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TUNING OF CHARACTERISTICS OF DYNAMIC DRIVING SUSPENSIONS IN AN AUTONOMOUS ROBOT WITH OMNIDIRECTIONAL WHEELS

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The article presents results of a research and development work on a suspension of an autonomous mobile robot with omnidirectional wheels. At the beginning, the research object and requirements for suspensions in mobile platforms are discussed. In the following part, a computational model used in the optimization process is presented. An important issue was to determine kinematic excitations generated by omnidirectional wheels, which was identified experimentally and used in numerical calculations. The obtained results were experimentally verified by tests with a prototype suspension node which was mounted on the "vehicle quarters" test stand.

Keywords: passive suspensions, control of vibrations, mobile robots

1. Introduction

AGV (automated guided vehicle) or AMR (autonomous mobile robots) mobile robot are increasingly commonly used for unmanned transport in modern warehouses and plants. One of their important features is the fact that they are autonomous, i.e. able to take decisions independently, which significantly facilitates logistic works in manufacturing and storage processes.

One of the main principles in designing modern robots is interoperability, ability to communicate between robots through the Internet of Things. As a result, we are currently witnessing the fourth industrial revolution or the so-called Industry 4.0.

The industrial and individual requirements concerning the agility of autonomous mobile robots pose a challenge for the constructors of driving systems. The driving mechanisms of robots or vehicles with traditional wheels are restricted to only one direction of movement. Vehicles or robots equipped with a conventional steering system are unable to move sideways and require a certain space to turn. As a result, driving platforms have difficulties with turning around or avoiding obstacles in narrow spaces. Various structural forms of wheels and driving platforms for multi-directional driving have been developed to improve the manoeuvrability of vehicles or mobile robots (Bae and Kang, 2916; Doroftei *et al.*, 2007).

There are several types of multi-directional wheels used in industrial applications. The simplest and best known is the self-tracking wheel. Multi-directional wheels, such as Mecanum (He *et al.*, 2019) wheel or the omnidirectional wheel (Byun *et al.*, 2001) are characterised by a more complex structure. In spite of the advantage over other solutions offered by the multi-directional wheel, it is observed that it generates vibrations by itself (Duda *et al.*, 2021) and that these vibrations are then transmitted through the suspension system to the body of the vehicle. These vibrations are induced in the vertical direction, as the castors transmit the forces from contact between the wheel and ground to the vehicle body. This results from the discontinuous contact surface between the wheel and ground. Such disadvantageous vibrations may reduce the accuracy of positioning of a robot or worsen the driving capacity of the vehicle (Bae and Kang, 2916; Wang *et al.*, 2017).

Authors of numerous academic publications noticed the problem of vibrations generated by omnidirectional wheels and caused by intermittent contact between the passive castors and ground (Adascalitei and Doroftei, 2011; Kundu *et al.*, 2017). Most attempts at solving this problem involve modification of geometry of the wheel so as to minimise the influence of the discontinuity of contact between the wheel and ground. Additionally, various materials characterised by a high attenuation level are used to produce the castor wheels in omnidirectional wheels. An example of minimising vibrations by changing geometry of the wheel is development of an alternative omnidirectional wheel presented in publications (Byun *et al.*, 2001; Park *et al.*, 2016). A more expensive solution that occupies more space inside the vehicle is development of a vibration damping system (Yu *et al.*, 2016; Kciuk *et al.*, 2014). Unfortunately, it often creates a barrier in the designing process and increases the price of industrial vehicles, which producers usually strive to minimise in the systems and robots. Some light non-commercial robots use simple suspension systems that are based on shock absorbers commonly used in model building, consisting of a spring and a vibration damper. The main aim of such suspension systems is to ensure that every wheel will press on an uneven ground, which is necessary for multi-directional movement (Martynowicz *et al.*, 2013).

In AGV vehicles, omnidirectional wheels are used because they provide a certain optimum among all multidirectional wheels. They have a relatively high bearing capacity and occupy little space in the vehicle in comparison to traditional wheels with a turning mechanism. Unfortunately, the problem of vibrations generated by this type of wheels is quite often forgotten in the designing phase, so that it becomes noticeable only when the effects are visible. The most frequent effect that occurs most quickly are damage to bearing nodes. Disconnecting electrical connections have also been observed.

One of the methods of searching for an optimum solution for the designed structure consists in conducting a model research with the use of numerical simulations (Burghardt *et al.*, 2021; Tomaszewski *et al.*, 2022). The numerical model allows for a practically unlimited number of tests for variable initial conditions. This paper presents the methodology for testing the models of AGV vehicles that allows selecting the optimum elastic and damping characteristic of the suspension system.

2. Description of the analysed object

The developed methodology is of a unitary nature and it was tested on a specific model, i.e. AGV IBP500 vehicle manufactured by Etisoft Smart Solution. The frame of the vehicle is made of corrugated aluminium profiles connected with bolts. Figure 1 presents a side view of the framework with the driving system located in the central part of the vehicle. Independent suspension nodes of omnidirectional wheels are installed in the furthest points of the framework. The elastic damping characteristics for the suspension were then selected in the further phases of the study.

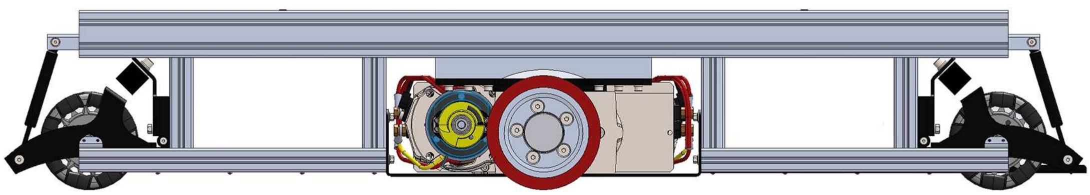

Fig. 1. Side view of the vehicle frame with the power and driving system

The suspension system consists of four independent swing arms mounted to the frame on one side with a rotational connection and to the shock absorber on the other side, which forms a classic swing arm suspension system. An omnidirectional wheel is installed in the swing arm. Two suspension nodes – left and right – are located symmetrically on the front and rear axles. The swing arm leap is limited by a rubber buffer. The vehicle moves around the manufacturing floor pulling a basket that weighs up to 500 kg, and the vehicle is attached to two pins mounted under the basket. The basket is not lifted, so it moves on its own wheels. None of the vertical forces generated by the vehicle have a significant influence on the movement of the basket, and vice versa. Due to that, further analyses focus on the dynamics of the AGV vehicle itself.

3. Requirements for suspension systems in AGV vehicles

The problems of selecting the optimum parameters of a suspension system for AGV IBP500 vehicle involve three main aspects that correspond to traditional suspension systems of vehicles moving on wheels, and are related to:

- minimising the transmission of vibrations caused by the shape of the envelope of an omnidirectional wheel;
- maximising the vehicle stability while accelerating, braking and overcoming obstacles, i.e. minimising the oscillating tilt of the vehicle to the front and rear, and minimising the phenomenon of driving outside the balance position;
- maximising the traction of the driving wheels during accelerating, braking and turning.

Each of the discussed aspects is important for functioning of the vehicle in the industrial environment, and failure to meet those conditions may result in damaging the vehicle, loss of adherence, falling out of the route or collision. These problems often result in interrupting the supply process in the manufacturing plant.

4. Modelling the driving system of the AGV vehicle

The effectiveness of functioning of suspension systems of wheeled vehicles that minimise the effects of forces caused by uneven roads on the body may be modelled with the use of models widely discussed in literature (Wei and Taghavifar, 2017; Weiss *et al.*, 2014). The driving system of AGV IBP500 vehicle is more complex than in the most popular 2-axle cars, and it has an additional separate driving axle. The model of the suspension system is based on six wheels mounted on three axles, where the middle axle is the driving one and is usually unsuspended. This type of vehicles usually move on flat surfaces of manufacturing facilities, where the only obstacles are floor dilatations, cables lying on the floor, etc. Considering the above, the authors proposed to evaluate characteristics of dynamic suspension systems with the use of a simplified model of the vehicle, also referred to as a quarter vehicle model (Verros etal, 2005). In order to obtain the quarter vehicle model, it is assumed that in specific conditions there is a possibility to uncouple flat vibrations of the vehicle. Due to the used suspension system of AGV IBP500 vehicle, assuming continuous contact between the driving wheel and ground, main vibrations of the vehicle will only result from oscillations around the axis defined by the driving wheel axle (Fig. 2).

The quarter vehicle model with two degrees of freedom (Fig. 3a) is one of the most popular models used in scientific publications on the dynamic properties of wheeled vehicles (Verms *et al.*, 2000, 2005).

In the analysed vehicle, the suspended weight is much larger than the unsuspended weight, and the rigidity of the suspension is significantly lower than the structural rigidity of the omnidirectional wheel. Such relations between the parameters are reflected in the responses of the

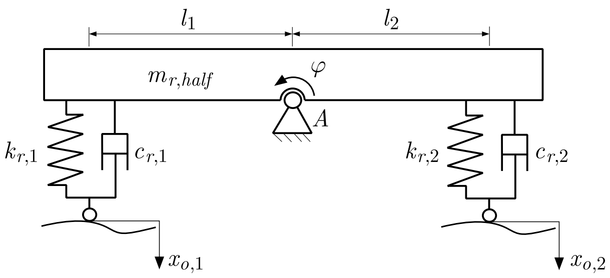

Fig. 2. Half vehicle model

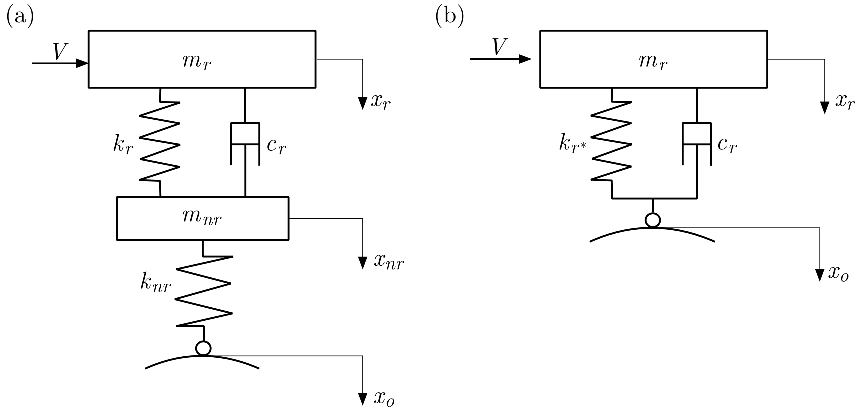

Fig. 3. (a) Quarter vehicle model, (b) quarter vehicle model with one degree of freedom

quarter vehicle model. As a result, this leads to lower values of the deflection of the wheel structure in the vicinity of the first resonance. It was assumed for modelling purposes that in the vicinity of the first resonance, the unsuspended weight only copied the road profile. Based on this assumption, the model with one degree of freedom was ultimately used in the modelling studies. The substitute rigidity k_{r^*} of the model with one degree of freedom (Fig. 3b) is in this case equivalent to the rigidity of suspension k_r. This model is so popular that the frequency of its use in academic publications equals that of the model with two degrees of freedom (Li *et al.*, 2004; Litak *et al.*, 2008).

4.1. Determination of the excitation profile

Researchers from the Department of Theoretical and Applied Mechanics of the Silesian University of Technology in Gliwice developed a test site which is designated for testing suspension columns of vehicles, including those equipped with omnidirectional wheels, used in mobile robotic applications. The test site is the subject of patent application entitled: "A device for testing vehicle suspension columns, especially for vehicles equipped with omnidirectional wheels and the manner of testing vehicle suspension columns" that was submitted to the Patent Office of the Republic of Poland under No. P. 432948. The aim of the proposed site for testing vehicle suspension columns is to measure displacements and accelerations transmitted to the suspension column and caused by the contact between the wheel and ground, depending both on the shape of the wheel and on the state of the surface on which the wheel is moving. If the displacement is measured, the result is the excitation profile x_0 presented in Fig. 3a,b.

Detailed information about the construction and the working principle of the test site is presented in publication (Duda *et al.*, 2021). For the purposes of the conducted analysis of dynamics, the excitation profile resulting from the interactions between the omnidirectional wheel and an industrial concrete floor was determined, taking into account such natural obstacles as, e.g. naturally occurring floor dilatations (Fig. 4).

Fig. 4. Test site for determination of the excitation profile

As a result of the conducted measurements, courses of the displacement as a function of time were obtained for various driving speeds, being the most common speeds of a typical AGV vehicle, i.e. 3 kph and 5 kph. Figure 5 presents a sample course obtained for the driving speed of 3 kph.

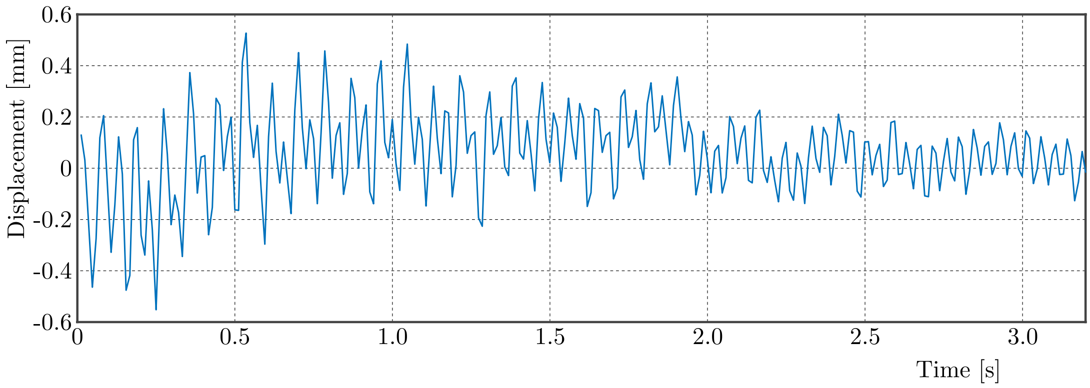

Fig. 5. Course of changes in the road profile for the driving speed of 3 kph

4.2. Computational model of the suspension system

As a result of the preliminary analysis of the structural solution of the suspension node, the following form was used, which is presented in Fig. 6.

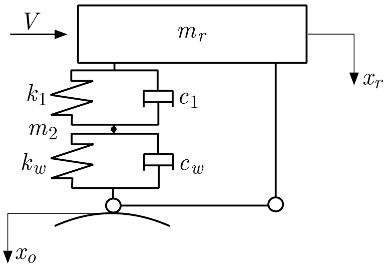

Fig. 6. Model of a suspension node with elastic-damping elements

This solution is based on a serial connection of two elastic damping elements, i.e. the shock absorber consisting of a pressure spring of the rigidity k_1 and length l_1 connected parallelly to a viscous damper of the damping coefficient c_1 and an anti-vibration mount of the rigidity k_w, damping c_w and length l_w.

The equations of motion of the analysed node take the following form

$$\begin{aligned} &m_r\ddot{x}_r + k_1(x_r - x_2) + c_1(\dot{x}_r - \dot{x}_2) = 0 \\ &m_2\ddot{x}_2 + k_1(x_2 - x_r) + k_w(x_2 - x_0) + c_1(\dot{x}_2 - \dot{x}_r) + c_w(\dot{x}_2 - \dot{x}_0) = 0 \end{aligned} \tag{4.1}$$

4.3. Numerical calculations

Numerical calculations conducted in order to determine the optimum parameters of the suspension system were realised according to the proposed scheme (Fig. 7). The calculations were performed in the MATLAB environment with the use of programme scripts created by the authors.

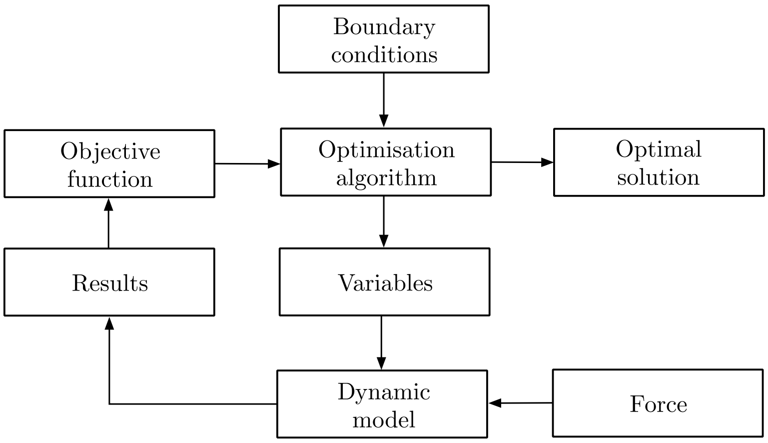

Fig. 7. Flowchart of the optimisation algorithm

The aim of the applied optimisation tool is to minimise the target function by selecting the appropriate parameters of this function. This tool is a separate software module that uses the embedded optimisation algorithms in the MATLAB environment. The selected optimisation algorithm is a genetic algorithm which is one of the evolutionary optimisation methods. It belongs to the class of heuristic algorithms. The search for possible solutions in order to find the best or potentially best solution takes place with the use of mechanisms of evolution and natural selection (Miettinen *et al.*, 1999).

The multi-criteria target function Fc was adopted in the following form

$$Fc = Fc_d w_1 + Fc + a w_2 + Fc_s w_3 \tag{4.2}$$

Individual components of the target function were defined as

$$\begin{aligned} &Fc_d = \sqrt{\sum_{i=1}^{n}(X - \overline{X})^2} \qquad Fc_a = \sqrt{\sum_{i=1}^{n}(A - \overline{A})^2} \\ &Fc_s = \sum_{i=1}^{n} X_i \qquad n = \frac{t}{dt} \end{aligned} \tag{4.3}$$

where: n – number of samples from the course, t – simulation time, dt – simulation step time-sampling time, X_i – value of the displacement at the i-th step, A_i – value of the acceleration at the i-th step.

The target function was formulated based on three criteria. The first one is the displacement criterion whose aim is to minimise the coefficient of transmission of the vibration displacement. It is calculated as the standard deviation from the course of displacements of the suspended weight. Such formulation of the task allows one to globally minimise all the amplitudes of the object displacement during motion. The second one is the acceleration criterion whose aim is to obtain the lowest value of the acceleration transmission coefficient, i.e. the standard deviation of the course of accelerations of the suspended weight. This in turn allows for the global minimisation of all amplitudes of object accelerations during motion. Finally, the third criterion is stability. Its aim is to obtain the lowest sum of consecutive values of the object displacement. This criterion also complements the previous ones, as the value of the standard deviation does not depend on time and it may take the same value at various durations of the simulation. The sum of consecutive values increases with each point at the set time intervals. For regular oscillations, the sum of consecutive values reflects the effects of mean and median at the same time while being free of their disadvantages in statistical terms. The analysis of the sum revealed that the higher the amplitude, the stronger the strive to minimise it, as it has a higher influence on the increase in the target function. This, in turn, influences the effect of the shortest time of return to the minimum value position, i.e. the balance position (Zimroz, 2007).

Each of the presented criteria is equally important for the selection of the appropriate technical solution, so the weights were selected so that the values of the partial target functions are similar. The given weight unit by which the partial target function is multiplied is the reciprocal of the unit of such a partial target function so that a dimensionless unit is obtained for the general target function. The numerical simulations of the model are preceded by an iterative process of weight assignment (Zitzler, 1999).

The decision variables in the analysed model (Fig. 6) are the rigidity coefficient k, viscous damping coefficients c and lengths l of individual elastic damping elements. The equations of motion that describe the quarter vehicle model (1 and 2) do not include the length of spring elements. As a result, the best solutions in the optimisation process may be springs of such a rigidity which, due to technological limitations, cannot be mounted in the suspension system. Due to that, the optimisation process was conducted with limitations, linking the rigidity of springs to their geometric parameters which should fall into limited ranges. In the analysed issue, the accuracy of the obtained decision variables is limited to one. This accuracy is sufficient, because for the sample solution, preparing a shock absorber of the rigidity of 7000 N/m and damping 500 Ns/m will carry an error that results from the technological capacity of springs of approx. 10 N/m and for the damper of approx. 5 Ns/m. Due to the above, it is not necessary to use a precise method of searching for the optimum solution by combining the genetic algorithm with one of the gradient methods. The lower accuracy of the searched solution may be increased by a more detailed search of the solution area. The basic parameters of the genetic algorithm were established for a population of 300 specimen and 12 generations.

The calculations performed with the use of the algorithm presented in the previous Section resulted in the values of parameters of the suspension model. Then, a prototype of the suspension system was created so that the elements of the actual system would reflect the parameters determined in the optimisation process. In order to protect the interest of the Etisoft Smart Solutions Company, these parameters are not presented here, as it would constitute violation of such a interest.

The developed solution was tested on the test site shown in Fig. 4 and compared to the solution previously used by the manufacturer (Fig. 1). Table 1 presents a comparison of vibration course parameters for the non-optimum suspension system used in AGV vehicles with the parameters obtained from the courses for the newly developed suspension node (Fig. 8).

A decrease in the value of displacement with an increase in driving speed is characteristic for the suspension system parameters selected in this way. Dynamic simulations and measurements

Table 1. Comparison of the course parameters of vibrations of the suspended weight for the currently used and the optimised structure of the suspension system

Type of wheel mounting	Speed					
	1 kph		3 kph		5 kph	
	Existing suspens. node	Optimum suspens. node	Existing suspens. node	Optimum suspens. node	Existing suspens. node	Optimum suspens. node
Maximum amplitude of displacement [mm]	0.29	0.48	0.53	0.35	0.67	0.25
Maximum amplitude of acceleration [mm/s^2]	5660	3547	21008	10470	29411	12500
Standard deviation of displacement [mm]	0.14	0.16	0.15	0.10	0.18	0.10
Standard deviation of acceleration [mm/s^2]	2297	1161	5987	3062	8382	4035

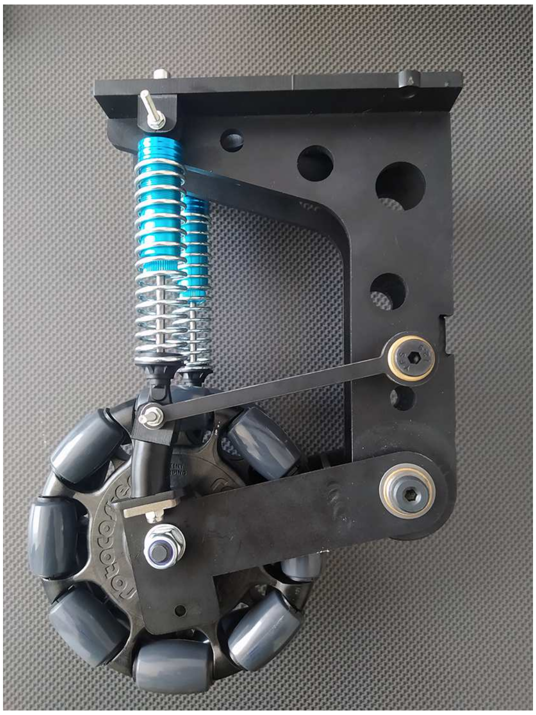

Fig. 8. View of the modified suspension system

of the currently used suspension system show an increase in the amplitudes of displacement with increasing speed, whereas for the developed prototype suspension node, the amplitudes of displacement decrease with increasing speed. Such characteristics result from the optimisation of parameters of the suspension system for the course of forced displacements found from the vehicle moving at typical driving speeds, i.e. 3 kph and 5 kph.

5. Conclusions

This study presents a methodology for shaping characteristics of dynamic suspensions of vehicles equipped with omnidirectional wheels, in particular in the applications in mobile robots. This strategy assumes obtaining the optimum parameters of elastic damping elements for the proposed structure of the suspension system based on a computer calculations tool. In order to select the optimum characteristic of the elastic damping element, its characteristic features, such as rigidity coefficients, damping coefficients and element length, were optimised. The optimisation was conducted in the MATLAB environment with the use of a tool that employs a genetic algorithm to minimise the target function. A software module was developed; a multicriteria target function was prepared based on the vibration transmission coefficient, which was the standard deviation of the course of displacements and accelerations of the suspended weight from the whole range of simulations. On the test site, the excitation profile was determined at various velocities of motion, resulting both from the shape of the envelope of the omnidirectional wheel and the quality of ground surface. The elastic and damping characteristics of the elements of the suspension system determined as a result of the conducted numerical simulations allowed us to design a new structure of the suspension node that was adapted to the conditions of mounting in AGV IBP500 robot.

The developed algorithms and computer programs are of a general nature, so they may be successfully used to determine structural properties of mechanical systems of a similar structural form. The proposed calculation models take into account the main physical phenomena in the analysed systems and determine their dynamic properties.

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