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OPTIMAL DESIGN OF AN ANTI-ACCIDENTS VEHICLE-BUFFER

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ABSTRACT

Too many passengers die or injure every year because of highway accidents. Most of the vehicle manufacturing companies are unable successfully to control this matter.

This paper handles the optimal design of a passive spring-damper buffer that can be attached to the vehicle from its front, rear or both sides to avoid catastrophic effects due to collision. The optimization toolbox of MATLAB is used to minimize an absolute error objective function to keep the dynamic motion of the crashing vehicle to below certain level without destroying the standing hit vehicle. A 100 mm level is set for this dynamic motion. The crashing speed is varied between 20 and 140 km/h and a vehicle mass in the range of 1000 to 6000 kg is considered. The required optimal values of the spring stiffness and damper damping ratio are defined against the crashing speed.

The whole process is reduced to the selection of a unit set of buffer parameters to protect crashing small and medium vehicles at speeds ≤ 140 km/h with maximum dynamic motions less that the 100 mm level. This reduces the whole design process to a passive buffer with 88.776 kN/m stiffness and a 2250 kNs/m damping coefficient. This avoids the need to active and semi-active expensive techniques.

KEYWORDS: Highway Accidents, Passive Buffer, Optimal Buffer Design, Semi-Optimal Buffer Design, MATLAB Optimization Application

INTRODUCTION

The author was travelling by bus between two Egyptian cities during October 2013. The traffic was stagnant because an accident on the highway. Suddenly, the bus was hit by a heavy truck with its full speed. Its engine was completely destroyed and it was pushed by the hit to a side way for about 100 m. The truck hit another microbus full of passengers who were between injured and killed. This was the motivation of this research work to reduce the side effects of highway accidents to minimum.

Sun and Goto (1996) simulated the performance of energy dissipating buffers during large earthquake. They studied the effect of the buffer gap and damping coefficient [1]. Kit (1996) handled the use of hydraulic bumpers with overhead and gantry cranes to avoid unprotected collisions and catastrophic accidents. He pointed out the importance of careful attention to ensure proper specification and application of hydraulic bumpers [2]. Bielecki, Holnicki and Jezeque (2001) presented a general concept of design of adapted structures equipped with controllable energy dissipating units. They applied their concept to a practical adaptive car buffer [3]. Otlacan et. al. (2006) presented the solution of problems encountered in the design of buffers for railway vehicles. They compared the characteristics of their proposed buffer with those of other involved buffers [4]. Li and Darby (2010) presented an approach for the optimal design of a buffer for a buffered impact damper. Their objective was to reduce the impact force and enhance the vibration control [5]. Elmarakbi (2010) proposed front end smart structure to improve vehicle frontal impact. He studied two types of frond end structures and developed analytical analysis providing valid, flexible models suitable for optimization studies [6]. Craciun and Mitu (2011) developed analytical models for fitting the experimental data obtained on different railway vehicles buffers. They proposed nonlinear model when dealing with the friction and elastic forces of the buffer [7]. Han, Gu and Lou (2013) designed a device (buffer) fixed on the rear beams of a truck chassis. They used the classical mass-damper-spring buffer design with a damper using non-Newtonian fluid [8]. Cui et. al. (2014) designed a flexible swap device and studied its dynamics using ADAMS. They studied the dynamics of the system under collision and adjusted the buffer parameters to reduce the vibration of collision. They provided the reasonable design parameters of the buffer [9]. Dumont and Maurer (2014) presented a model for elastomer buffers for railway vehicle dynamics. Their work was based on the nonlinear rubber spring model of Berg [11] assuming that the forces encountered by the elastomer rubber are elastic, friction and viscous [10].

ANALYSIS

Dynamic System

The buffer is a spring-damped system connected in parallel and fixed to the vehicle chassis from the front and rear sides. The buffer has a spring of stiffness k and damping coefficient c. The buffer can physically replace the bumper of the vehicle. The vehicle is assumed in the stopping condition while it is hit by another un-buffered vehicle of mass M and moving with a speed V. This dynamic system is illustrated in Figure 1

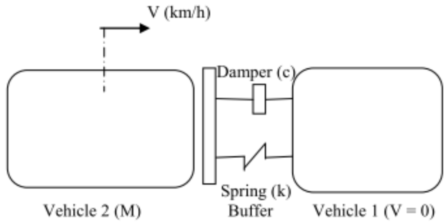

Figure 1: Vehicle-Buffer Dynamic System

Upon collision, the dynamic system is a mass-spring damper dynamic system of dynamic motion, say x.

The system differential equation assuming linear elastic and damping characteristics is:

$$M\, d_2x/dx^2 + c\, dx/dt + kx = 0 \qquad (1)$$

The buffer parameters are:

- Spring stiffness, k.
- Damper damping coefficient, c.

The stopping vehicle is hit by a vehicle of mass M and velocity V. Thus, the initial conditions required to solve the dynamic system model of Eq.1 are:

$$\left.\begin{array}{l} x(0) = 0 \\ dx/dt(0) = (10^6/3600)\, V \quad \text{mm/s} \end{array}\right\} \qquad (2)$$

The dynamic system having the differential equation of Eq.1 has the two important design parameters [12]:

- **Natural Frequency:** $\omega_n = \sqrt{(k/M)}$ rad/s
- **Damping Ratio:** $\zeta = c / (2M \omega_n)$

The solution of Eq.1 depends on the level of damping in the buffer. Of course, it is required to absorb the collision energy without any oscillation of the hitting vehicle of any damage to the hitted vehicle. This is can be achieved through:

- Using an over damping characteristics for the buffer-vehicle system (i.e. $\zeta > 1$)
- Transmitting the impulsive force due to impact to the chassis at a number of points to load the chassis from a number of points and hence decrease the possibility of its plastic deformation (permanent damage).
- Selecting buffer spring that it can provide elastic deflection of (say) 100 mm without reaching its solid length.

With an over damped characteristics, the dynamic motion of the hitting vehicle after collision is governed by the equation [12]:

$$x = C_1 \exp(a_1 t) + C_2 \exp(a_2 t) \tag{3}$$

where the parameters a1 and a2 depend only on the dynamic system damping ratio, ζ

That is [12]:

$a_1 = -\zeta + \sqrt{(\zeta^2 - 1)}$ and

$a_2 = -\zeta - \sqrt{(\zeta^2 - 1)}$

The time response constants C_1 and C_2 depend on the initial conditions x(0) and dx/dt(0) and the system parameters ω_n and ζ. That is [12]:

$$C_1 = \{x(0)\omega_n(\zeta + \sqrt{(\zeta^2 - 1)} + dx/dt(0)\} / \{2\omega_n \sqrt{(\zeta^2 - 1)}\}$$

and

$$C_2 = \{-x(0)\omega_n(\zeta - \sqrt{(\zeta^2 - 1)} - dx/dt(0)\} / \{2\omega_n \sqrt{(\zeta^2 - 1)}\}$$

Time Response Nature

If we consider a buffer of parameters 20 kN/m stiffness and 110 kNs/m damping coefficient fixed to a vehicle which is hit by a 2000 kg vehicle moving with 20 km/h speed. The hitting vehicle will have the dynamic motion shown in Figure 2.

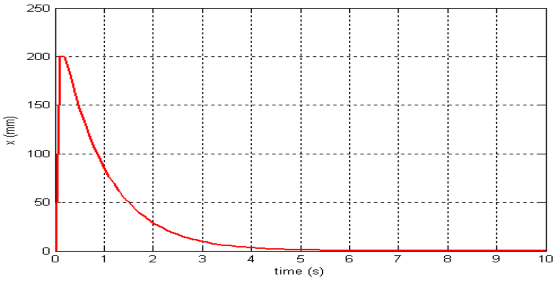

Figure 2: Vehicle-Buffer Time Response to Arbitrary Buffer Parameters

The response reveals the following characteristics:

- Rapid increase in vehicle motion from zero to a maximum motion (buffer spring deflection) of 200 mm.
- Decrease to zero motion after about 6 seconds.

This is an unaccepted response since it will exhibit a maximum motion of 200 mm which is greater than the 100 mm limit of the buffer. Here, comes the objective of the optimal design of the buffer to assign the buffer parameters such that the 100 mm limit will not be exceeded for a specific range of hitting vehicle mass and speed.

OPTIMAL BUFFER DESIGN

It is desired to assign the buffer parameters (k and c) such that upon collision, the maximum deflection of the buffer elements will not excedd 100 mm for any vehicle within 1000 to 6000 kg mass and speed within 120 km/h.

The sum of absolute error (IAE) is used as an objective function, F required by the optimization process. Thus:

$$F = |x_{max} - x_{maxdes}| \tag{4}$$

where x_{max} = maximum vehicle motion.

x_{maxdes} = maximum desired vehicle motion (100 mm).

The optimization procedure used depends on the MATLAB optimization toolbox using the command "*fminunc*"[13]. Thus, it does not need the definition of any functional constraints. In this case the judgement of the optimal design results depends only on the value of the objective function, F.

OPTIMAL DESIGN RESULTS

A MATLAB code is written with buffer parameters k and c as input parameters who are evaluated by minimizing the objective function (Eq.4) using the command "*fminunc*". Vehicle masses of 1000, 2000, 4000 and 6000 kg are considered. Hitting vehicle speed in the range 20 to 140 km/h are considered. The optimal buffer parameters are given in Figure 3.

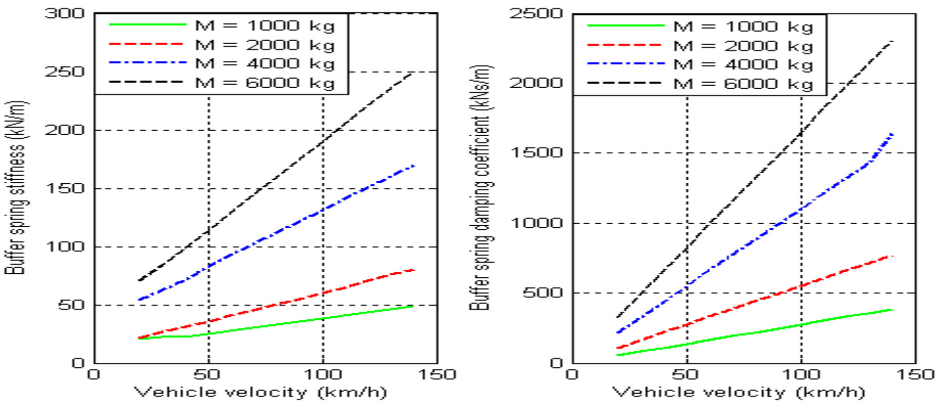

Figure 3: Optimal Buffer Parameters

To check the validity of the optimal design procedure, consider the mass vehicle of 2000 kg and speed of 20 km/h. The optimal buffer parameters are:

$k_{opt} = 21.779$ kN/m and

$c_{opt} = 109.23$ kNs/m

The time response of the hitting vehicle after collision with the buffer is shown in Figure 4 compared with the nonoptimal buffer parameters.

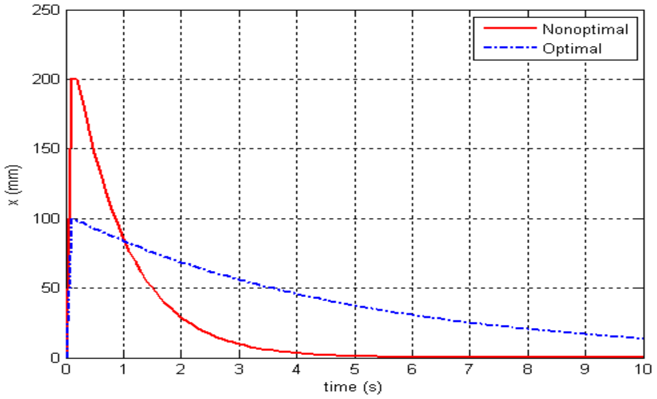

Figure 4: Optimal and Nonoptimal Vehicle Time Response Upon Collision

APPLICATION OF THE OPTIMAL DESIGN RESULTS

- Since the optimal design parameters of the buffer are function of the vehicle mass and speed as shown in Figure 3, a passive design of the buffer is not suitable.
- The right solution is to apply the active vibration isolation technique to adjust the buffer parameters [14-18].
- Or, as an alternative, the semi-active vibration isolation technique may be used to adjust the spring stiffness and damping coefficient separately [19-23].
- The procedure will be much simplified if it is possible to considered the buffer as a passive one. This is will be studied in the next section.

FURTHER DESIGN SIMPLIFICATION

- The optimal spring stiffness is in the range: 20.26 – 250.49 kN/m.
- The optimal damper damping coefficient is in the range:53.99 – 2309.5 kNs/m
- The stiffness range ($k_{max} - k_{min}$) is 230.23 kN/m.
- The damping coeeficient range ($c_{max} - c_{min}$) is 2255.5 kNs/m.
- Therefore, the optimal stiffness of the buffer spring has the minimum range.
- Considering the mean of the optimal stiffness values using MATLAB, the mean optimal stiffness is: k = 88.7761 kN/m
- The level of the damping coefficient highly affects the dynamics of the buffer.
- With the help of MATLAB programming, the effect of buffer damping when fixing the buffer spring stiffness at

88.7761 kN/m was investigated such that for the vehicle mass range and speed range covered in this research, the maximum hitting vehicle motion must not exceed 100 mm.

- The result is a buffer damping coefficient of 2250 kNs/m.
- By this simplification, the buffer is transferred to be a passive buffer having fixed and unique parameters.
- This will be much cheaper than the active or semi-active buffers.
- The dynamics at an extreme conditions of 6000 kg hitting vehicle mass and 140 km/h speed is shown in Figure 5.

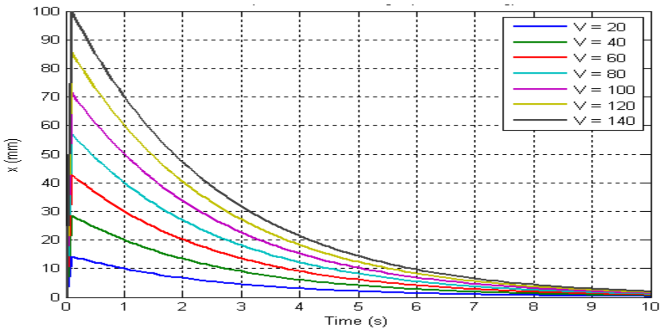

Figure 5: Hitting Vehicle Time Response with Semi-Optimal Buffer Parameter for a 6000 kg Vehicle

The same semi-optimal parameters of the buffer are applied to a small vehicle of 2000 kg mass. The dynamics of the 2000 kg hitting vehicle are shown in Figure 6.

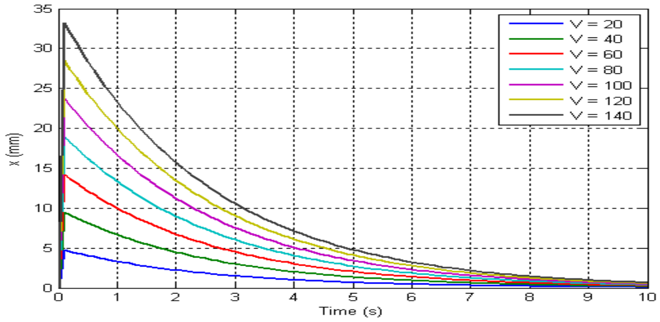

Figure 6: Hitting Vehicle Time Response with Semi-Optimal Buffer Parameter for a 2000 kg Vehicle

CONCLUSIONS

- A spring-damper buffer was suggested to avoid catastrphic death or injury.
- Exact optimal design of the buffer was presented in the paper which can be applied using active or semi-active approaches.
- The design procedure was reduced to a semi-optimal approach leading to a passive buffer.
- The design process was reduced to the selection of a unique buffer parameters of 88.776 kN/m stiffness and a 2250 kNs/m damping coefficient.
- With the assigned buffer parameters the hitting vehicle maximum motion will not exceed 100 mm for 6000 kg vehicles and 33 mm for 2000 kg vehicles.

- Other vehicle of masses between 2000 and 6000 kg will have maximum motion apon collission between 33 and 100 mm.
- Heavier vehicles will exhibit more dynamic motion which required readjusting of the damping coefficient of the buffer either in its passive form or in its semi-active form.

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