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Heavy Military Land Vehicle Mass Properties Estimation Using Hoisting and Pendulum Motion Method

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ABSTRACT

Mass properties such as the centre of gravity location, moments of inertia, and total mass are of great importance for vehicle stability studies and deployment. Certain parameters are required when these vehicles need to be arranged inside an aircraft for the carrier to achieve proper mass balance and stability during a flight. These parameters are also important for the design and modelling process of vehicle rollover crash studies. In this study, the mass properties of a military armoured vehicle were estimated using hoisting and pendulum method. The gross total weight, longitudinal and vertical measurements were recorded by lifting the vehicle using a mobile crane and the data were used to estimate the centre of gravity. The frequency of vehicle oscillation was measured by applying swing motion with a small angle of the vehicle as it is suspended on air. The centre of gravity and mass moment of inertia were calculated using the vector mechanics approach. The outcomes and limitations of the approach as discussed in details.

Keywords: Combat; Vehicle dynamics; Simulation; Kinematics; Vehicle stability

1. INTRODUCTION

Centre of gravity (CG) and moment of inertia are two crucial parameters in analysing the dynamics and mechanical system of a body[1-2]. Low CG and moment of inertia in the body axis provides a vehicle with high manoeuvrability, as well as satisfactory control and stability[3-5]. Inertial properties must be determined precisely as they have imperative effects on vehicle dynamics.

Mass properties are important factors in understanding the stability and mobility issues of heavy-duty military land vehicles such as armoured vehicles. For example, in terms of stability issues, land vehicles can experience many sub-events following improvised explosive device (IED) explosion comprising the localised deformation of the vehicle floor and blast-off because of the tenacity of the forces exerted by an IED[6-7]. By varying the point of impact of the IED toward the vehicle's underbelly, the vehicle can also be exposed to rollover effect[7]. Unlike a standard commercially available vehicle, armour vehicles have lower rollover stability thresholds with heavier loads, narrower tracks, and higher CG.

In terms of defence mobility aspect, when deploying land vehicles, such as trucks, armoured vehicles, or subjects of aerial transportation, each vehicle should be measured and weighed in order to find the required information e.g., the gross vehicle weight, the weight of individual axles, and the CG or centre of balance (CB)[9-10]. This operation is generally performed at airport sites where vehicle and mobile weighing systems are available, and it is conducted using a manual tape measurement and weighing scales. Weighing scales are positioned on the ground or other suitable surfaces, and the tires of vehicles are positioned onto the scale platform, as shown in Fig. 1.

The outputs from respective weighting measurements on the similar axle are used to determine the wheel axle weight, e.g., front axle weight (FAW) and rear axle weight (RAW). The measuring tape is used to measure the distance between the axles from the front bumper to the centre of the front axle, e.g., front overhang (FOH), rear overhang (ROH), and wheelbase (WB)[9-11]. The moment of the vehicle is obtained by multiplying the weight by the distance from the reference datum line (RDL). This information is used to determine the gross vehicle weight and longitudinal position of CB. In certain occasions, such as in vehicles with more than three axles, more portable scales are then required, and the procedure must be conducted in stages because the scales must be transferred from axle to axle[9-11].

For tracked vehicle or skid mounted type cargo, the CB is determined using a scale and wooden beam or pole, as shown in Fig. 2. By placing the object onto the beam and by centring it until it balances, the CB location and the total gross weight are marked[9-11].

However, for remote sites or airstrips where a weighting system is unavailable, the air deployment process may not be possible for and the method of determining weights are resolved with a coordinated approach by the respective command personnel[9-10].

Several techniques for the evaluation of the inertial and mass characteristics of rigid bodies have been proposed by

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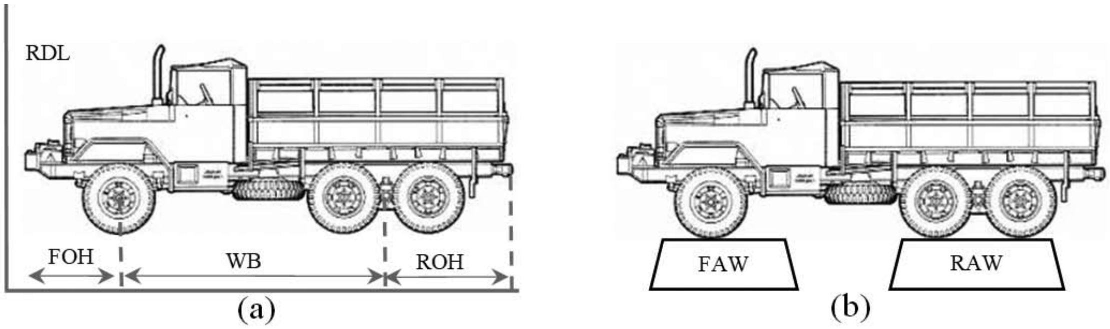

Figure 1. (a) Measuring the distance between axles and (b) the vehicle total gross weight.

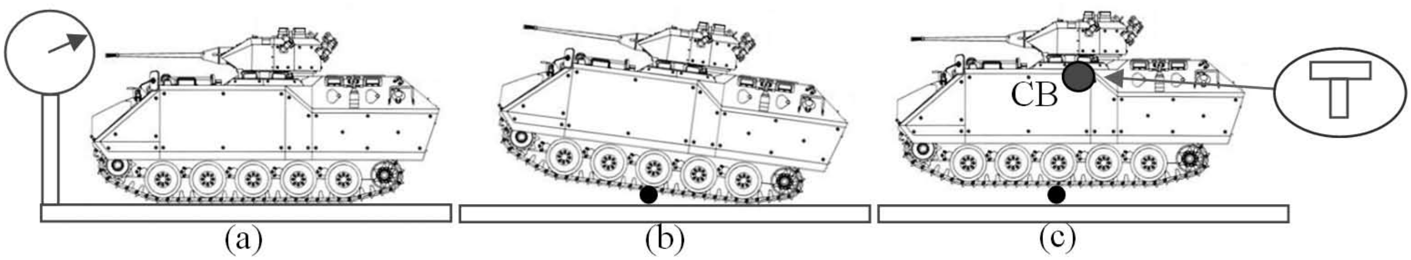

Figure 2. (a) Measuring the total gross weight (b) Marking the titling point of vehicle and (c) Marking the CB location.

a number of researchers[12-16]. Each method yields different accuracies and varies in measurement complexity and cost. The first method is determining the oscillation frequency of the object at about the fulcrum or pivot axis, in which the object is constrained to only one axis. The inertial characteristics can be determined by solving the least-squares identification problem[12-13]. However, this method requires specific tools and multiple experiments. The other methods proposed use specialised measuring gadgets, which direct the subject into desired motion. These methods can identify all the unidentified inertia parameters of the object; however, the tool is typically expensive and quite complex to handle. Another approach utilizes the frequency response function or modal analysis in determining the inertial characteristic. This approach often involves the stiffness and damping characteristics of the support component[15-19]. The simplest method is suspending the rigid body with one or more cable and subjecting it to a pendulum motion[20-22]. The period of the object to complete one full oscillation can be measured and then used to calculate the inertial properties.

In this paper, the hoisting and pendulum method was used to estimate the mass properties of a six-wheeled armoured vehicle. This method was selected due to its simplicity and cost-effectiveness. A mobile crane that can lift the vehicle was used to suspend the vehicle vertically above the ground level. Note that a commercial mobile lift crane is usually equipped with a load cell system in the driver's console, which is an added advantage as it can directly measure the weight of the vehicle. Also, mobile crane provides flexibility to the ground operator in manoeuvring the heavy vehicle to any position or arrangement when compared to a platform-based weighing system. Furthermore, this method is suitable for measuring any heavy armoured vehicle that varies in shape, as the method does not require any specific jig or mount.

2. METHODOLOGY

2.1 Determination of Centre of Gravity

A SIBMAS AFSV-90 armoured vehicle hull was lifted off the ground by using a Kato NK250-V Mobile crane that can lift a maximum load of 25 tons, as shown in Fig. 3(a). The vehicle was rigged using four points of the harness, and the gross weight of the vehicle was measured when vertically lifted at 3 meters above the ground. In order to estimate the location of the CG, a plumb bob on a string was hung from the crane hook, as shown in Fig. 3(b). The plumb bob line displays the centreline, C_L, which represents a line that is equidistant from both sides of the vehicle. The plumb bob static location can also indicate the CG spot at the longitudinal axis.

The conventional method for estimating the longitudinal location of the CG requires the front and rear axles to be measured by using weighing scales and by measuring the wheelbase of the vehicle. However, the use of a mobile crane could be modified by suspending the front end of the vehicle while the rear tires are still on the ground or vice versa. The CG variables (hoisting load and distance) of the vehicle are measured as shown in Fig. 4. The vehicle was lifted slightly above ground level with a small angle that can be neglected in the calculation. In this procedure, variables such as the angle of tilt θ, the front end reaction force, F_f and the distance rear tire reaction force F_r to the front end reaction force, are measured directly. The front end reaction force value was obtained from the mobile crane console where it is connected to the load cells of the crane.

From Fig. 4, the distance of *a, b* along the vehicle longitudinal axis was calculated using the summation of force along the vertical axis of the vehicle and the summation of moment force at point CG. The equilibrium of vertical forces acting on the vehicle at the *z*-axis is defined as:

$$\Sigma F_z = 0 \tag{1}$$

(a) (b)

Figure 3. (a) Measuring the vehicle gross weight and (b) Centerline (CL) marking.

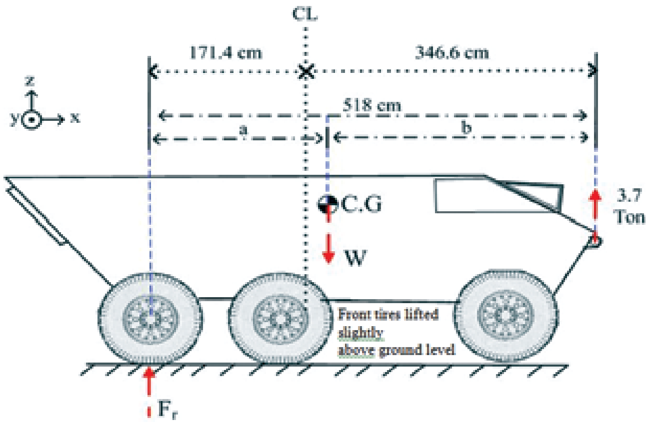

Figure 4. Line diagram of the vehicle suspended slightly above ground for horizontal CG calculation.

$$F_r - W + F_f = 0 \tag{2}$$

where F_f is the vertical force at the front end of the vehicle (measured at 3.7 tons) by hoisting the front axle until the tire surface is slightly above ground, W is the vehicle total weight and F_r is the vertical force at the rear end of the vehicle. The equilibrium of vertical forces at the contact point of the rear wheel with the ground on the *z*-axis is defined as:

$$F_r - W + 3.7 = 0 \tag{3}$$

The equilibrium of moment force at the contact point of the rear wheel with the ground, on the *x*-axis:

$$\sum Mx_{CG} = 0 \tag{4}$$

The expression of the summation of moment at point CG is defined as:

$$F_r a - 3.7b = 0 \tag{5}$$

The height of the CG or I_z can be estimated by lifting either side of the front or rear section of the vehicle. Figure 5 shows the line diagram of the vehicle whereas the actual rigging process was set at the rear end of the vehicle can be shown in Fig. 6. The tilt angle was calculated by measuring the parameters of the front and middle tire center of the wheel to the ground. Figures 5 and 6 depict the armoured vehicle hoisted at a certain degree and following the convention of geometry as derived by Fricke[23], where the height of the CG can be determined using Eqn. (6)

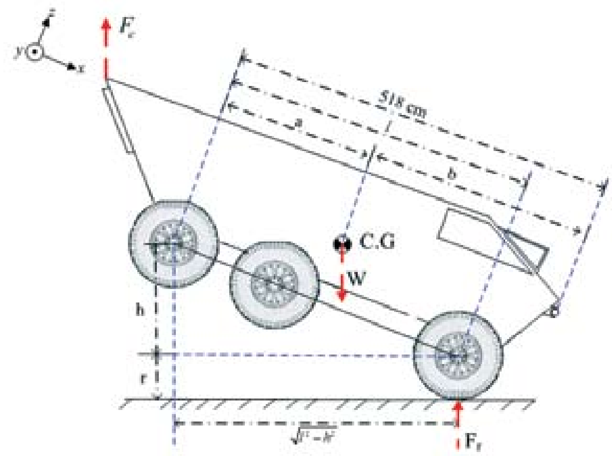

Figure 5. Line diagram of vehicle suspended at the rear end mount.

$$I_z = \frac{l\sqrt{l^2 - h^2}\left(w_h - w_f\right)}{hw} + r \tag{6}$$

where I_z is the height of CG above ground, l is the armoured vehicle wheelbase, h is height of the lifted rear axle, w_h is the weight on the rear axle when hoisted, w_f is the weight on the front axle, w the total weight of the armoured vehicle and r is the tire wheel radius.

The height of the CG can be estimated by hoisting either side of the front or rear section of the vehicle. Figure 5 also shows the line diagram of the vehicle, whereas the actual rigging process was set at the rear end of the vehicle can be observed in Fig. 6. The tilt angle was calculated by measuring the parameters of the front and middle tire centre of the wheel to the ground. The vehicle was lifted an acceptable height at the rear end and based on the measurement taken, the tilt angle was calculated at 45-degree angle. For this study, it is assumed that the compression or extension of the suspension elastic elements such as springs do not affect the CG position by the displacement of the wheels.

2.2 Determination of the Mass Moment of Inertia

The moment of inertia of the vehicle along the x-axis was measured by oscillating the vehicle in the longitudinal direction, whereas the moment of inertia along the y-axis was derived by

Figure 6. Measurement process to determine the height of the CG (hoisting at rear end).

oscillating the vehicle along the lateral direction as shown in Fig. 7. Subjecting a pendulum motion to the suspended vehicle enables the measurement of the oscillation period. The vehicle was displaced by a small angle θ', with gravity acting on the centre of mass as shown in Fig. 8.

Figure 7. Initiation of the lateral oscillation at the determined vehicle's center line (longitudinal axis).

Based on Fig. 8, the torque about the pivot point is defined as:

$$\tau = -l\left[\left(mg\sin(\theta')\right)\right] \tag{7}$$

The rotational equation of motion at the pivot point is then derived as:

$$\tau = -l(mg\sin\theta') = I\alpha \equiv I\frac{d^2\theta}{dt^2} \tag{8}$$

where τ is the restoring torque from the tension from the cable, α is its angular acceleration and

I is the pendulum's rotational inertia about the pivot point. In the limit of the small angle θ', it can be assumed that the vehicle body executes a simple harmonic motion. The pendulum motion was completed at a small angle so that the velocity of the swing is considered low; thus, the drag force of the vehicle can be neglected. Given a minimal angle of oscillation, a small angle approximation can be accomplished in Eqn. (9) as follows

$$\sin\theta' \approx \theta' \tag{9}$$

As with the simple pendulum, Eqn. (8) reduces to the simple harmonic oscillator equation for small angles, as shown below:

$$\alpha = -\frac{mgl}{I}\theta' \tag{10}$$

The equation for the angle $\theta(t)$ is given by:

$$\theta(t) = A\cos(\omega t) + B\,sin(\omega t) \tag{11}$$

whereas the angular frequency is given by:

$$\omega \cong \sqrt{\frac{mgl}{I}} \tag{12}$$

The period oscillation value is then used to calculate the moment of inertia as shown in Eqn. (13):

$$T = \frac{2\pi}{\omega} \cong 2\pi\sqrt{\frac{I}{mgl}} \tag{13}$$

where I is the moment of inertia with respect to the pivot point, m is the mass and l is the length from the pivot point to the centre of mass of the vehicle. The period of oscillation of the vehicle under pendulum motion was measured and repeated six times to produce the average value of the period.

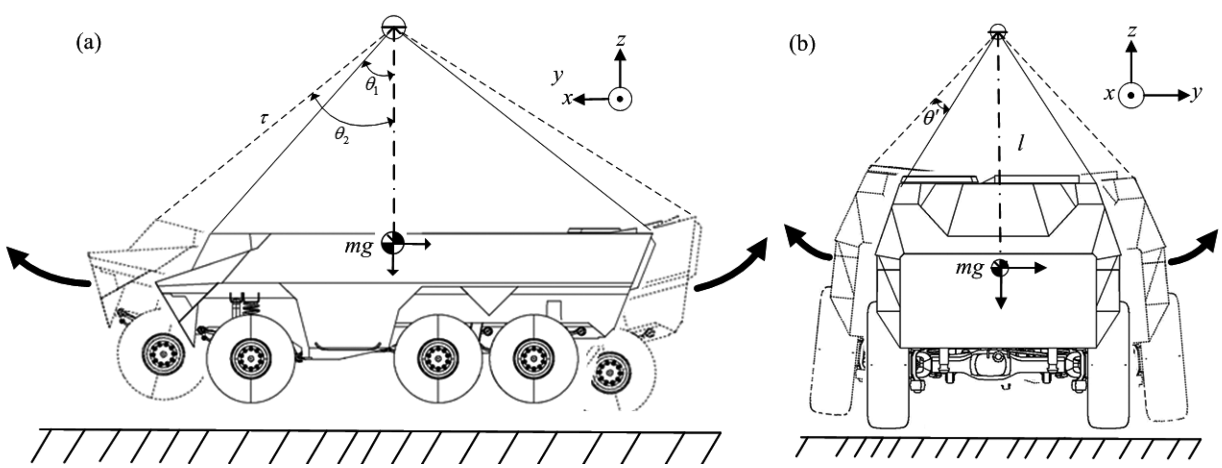

Figure 8. Diagram of vehicle under swing motion along (a) longitudinal direction and (b) lateral direction.

3. RESULTS AND DISCUSSION

The gross total weight of the vehicle was measured at 12.4 tons, and by solving Eqns. (2), (4) and (6), yields the result of each parameter, which is as shown in Table 1. Once the CG (at longitudinal axis) for the vehicle was determined at the position of 83.00 cm from the ground, *j* and 179.64 cm from the centre of the rear wheel, *a*, the length of the pivot point to the body centre of mass, *l* can be then measured. The calculated CG location shows a good agreement with the estimated CL at about 4.58 per cent and 2.43 per cent differences when compared to the rear and front end rear points of the vehicle, respectively. The vehicle height (hull) was measured at 224.00 cm whereas the height of CG, I_z was calculated at 196.84 cm. Although the calculated vehicle I_z is relatively high, it does not represent the actual I_z of an operational SIBMAS AFSV-90 armoured vehicle. The test vehicle used in the experimental work (measured at 12.4 tons) did not include the turret, 90 mm Cockerill Mk III gun, power train and auxiliary components, *etc.* An actual combat-ready SIBMAS AFSV-90 was reported by Foss[24] to weight around 14.5 to 18.0 tons (based on role) and therefore it can be assumed that the actual I_z should be lower than the calculated I_z of 196.84 cm.

Table 1. Parameter values calculated after measurement

Parameter	Distance of	Value of parameter
a	Rear wheelbase point to C.G point	179.64 cm
b	Front lift point to C.G point (horizontal)	338.36 cm
I_z	Height of C.G point (vertical)	196.84 cm
	Rear tilt angle	45 degree
W	Vehicle weight	12.40 ton
	Rear tire reaction force	8.10 ton
C_{L-R}	Rear lift point to center line point (horizontal)	171.40 cm
C_{L-F}	Front lift point to center line point (horizontal)	389.50 cm

Tables 2 and 3 show the values of the distance, *l* and the periods of oscillation recorded during the measurement procedure, respectively. From Table 2, the inertial property of the armoured vehicle can now be calculated by rearranging and solving Eqn. (13). The moment of inertia of the armoured vehicle was computed at 1088.97 × 10^3 kgm^2.

The moment of inertia and the CG values estimated using this approach can be used as approximate values for further vehicle dynamics and stability related calculations.

However, this approach has several limitations. Prior initiating the oscillation of the vehicle body, extreme care was taken to ensure that the front and rear sections must swing on the same plane (parallel) and should not sway from one another. Also, a special arrangement must be taken prior to the hoisting procedure such as the vehicle's suspension motion to be in locked condition. During the hoisting process, the vehicle suspension spring can expand due to the weight of the axle thus create vertical displacements of the wheels. This may lead to incorrect measurements that will be used to estimate the position of the vehicle's CG.

Table 2. Distance of *l* and average period oscillation recorded for moment of inertia along the x-axis (longitudinal)

Parameter	Values
L	468 cm
Period of oscillation	Time (s)
1	7.92
2	7.69
3	7.92
4	7.83
5	8.36
6	8.15
Average	7.98
Mass moment of inertia, I_x	918.30 × 10^3 kgm^2

Table 3. Distance of *l* and average period oscillation recorded for moment of inertia along the y-axis (lateral)

Parameter	Value of parameter
L	468 cm
Period of oscillation	Time (s)
1	9.18
2	8.82
3	8.75
4	8.08
5	8.55
6	8.73
Average	8.69
Mass moment of inertia, I_y	1088.97 × 10^3 kgm^2

4. CONCLUSIONS

The mass moment of inertia and the centre of mass is two important characteristics in assessing vehicle dynamics and stability. In this work, the hoisting and pendulum method was utilised to estimate the moment of inertia of a six-wheeled armoured vehicle. Results indicated that the methods demonstrate an alternative option for estimating the mass properties of heavyweight vehicles apart from using the conventional weighing platform. The methods require the use of mobile crane that can lift the front and rear mounts of the vehicle and that can perform pendulum-like oscillation motions. The moment of inertia along the longitudinal and lateral axes obtained for the armoured vehicle were918.30 and 1088.97 kgm^2, respectively, whereas the centre of mass was located 83 cm above the ground and 179 cm from the point of the rear wheel centre.

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Contribution in the current study, he have contributed in the experimental setup and data collection.