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INFLUENCES OF A SERVO-ASSISTIDED MOTORIZATION OVER THE DYNAMIC BEHAVIOR OF WHEELCHAIR

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Abstract. *The aim of this article is to study the dynamic behavior of a system composed by a child and a wheelchair during the propulsion. The modeled system corresponding a vehicle with propulsion on the rear wheels, steering is on the front wheels, however it is induced by application of different moments in the propeller wheels. The modeling plan used to study was the top view of the system. Therefore the study objecive is the dirigibility of the system. The modeling used was a linear model for the rigid wheels of the wheelchair. The forces over the four wheels of the vheicle were modeled using a double single-track model. Finally, after the determination of these wheel equations, was applied the Newton-Euler and Jourdan equations to obtain the system dynamic equations. It results in equations for the translations in the directions longitudinal and transversal as also one equation for the the yaw angle determination of the system. The simulation of these equations allows studing the system behavior with or without a propulsion system auxiliary, servo-assisted, in terms of the dirigibility and security conditions.*

Keywords: *wheelchair, dirigibility, modeling, servo-assisted*

1. Introduction

Wheelchairs have suffered a great development in the last years, however studies of its dynamics behavior have practically not occurred, and it is important because allows the improvement of the users security conditions.

Although concern with the safety of a wheelchair can sound excessive, it has as justification the fact that according to Dvorznak et al., 2001, annually happen about 36000 accidents with wheelchairs users, and in almost totality of these accidents are tumbling and falls.

Looking to increase system (wheelchair and user) safety conditions first of all it is important to know how the user propels the system, what it means what propulsion force characteristics and its maximum value, because these variables are the main users interactions for the movement. These variables depend on many subject factors like age, physical condition, lesion level, etc.

The preference for the single track model is based on recent works of auto vehicles stability (Lombardi Jr. 2002, Buckholtz 2002 a,b, Sayers and Han, 1996 and Liu and Peng, 1996), this model allows finding a simple model but able to identify the main dynamic conditions of the system.

By observation of commercial trading wheelchair can be asseverated that the majority of manual wheelchairs, could be wheels defined as rigid, thus it can be applied the linear model for the wheels (Huston 1982 e Becker 1997, Lombardi Jr. 2002) which it will be later incorporated into wheelchair movement equations for the dynamical analysis.

2. Considerations about the propulsion force

In this section only the two main factors for the biomechanical modeling will be presented, these factors are the propulsion standard and the force cycle characteristics.

For this study, it was considered that the movement happens only in the user sagital plan, what is consistent with the movement observed in recent studies of Souza (a and b, 2000), Dallmeijer et al.,(1994), Becker (2000) Lombardi Jr. (2002). Each manual wheelchair user adapts to a propulsion standard, or in other words, the trajectory build by the upper extremity during the propulsion. Souza (a and b) relates that there are 4 standards for wheelchair propulsion, they are: arc, semi-cycle, simple looping and double looping, in this paper will be used only the arc as upper extremities movement.

In the same way it will be considered that the propulsion force has regular characteristics, and it can be divided in three parts (*T1,T2* e *T3*), where *T1* is the time necessary to the user applies the force begins at zero until the maximum value (*Fmax*), which is dependent on users characteristic (lesion level, physical condition), *T2* is the time when the force remains constant until the moment to release the hand, *T3* is the time to goes back the hand until the initial contact point to repeat the cycle. It was adopted the values *T3* equal to 1,0 s for plan paving e 0,4 s for slope paving *T2* was considerate 3 times bigger than *T1*.

Combining these two information mentioned previously, the propulsion force pattern is shown on the following figure:

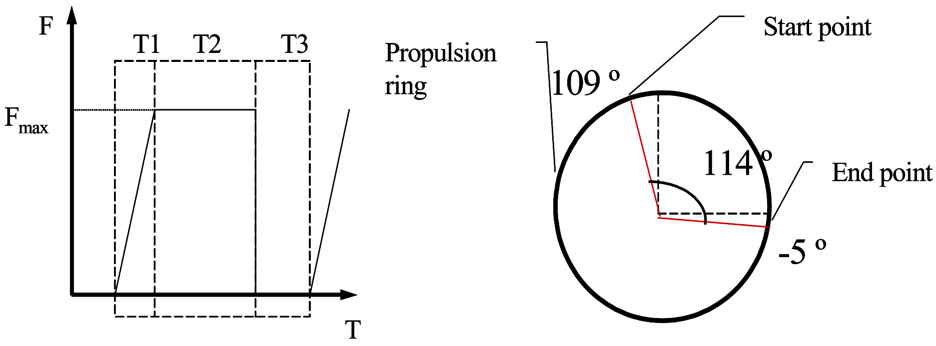

Figure 1. Characterizes of Propulsion Force definition

The maximum propulsion force value (*Fmax*) depends on the biomechanical characterizes of the subject, thus in this paper, as the aim is studying the dynamical behavior of the system will be assumed that the user is always able to apply the necessary force for the movement. The force necessary for the movement is the sum of all forces of rolling movement over the wheel and the weight component if convenient (slope plane).

3. Reference System

It is important to define one system of reference for the modeling, thus all comments about directions could be understood easily. The system of reference become easy too expresses the equations properly using transformation coordinated matrix to express the forces and the displacements.

The system of reference used in this paper is in accord to the SAE (Society of Automotive Engineering), shown on fig. 2 because it is a convention used by automotive engineer in many works. Besides as the equations developed in this paper can be applied as first approximation for a vehicle model, the authors considered convenient adopted this system.

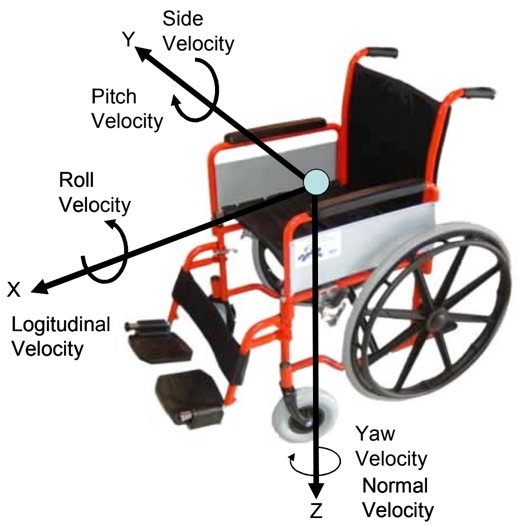

Figure 2. Definition of the Reference System according to SAE

4. Considerations about the wheel

The wheel is the component of interaction between the pavement and the system, the wheelchair. Modeling the wheel is a very difficulty process because the variables are non-linear and there are many factors, which have influence over the model as example, the pressure in the wheel, the velocity, the temperature, etc.

Non-linear models are useful for more complex modeling like the automotive modeling, but for wheelchair model the literature (Becker, 1997 and Lombardi Jr., 2002) has used linear models and has obtained very good results. Beside, by experimental observation, the wheel of commercial trade wheelchair can be considerate as rigid. As result, this assertion allows consider the uncoupling of the wheelchair movement equations.

Another important consideration about the wheel model is about the sliding, which is characterized by the relative movement between the instantaneous contact points, what it shows that the transmission forces are higher than the friction force. In this paper will be assumed that the wheel movement over the paving is a rolling movement, thus the sliding do not occur.

4.1. Linear model of the wheel

In their work Huston, 1982, Chang e Lee 1990, Becker 1997, Lombardi Jr.,2002 consider a stiffness wheel, a perfect rolling and the effects of the velocity over compression and traction of the wheel filaments were not considered. It was considerate only the wheel sliding angle (ψ), and the reaction transversal force (Fy).

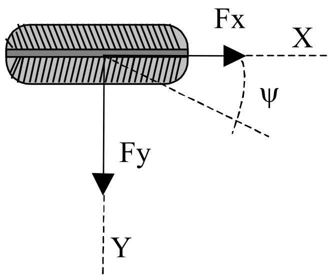

Figure 3. Forces scheme actuating over the wheel

The force Fy, transversal force, could be represent by its definition as being:

$$Fy = -C\psi * Tan(\psi) \tag{1}$$

Where $C\psi$ is the strictness movement wheel. The longitudinal force (Fx) for the rear wheels is the sum of the subject propulsion force and the rolling resistance force and for the front wheel the only term is the rolling resistance. The front wheels were considered aligned with the movement direction, thus the off-set influence due by the front wheels were not modeled.

4.2. Other forces acting over the wheel

The longitudinal force (Fx) and the transversal force (Fy) are not the only forces acting over the wheel, there are other forces which depend on the weight force, the rolling resistance, friction force and also of the track inclination. It is important to considerate that the system can drive for irregular pavements like as example a slope, and thus will have its movement affected by appearing resistance force to the movement.

The most general situation for a pavement is a double inclination, which represents two rotations over the roll (axis X, represented by the variable γ) and pitch (axis Y, represented by the variable φ) angles, as shown on fig.4:

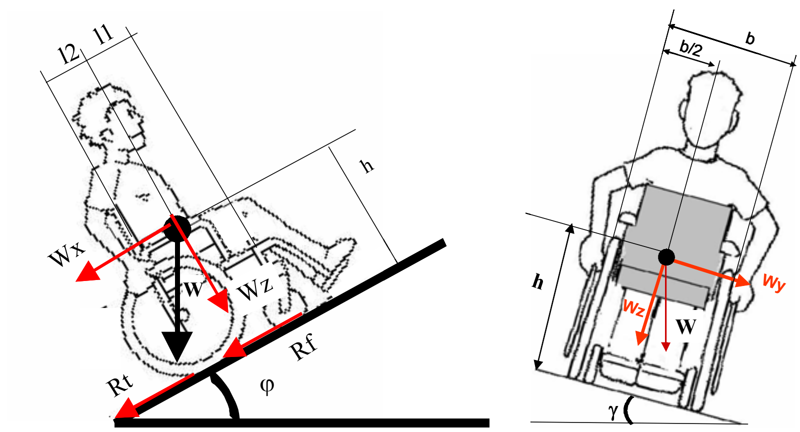

Figure 4. Forces diagram acting over the system in double inclination plane

Considering the follow geometric variables of the system: h, center of gravity height (CG), b, distance between wheels, l2, distance between the CG and the rear shaft, l1, distance between the CG and the front shaft, W as the weight of the system (wheelchair and subject), Wx, Wy and Wz the weight components over the direction X, Y and Z, and the forces *Rt* and *Rf* as rolling resistance. The weight components are represented over the wheels because it is easier to represent this force on the model.

The total resistance forces, R_i, is the sum of de forces shown on fig.4, for each wheel and can be defined as:

To the front wheels:

$$R_1 = R_2 = \begin{Bmatrix} -\frac{m.g.l2}{2.L}.\sin(\varphi) - \mu.\frac{m.g.l2}{2.L}.\cos(\varphi).\cos(\gamma) \\ \frac{m.g.l2}{2.L}.\cos(\varphi).\sin(\gamma) \\ \frac{m.g.l2}{2.L}.\cos(\varphi).\cos(\gamma) \end{Bmatrix} \quad (2)$$

And to the rear wheels:

$$R_3 = R_4 = \begin{Bmatrix} -\frac{m.g.l1}{2.L}.\sin(\varphi) - \mu.\frac{m.g.l1}{2.L}.\cos(\varphi).\cos(\gamma) \\ \frac{m.g.l1}{2.L}.\cos(\varphi).\sin(\gamma) \\ \frac{m.g.l1}{2.L}.\cos(\varphi).\cos(\gamma) \end{Bmatrix} \quad (3)$$

5. Dynamic Model

The dynamical model is based on the Newton-Euler and Jourdan equations and the aim is to develop the dynamic equations for computational simulation. All equations were written on the non inertial base over the system CG.

These equations represent the system dynamical behavior related to the propulsion forces acting over the rear wheels, and with servo-assisted assembly the motor actuation is added in propulsion force. It is important to remember that the steering occurs on front wheel, and the steering forces are always equal to zero because the front wheels are free and the changing direction is made by different forces acting over the rear wheels.

In the follow figure, fig. 5, it is represented the diagram of free body (DFB) of the wheel of system; this figure is enough to represent all important system forces, which are the transversal and longitudinal forces acting over the front and rear wheels. Each force is denoted by a sub-index from 1 to 4 which represents the number of wheel as shown on figure.

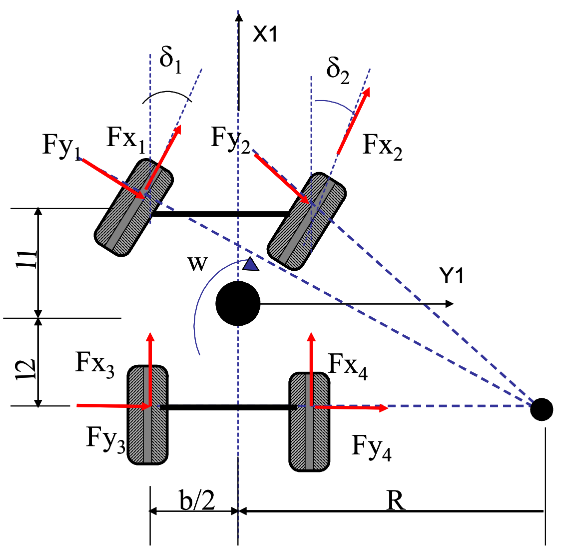

Figure 5. Free Body Diagram for the wheelchair

It can be observed that even the longitudinal force as the transversal forces are influenced by the resistance forces defined previously, so for the transversal force the expressions are:

$$Fy_1 = C\psi_f.\psi_1 - \frac{m.g.l2}{2.L}.\cos(\varphi).\sin(\gamma) - Fat_1 \quad (4)$$

$$Fy_2 = C\psi_f.\psi_2 - \frac{m.g.l2}{2.L}.\cos(\varphi).\sin(\gamma) - Fat_2 \quad (5)$$

$$Fy_3 = -C\psi_t.\psi_3 - \frac{m.g.l1}{2.L}.\cos(\varphi).\sin(\gamma) - Fat_3 \quad (6)$$

$$Fy_4 = -C\psi_t.\psi_4 - \frac{m.g.l1}{2.L}.\cos(\varphi).\sin(\gamma) - Fat_4 \quad (7)$$

The variable Fat_i used on previous equations represents the lateral friction force, what is responsible for avoid lateral slip movement.

For the longitudinal forces the expression are much similar to the expression for the resistance forces despite of the terms *F3* and *F4* on longitudinal forces Fx_3 and Fx_4, which are the forces applied by the wheelchair user during the manual propulsion or the forces applied by the user and the motorization system during the servo-assisted propulsion.

$$Fx_1 = -\frac{m.g.l2}{2.L}.\sin(\varphi) - \mu.\frac{m.g.l2}{2.L}.\cos(\varphi).\cos(\beta) \quad (8)$$

$$Fx_2 = -\frac{m.g.l2}{2.L}.\sin(\varphi) - \mu.\frac{m.g.l2}{2.L}.\cos(\varphi).\cos(\beta) \quad (9)$$

$$Fx_3 = F_3 - \frac{m.g.l1}{2.L}.\sin(\varphi) - \mu.\frac{m.g.l1}{2.L}.\cos(\varphi).\cos(\beta) \quad (10)$$

$$Fx_4 = F_4 - \frac{m.g.l1}{2.L}.\sin(\varphi) - \mu.\frac{m.g.l1}{2.L}.\cos(\varphi).\cos(\beta) \quad (11)$$

Now, applying the Newton-Euler and Jourdan equations, it is possible to obtain expression for $\dot{Vx}$, $\dot{Vy}$ e $\dot{\omega}_z$, respectively longitudinal, transversal and angular accelerations of the system. The equations resulting from this procedure is the following:

$$\sum Fx = m.ax \Rightarrow$$
$$Fx_3 + Fx_4 + Fx_1.\cos(\delta_1) + Fx_2.\cos(\delta_2) - Fy_1.\sin(\delta_1) - Fy_2.\sin(\delta_2) = m.(\dot{Vx} - Vy.\omega_z) \quad (12)$$

$$\sum Fy = m.ay \Rightarrow$$
$$Fy_3 + Fy_4 + Fy_1.\cos(\delta_1) + Fy_2.\cos(\delta_2) + Fx_1.\sin(\delta_1) + Fx_2.\sin(\delta_2) = m.(\dot{Vy} + Vx.\omega_z) \quad (13)$$

$$\sum Mz = Iz.\dot{\omega}_z \Rightarrow$$
$$\frac{b}{2}.(Fx_3 - Fx_4) + l1.(Fx_1.\sin(\delta_1) + Fx_2.\sin(\delta_2)) - l2.(Fy_3 + Fy_4) + l1.(Fy_1.\cos(\delta_1) + \cdots \quad (14)$$
$$+ Fy_2.\cos(\delta_2)) + \frac{b}{2}.(-Fx_2.\cos(\delta_2) + Fx_1\cos(\delta_1) + Fy_2\sin(\delta_2) - Fy_1.\sin(\delta_1)) = Iz.\dot{\omega}_z$$

Using the equations 12, 13 and 14, it is possible to simulate the dynamical behavior for a system composed by a wheelchair and a user, carrying out the aim of this paper. To follow some graphics will be presented and will show the dynamical behavior for a manual propulsion wheelchair, over a plane floor. The following simulations will be based on the values presented on table 1. The wheelchair geometric characteristics were based on ABNT 9050:

Table 1. Definition and values of the variables used for simulations

Symbol	Definition	Value / [Unit]
m	Mass of the system	110 [Kg]
L	Distance between the wheelchair shaft	0.5 [m]
l1	Distance between the CG and the front shaft	0.3 [m]
l2	Distance between the CG and the rear shaft	0.2 [m]
b	Wheelchair width	0.7 [m]
Izz	Inertia momentum of wheelchair	6.78 [m^4]
μ	Rolling friction coefficient	0.015 [ ]
h	CG height	0.5 [m]

The inertia momentum for the wheelchair was assumed as being equal to a cube with dimensions bxLxh.

Beside the propulsion force provide by the user was assumed as equal and enough for the movement, (F3 = F4 = 16.18 N) for the first simulation, in this simulation will be observed that the system will have a linear displacement because this hypothesis.

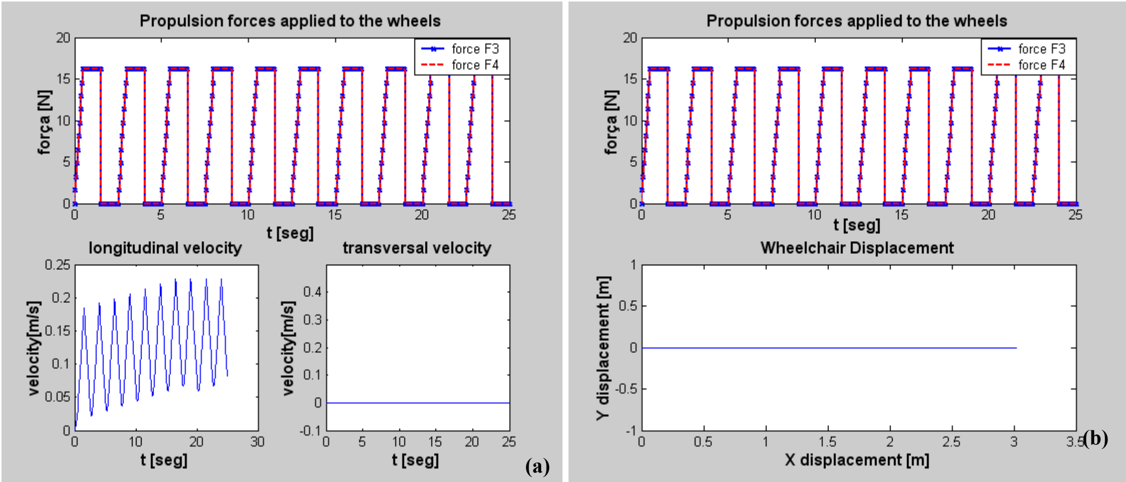

Figure 6. Wheelchair Velocity (a) and Wheelchair Displacement

Can be observed by fig. 6 (a) that wheelchair has an irregular behavior in terms of the longitudinal velocity (forward movement) due by the propulsion force. When there are a propulsion force bigger then zero the wheelchair tend to increase its velocity, when it not occurs the tendency it to decrease the velocity because the rolling resistance force. The transversal velocity is zero, what it is mean that the wheelchair has no sliding movement.

The fig.6 (b) represents the wheelchair displacement when the propulsion forces are equal, as mentioned before the wheelchair system change its direction using different forces on the rear (or motor) wheels. In the follow figure, fig. 7, is shown that a little difference between the force can change so much the system displacement and its direction. In this simulation was used F4 = 16.18N and F3 was increased in 5 %.

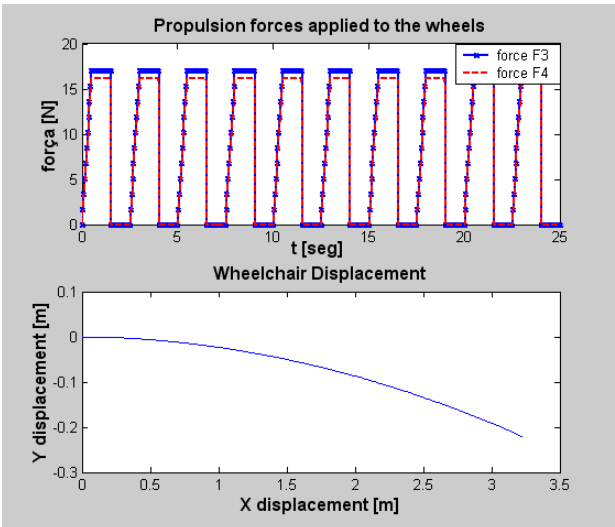

Figure 7. Wheelchair displacement with different propulsion forces.

6. Servo Assisted System

A servo-assisted mechanism for a wheelchair can improve the user locomotion capability and at the same time it does not allow that him remain without making exercises. It is important because it allows the user to development the upper extremities muscles. The locomotion improvement occurs because with less effort is necessary to propel the wheelchair. So the physical effort to propel a wheelchair is no excessive and the upper extremities joints will not development repetitive effort lesion.

The servo assisted mechanism concept is a group of motors fixed to the wheelchair able to propel the system but only turns on when the user force acting over the propulsion ring is higher then a specific value set by a doctor or a therapist.

The follow figure, fig.8, represents two situations (a) the system without a servo assisted mechanism and (b) with a servo assisted mechanism, the user physical conditions also been changed, in these simulations the user is able to apply only 50% of the total force necessary to the wheelchair movement.

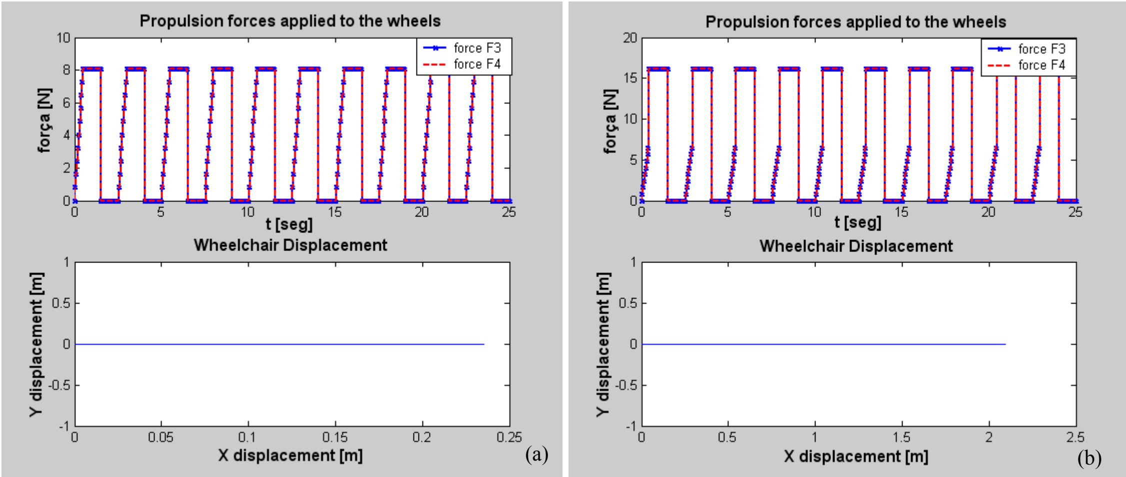

Figure 8. Comparison between a system without servo assisted mechanism (a) and a system with a servo assisted mechanism (b)

It can be observed by figure, fig 8, that the displacement of the system is larger when the servo assisted mechanism is used, in this figure is shown that the total forces over the wheels without the servo assisted mechanism (F3 and F4) are smaller then the total forces over the wheels (F3 and F4) founded in the system with servo assisted mechanism, because the motorization system is turned on.

The control strategy used for this simulation is a control like "on-off" what it is mean that when the force over the propulsion ring is higher then a specific value (in this case, more then 40% of total force necessary to movement) the motor are turned on supplying the 50% of the total force necessary to the system movement.

The system was simulated again, however in this time with a little difference between the propulsion forces acting over the ring propulsion, simulating a user that can not to aplly the same force over the ring the same case as shown on fig. 7. The result of this simulation with a servo assisted mechanism is a little change direction perception over the system displacement.

The differences found between the figs. 9 and 7 is because with the servo assisted mechanism the motors act independently over each wheel and this independence results in turning on the motors at different instant of time what minimizes the effect of different propulsion forces.

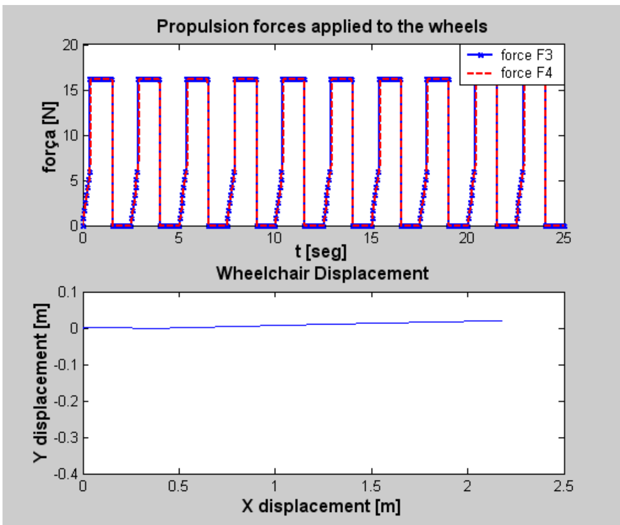

Figure 9. Wheelchair displacement with different propulsion forces acting over a system with servo assisted mechanism

7. Conclusions

First of all, the equations presenting in this paper are general and can be applied on any kind of back traction vehicle. The equations are very coherent with a usual wheelchair; this can be confirmed observing the graphics for displacement and velocity presented on previous sections, mainly observing the behavior when different forces are applied to the propulsion ring.

Another important contribution of this paper is the methodological approach to understand the wheelchair propulsion and its effects over the wheelchair dynamical behavior. Only after knowing this behavior a designer will be able to propose improvements in wheelchair design.

The servo-assisted concept is a new kind of motorization for wheelchair presenting in this paper. It allows the wheelchair users development the upper extremities member without risk to development repetitive effort lesions. But the conception success depends on the previous model of the system. This model will allow simulations of the dynamical system and it allows obtaining the dynamical system response related to the control algorithm applied to the motors.

This motorization system shows its efficiency during the dynamical simulations, mainly when the user is not able to development the total force to propel the wheelchair, without the system the wheelchair had a little displacement and with the system the displacement was almost the same as presented in a usual situation.

This simulation of the control system can safe time and money in the product development, besides the simulation is a kind of test more safety than testing the motorization system using people.

To sum up the servo-assisted motorization system shows a very important concept of wheelchair motorization and its control system must be carefully development to reach all the project possibilities and in this way increase the handicapped people quality of life.

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