Dynamical and structural analysis of a Bronze Age war chariot

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Abstract. The introduction of two-wheel chariots, pulled by horses, was a key technological innovation in the Bronze Age. Archaeological evidences, found in Northern Africa, Europe and Asia, allowed identifying various chariot typologies and understanding their main features. However, many questions about the function of single pieces and the behavior of the vehicles are still open. In a previous work, a war chariot wheel, found in northern Italy and known as the “Mercurago wheel”, was studied with an engineering approach. In this paper, the whole vehicle, to which the wheel was hypothesized to belong, was studied. In particular, two chariot typologies, differing mainly for the axle position, were analyzed. The stiffness of the various chariot parts were characterized by means of static finite element analyses. These data were subsequently used as input parameters in running multibody dynamics simulations. Finite element dynamical simulations were carried out as well. The analyses results allowed determining the crucial effect of some parts, particularly the cockpit floor, in favoring the passenger stability in dangerous conditions, such as bumping. The effect of the axle position on the passenger and wheel trajectory were evaluated as well.

1. Introduction
The two-wheeled chariot was a key factor in the development of Bronze Age civilizations [1]. After the domestication of the horse, ancient engineers understood that lightweight, resistant and agile vehicles could provide a decisive advantage, mainly in fighting, but even in hunting and traveling. Initially developed in Syria and Northern Mesopotamia around the 2000 b.C., they quickly spread in all the Middle East, Egypt, Greece, as well as in Europe.

Common elements of all chariots were those schematically shown in Figure 1. The two wheels, usually with an optimized shape in terms of resistance/weight ratio, were rotating around a fixed axle. The axle was fixed to the vehicle body, which included the cockpit, the pole and the yoke. The fixed elements should be tightly connected by leather stripes. As observed in some evidences [1], the cockpit floor should be obtained by interwoven leather stripes.

Within these common features, a variability can be found in shape, structure and assembly of the chariot elements. The wheels were mostly spoked, with four, six or even a larger number of spokes. A remarkable exception is the crossbar wheel, which was diffused among Greek and Italic peoples in Early Bronze Age [2]: being lighter than disc wheels, and simpler to assemble than spoked wheels, the crossbar wheel is thought to be an intermediate step in the evolution from the former to the latter. The wheel of Mercurago is a famous example, which was studied by Mazzù et al. [3] from an engineering point of view, revealing the surprising grade of technology staying behind the concept of such wheel. The pole
could have a variably curved shape, to compensate for the difference of height of the attachments to the yoke and the axle. Sandor [4],[5] highlighted the advanced design of the poles of the Egyptian “Tutankhamun-class” chariots: they were steam curved in order to provide an optimized shape in terms of elasticity and shock absorption. These chariots were the most advanced ones in the Bronze Age, having even many other technical solutions for stability, oscillation damping and safety. Another key issue is the position of the axle under the cockpit: Egyptian and Assyrian chariots were attached at the rear end of the cockpit, whereas Greek, Roman and Celtic axle were attached just below the traveler feet [5],[6]: the former solution weighed more on the animal back, but on the other hand increased the elasticity of the cockpit support.

Figure 1. Scheme of an ancient war chariot

Despite these issues are mainly technical, there are not so many engineering studies of ancient chariots. Sandor [4],[5] and Rovetta et al. [7] addressed some technical issues in the Tutankhamun-class chariots, mainly related to the elasticity and damping properties of the chariot members and connections. Sandor again [8] and Rossi et al. [9] analyzed the technical evolution of road transport devices from the Bronze Age to the Roman Empire.

Recently, Mazzù et al. [10] made a preliminary study to assess a war chariot running dynamics by means of a simulator based on concentrated parameters. In [11] they introduced dynamical Finite Element (FE) analysis to assess the loads on the chariot wheels.

In this paper, the war chariot dynamics was assessed by means of Finite Element (FE) and Multi Body (MB) simulation, mainly aimed at evaluating the vehicle stability in extremely dangerous situations such as bumping over a stone or a root emerging to the surface. The effect of the axle position and the role of the vehicle body members in stability were investigated. The FE models were used with a twofold scope: a) determining the elastic properties of the chariot members to be used in the multibody analyses, by means of static simulations; b) performing a dynamical analysis of the chariot in symmetric and asymmetric bump over a soil asperity. The FE analyses allowed considering the bodies’ deformability, this way providing realistic estimations of the stress and strain fields in the chariot member; however, dynamical FE analyses are computationally expensive and hardly allow considering some key factors, such as internal damping of the transported bodies the chariot members. For this reason, multibody dynamical simulations were carried out as well.
2. Method of analysis

2.1. Finite Element dynamical models
The FE models of the chariot with the passengers are shown in Figure 2: Figure 2a shows the model of a chariot with the axle centered under the cockpit floor, about to bump with a cylindrical obstacle with both wheels (symmetric bumping), whereas Figure 2b shows the model of a chariot with the axle in rear position, about to bump with a spherical obstacle with a single wheel (asymmetric bumping).

![Figure 2. FE model a) of a chariot with central axle in symmetric bump; b) of a chariot with rear axle in asymmetric bump.](image)

The soil was modeled as a rigid surface. The asperities were modeled as a half cylinder with radius of 30 mm and a half sphere with radius of 30 mm, in the symmetric and asymmetric bump simulations, respectively. The chariot members were modeled with linear tetrahedron or brick elements. The transported men were modeled with solid elements as well, just to provide a realistic mass distribution, not a realistic behavior of living passengers. The pole, the axle, the cockpit and the joints were connected with sticking contact; the wheels were connected to the axle with unilateral contact, so that they could revolute around it. Unilateral contact was set between the men and the chariot. The linear elastic material properties summarized in Table 1 were assigned to the model bodies. The properties of the structural members (pole, axle, wheels and cockpit framework) are typical of a hardwood solicited along the fiber direction, whereas those of the joints and the cockpit floor are typical of a compressed leather [3]. The total chariot mass was 41 kg. The elastic modulus of the men material was chosen arbitrarily; its density was chosen such to obtain a mass of 80 kg for each man. The chariot and the passengers were imposed to impact the obstacle with an initial velocity of 40 km/h, and the pole end was supposed to keep on running rectilinearly with the same velocity. A general Earth’s gravitational field was imposed.

| Member               | Material  | Elastic modulus (N mm⁻²) | Poisson ratio | Density (kg m⁻³) |
|----------------------|-----------|--------------------------|---------------|-----------------|
| Chariot (structural) | Hardwood  | 11600                    | 0.3           | 615             |
| Chariot (joints-floor) | Leather | 9000                     | 0.35          | 1000            |
| Man                  | Undefined | 1000                     | 0.3           | 1250            |

2.2. Multibody models
The MB model was constructed by defining a basic scheme to reproduce the system (see Figure 3), referring to the case of the chariot with central axle. After an adequate analysis, it was found that the system could be modeled as the following: the chariot wheels, the main body of the vehicle, raising part
of the pole, horses’ yoke. Driver and passenger were modeled by equivalent masses and inertias, linked to the chariot by a couple of spring/dampers. The constraint between these springs/dampers and the men is unilateral, because chariot passengers are supported but not joined to the chariot.

![Multibody model](image)

**Figure 3.** Multibody model used in the dynamical simulations for asymmetric bump

In the system, the pole is the key element to define the vehicle behavior, so it was decided to split it in three parts to better simulate its interaction with the rest of the vehicle. The proximal part to the chariot body was rigidly tied to it. The other part of the pole was linked to the former by means of a universal joint. Since that joint had 2 degrees of freedom (DOF) it was necessary to manage these by means of proper springs and dampers. In particular, it was chosen to separate in the best possible way the horizontal stiffness and the vertical stiffness. At the other end, the central part of the pole was linked to the yoke by means of a 1 DOF constraint. The single degree of freedom is rotational around the axis of the pole; this DOF was managed by means of a torsional spring with damper. In total the model was composed by 7 parts (plus 2 auxiliary parts), managed by means of 5 spring and dampers. The yoke was constrained to a couple of non-physical sliding guides, to simulate the horses.

Once the model was established in terms of bodies and constraints, it was essential to assign a correct value to each spring and damper. The spring elastic constants were determined by static FE analyses, using the same models as in the dynamical FE analyses. Several simulations were carried out, each one characterized by a system of loads and boundary conditions able to identify the directional deformability of the main members. In particular, the vertical deformability of the cockpit floor, and the vertical, longitudinal and lateral deformability of the pole and the axle were determined.

As each spring affects the behavior of the whole vehicle, an iterative process was necessary to find the correct values for each parameter for the MB simulation. To start the procedure, a set of single direction FEM tests has been conducted to find the whole vehicle spring and damping values. After an initial set of attempt values for the lumped parameters mentioned before, the MB model was submitted to a particular set of tests, e.g. drop test from a fixed altitude. In particular, these dynamic tests, as aforementioned, were very useful to set the correct values for damping characteristic related to the single DOF. The determination of each single damping value has been set also by means of an iterative procedure similar to the one used for the stiffness of the springs. As a rule of thumb, damping has been set initially to the critical value for each single DOF. The damping values were valued as satisfactory once the number of total oscillations before the system converged in the band of 10% of initial displacement in 3 oscillations; this is an arbitrary value, but it can be reasonably considered reliable for the vehicle under investigation. A total of about 70 calibration dynamic test has been performed. The
properties assigned to springs and dampers in the model are summarized in Table 2, where the member numbers refer to the notations of Figure 3.

**Table 2. Properties of springs and dampers in the MB simulations**

| Member | Axial springs/dampers | Torsional spring/damper |
|--------|-----------------------|-------------------------|
|        |                       |                         |
|        | 1                     | 2                       | 3     | 4     | 6   | 7   | 5 |
| Damping coefficient (N s mm$^{-1}$) | 6.0 (Case 1) | 0.0 (Case 1) | 6.0 (Case 2) | 0.7 (Case 2) | 0.7 (Case 3) | 0.7 (Case 3) | 0.5       | 0.5       | 0.5       | 0.5       |
| Elastic constant (N mm$^{-1}$)    | 7.80     | 7.80     | 150     | 330     | 2855     | 2855     | 90000     | 200       | 200       | 90000     |

Once the model had been correctly set-up, the same dynamic tests as previously executed in the FE software were carried out. The chariot has been subjected to a constant acceleration ramp to gain speed to 40 km/h in about 10 seconds, followed by few second of constant speed before hitting the obstacle. The obstacles were modeled as in the FE analyses for symmetric and asymmetric bump. In order to evaluate the effect of damping due to the cockpit floor and the passenger legs, for each event three cases were simulated, characterized by different values of the damping coefficient under the passenger feet. In the first case, the left man had very high damping and the right one no damping; in the second case, the left man had very high damping and the right one moderate damping; in the third case, both had moderate damping. The cases with asymmetric damping coefficient correspond to a leg reaction differentiated between the two passengers.

### 3. Results

#### 3.1. FE simulations

![Figure 4. FE simulation of the central axle chariot: a) in symmetric bump; b) in asymmetric bump](image)

Figure 4 shows the chariot with the central axle in an instant of the simulations of symmetric and asymmetric bump. Figure 5a shows the vertical displacement of the left wheel and the left passenger head of both central and rear axle chariots in symmetric bump; Figure 5b shows the same quantities in asymmetric bump. These results show that in symmetric bump the rear axle chariot causes a worse...
condition for the passengers, because their weight is partly supported also by the pole, which is a flexible element acting as a spring: first, the pole is bended downwards by the dynamical load of the passengers, then it releases the accumulated energy increasing the upward push. In the central axle chariot the whole weight is supported by the axle, and the energy transmitted to the vehicle is more balanced between the chariot and the passengers. In the asymmetric bump, the effect on the left passenger is not so much different between the two cases, but the effect on the wheel is worse in the rear axle chariot, due to the increased torsional effect on the pole.

![Diagram showing vertical displacement of the left wheel and left passenger head](image)

**Figure 5.** Vertical displacement of the left wheel and left passenger head in central and rear axle chariots: a) in symmetric bump; b) in asymmetric bump

### 3.2. MB simulations

The MB simulations allowed evaluating especially the effect of damping under the passengers’ feet, related to the intrinsic energy dissipation of the cockpit floor. Figure 6 shows the vertical displacement of the wheel centers and passenger heads in symmetric bump. As the wheels are concerned, the maximum height varies around 60-80 mm in all cases, without dramatic differences between them; only in the first case, the wheel under the undamped passenger (the right one) shows a bounce, after the first jump, significantly higher than in the other cases. As the passengers are concerned, on the contrary, the damping coefficient has a strong influence. In case 1, the right passenger, who has no damping under his feet, after the bump begins to oscillate with an amplitude of about 140 mm; the left passenger, on the contrary, does not oscillate, but has a single jump of approximately the same amplitude. This is because the very high damping coefficient makes the damper almost rigid. In case 2, when a moderate damping is added under the right passenger, his oscillations are significantly reduced, but even the height reached by the passenger aside is significantly reduced. In the case both passengers have moderate damping under their feet, both the height reached by their heads and the oscillations are dramatically reduced.

Figure 7 shows the same results in asymmetric bump; in cases 1 and 2, the obstacle is bumped by the right wheel, which is the side of the passenger with null and lower damping coefficient, respectively. The effect of damping on the passenger standing on the less solicited side is reduced; on the contrary, the response of the right-hand man is strongly influenced by the damping under his feet: in both cases with damping (case 2 and 3), the wheel jump amplitude is reduced by around 2/3 with respect to the case of no damping, and the head maximum height by around 1/2.
Figure 6. Vertical displacement in symmetric bump of: a) the wheel centers; b) the passenger heads.

Figure 7. Vertical displacement in asymmetric bump of: a) the wheel centers; b) the passenger heads.
4. Conclusions
A preliminary study of the dynamical behaviour of a Bronze age war chariot was carried out by means of finite element and multibody approaches. In particular, the role of the axle position and the damping effect due the cockpit floor and to the passenger legs were investigated.

The comparison made by dynamical finite element simulations of the chariots with central and rear axle showed that the latter, without consideration of damping, could be a less stable solution for the passengers’ stability in case of dangerous events such as bumping over soil asperities in full running, as the pole could act as a spring able to accumulate deformation energy and subsequently release it on the passengers. On the other hand, the multibody dynamical simulations showed that the damping acted by the cockpit floor and by the legs on the passenger dynamical behaviour was a key factor for their stability, strongly influencing the height of their jumps in such events.

The damping coefficient, mathematically simulated in this paper, in practice depended on the way the cockpit floor was made, as well as on the passenger ability of absorbing shocks with the movement of legs. Therefore, the realization of the cockpit floor was not a trivial issue for the ancient chariot makers: the interwoven leather stripes pattern should have the function of dissipating dynamical energy by means of the friction between the stripes themselves. Under this consideration, the way of realizing the floor and its effect on both the rear and central axle chariots is a matter of further study.

Despite the approximations introduced in the models, the study helps individuating some key factors in the chariot dynamics, providing some guidelines for a future deepening which will include the realization of a full scale physical model.

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