wheel shaft, the generalized moment, $M(\theta)$, becomes

$$M(\theta) = T(h_{11} - h_1) + \sum_{i=1}^{4} \sum_{j=1}^{8} m_j g (h_{gjx} \sin\phi - h_{gjy} \cos\phi) - C_d \dot{\theta} \tag{5}$$

where T is the driving torque on the crank shaft, Th_{11} is the driving torque on the wheel shaft, $-Th_1$ is the reaction torque on the body of the horse, $\sum_{i=1}^{4} \sum_{j=1}^{8} m_j g (h_{gjx} \sin\phi - h_{gjy} \cos\phi)$ is the torque generated by the gravity force of each link in the wooden horse carriage during downhill, and C_d is the damping coefficient of the system.

4 Results and Discussion

The dynamic motion simulation of the wooden horse carriage can be obtained by way of using the fourth-order Runge–Kutta numerical method. Figure 2 shows that when the slope angle is 4 deg

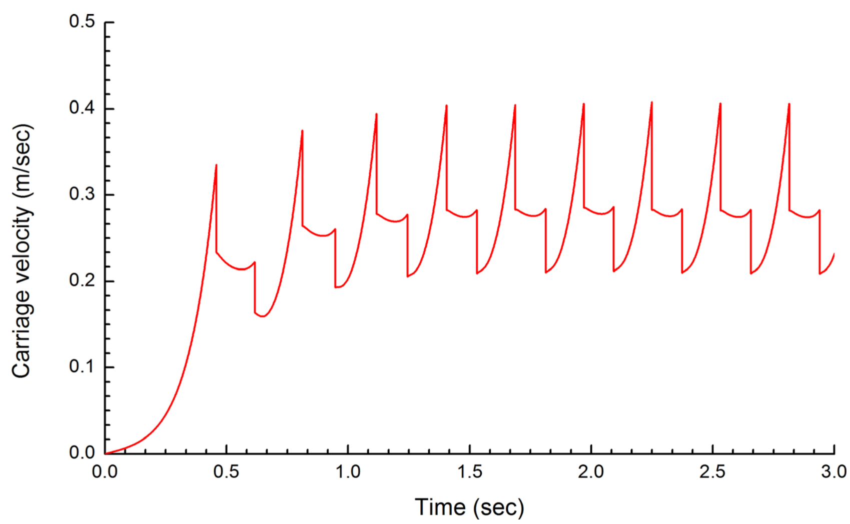

Fig. 2 Dynamic response during downhill without damping

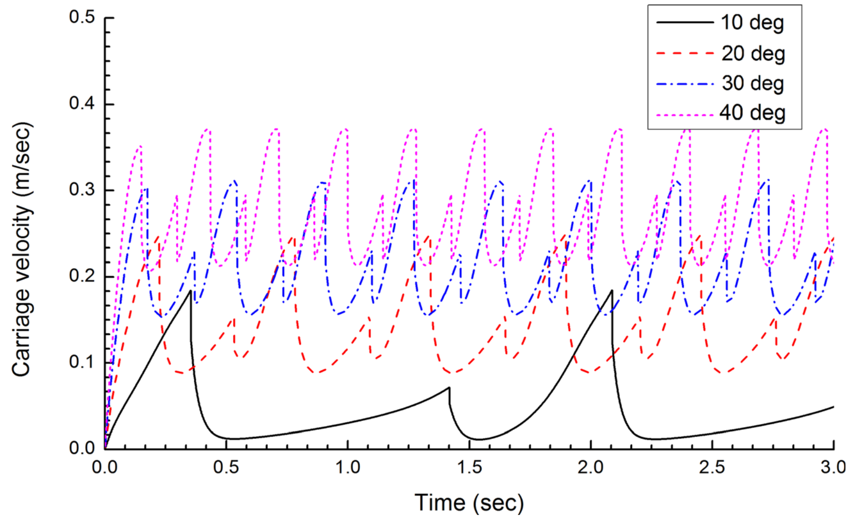

Fig. 3 Dynamic responses during downhill with different slopes

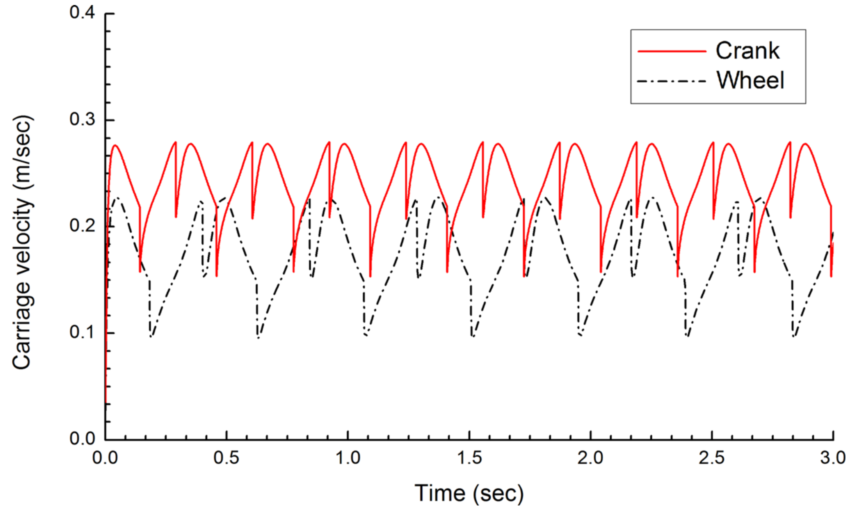

Fig. 4 Dynamic response of the walking machine

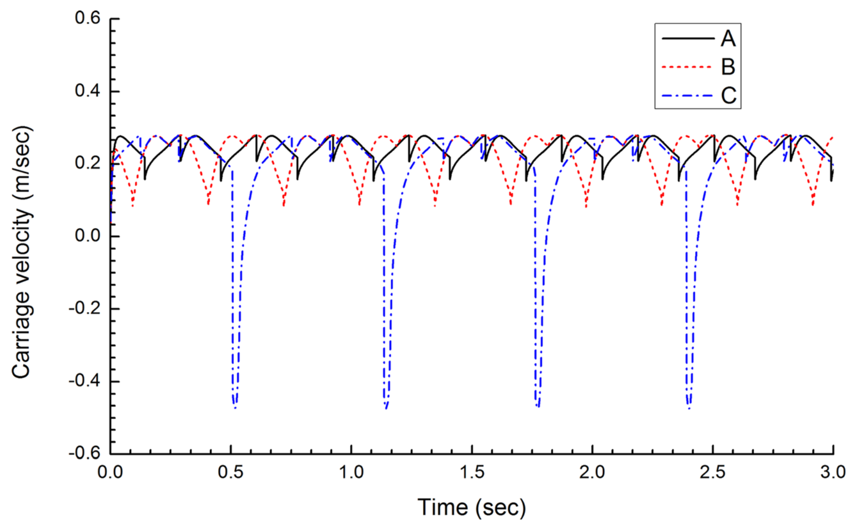

Fig. 5 Velocity of carriage

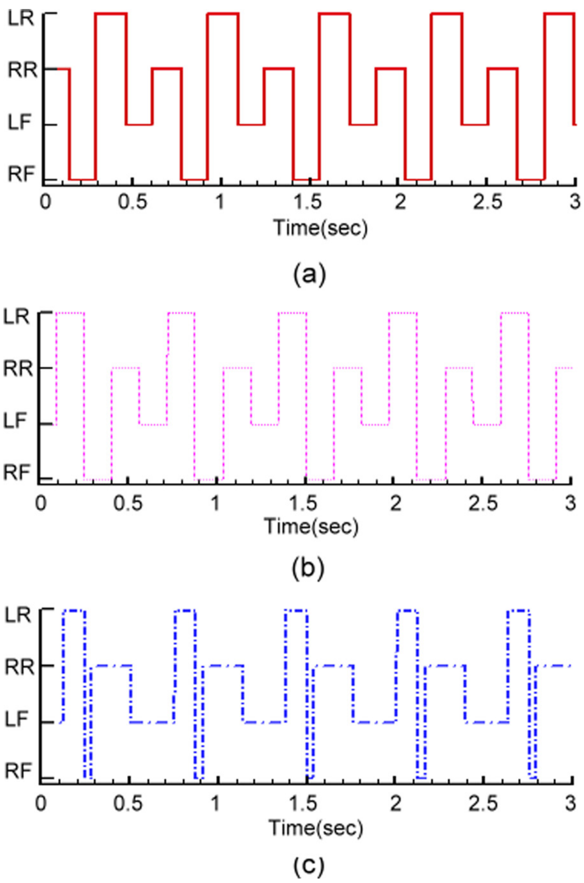

Fig. 6 Stance leg sequence

downhill without considering the system damping, the torque generated by the gravity force of all links in any crank position of the wooden horse carriage is greater than zero, i.e., the wooden horse carriage can walk downhill automatically. And, an experiment is performed to confirm this result. The reconstructed ancient Chinese wooden horse carriage is placed on a 1.50 m long slope with 4 deg inclined and allowed to move down freely. It takes 6.2 s to finish the slope and the average velocity is about 0.242 m/s. The average carriage velocity in the course of the slope from simulation is about 0.253 m/s as shown in Fig. 2. The confirmed velocity is slightly smaller than the simulated velocity due to the effect of friction on joints.

Figure 3 shows the velocity under 0.005 N·m·s damping of the same carriage downhill with different slope angles driven by gravity. When the slope angle is 10 deg, the velocity of the carriage is low and the fluctuation is high. The average velocity of the carriage increases with the slope angle, but the magnitude of fluctuation does not decrease significantly. However, for the common wheeled vehicles, they will reach a maximum constant velocity when the driving force and resistance are equal. Figure 4 illustrates the dynamic response of the wooden horse carriage on a flat ground under a driving torque of 0.5 N·m acting on the shaft of the wheels and the shaft of the crank, respectively. As shown in the figure, when the driving torque acts on the wheel shaft and crank shaft, the carriage speed fluctuates at about 0.16 m/s and 0.24 m/s, respectively. The results show that the carriage velocity is faster when the driving torque acts on the crank shaft than that on the wheel shaft. Therefore, in what follows, the driving torque of the wooden horse carriage acts only on the crank shaft in order to obtain better transmission efficiency.

Figure 5 illustrates the velocities of the carriage with different crank arrangements. The fluctuation of existing design A is smaller and the motion is smoother. But the fluctuation of design C is unacceptably huge, changing from positive value to negative instantly while walking forward. The reason is that the walking machine is braced by its four legs against the ground in turn and, in the instant of changing the stance leg, the velocities of the two legs differ. When the walking machine moves forward, the velocity of the next stance leg is less than that of the current stance leg. The velocity difference of designs A and B between the current and next stance legs is smaller, thus reducing deceleration and skidding and making the speed considerably stable. But the velocity difference of design C is larger, thus causing huge decelerating and skidding.

Figure 6 shows the sequence of the stance legs. The legs of design A are lifted off or touched down on the ground separately in the sequence of right rear, right front, left rear, and left front legs. The legs of design B are in the sequence of left front, left rear, right front, and right rear legs. The stance leg sequence of design C is the same as design B. But the stance time of right front leg is shorter and the right rear leg is longer. Generally speaking, the stance time for each leg should be the same and the motion of the horse carriage will be stable and smooth. Therefore, from the point of view considering the stance leg sequence, it is obvious that design C is poor.

Figure 7 shows the variations in the pitch angle of the wooden horse carriage. The pitch angles of designs A and B are small but

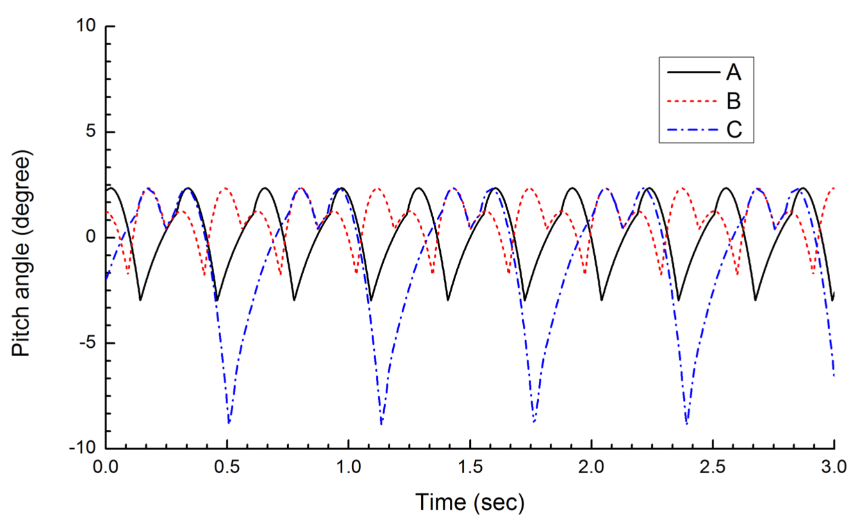

Fig. 7 Pitch angle

design C is considerable, ranging between −9.0 deg and +2.4 deg. Variations in the vertical height of the crank shaft produce changes in the pitch angle. The vertical height of the crank shaft of design C changes from 0.049 m to 0.073 m, indicating a considerable variation. This causes the large pitching of the carriage. When the pitch angle increases, the duty factor for front legs reduces and that of the rear legs increases. On the contrary, when the pitch angle reduces, the duty factor for front legs increases and that of the rear legs reduces. For regular gait, the duty factors for all legs must be arranged as close as possible. As a result, the variation of pitch angle would be as small as possible.

5 Conclusion

This work first introduces the assembly of the mechanism of an ancient Chinese wooden horse carriage and proposes two new arrangements of cranks. The basic theory behind the equation of motion is briefly introduced and solved by using Runge–Kutta method. The results demonstrate better transmission efficiency when the driving torque of wooden horse carriage acts on the crank shaft. The analysis of crank arrangements shows that existing design A and new design B have better performance in dynamic responses, including velocity stability of the carriage, stance leg sequence, and pitch angle. This means the phase angle between front and rear legs on the same side should be 0 deg or 90 deg and the one between the legs on the different sides should be 180 deg. The results from this research are beneficial to the future reconstruction of the ancient Chinese wooden horse carriage and other walking machines.

Acknowledgment

The authors are grateful to the National Science Council of the Republic of China (Taiwan) for supporting this research under Grant No. NSC 101-2221-E-168-007.

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