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OPTIMIZATION OF KINEMATIC PROPERTIES OF MECHANISM

OPTIMALIZACE KINEMATICKÝCH VLASTNOSTÍ MECHANISMU

Abstract

The paper deals with an analysis and an optimization of the truck shifting mechanisms. The aim of the work is to optimize the trajectory of a shifting lever hand-grip in order to obtain an acceptable ergonomic trajectory. A mathematical surrogate of the shifting mechanism has been constructed and the following use of the optimization algorithms resulted in several modifications of mechanism dimensions.

Abstrakt

Příspěvek se zabývá kinematickou analýzou mechanismu řazení. Cílem je optimalizovat dráhu řadící páky tak, aby tato dráha bylo co nejpřijatelnější z ergonomického i uživatelského hlediska. Byl vytvořen matematický model kinematiky mechanismu. Pomocí citlivostní analýzy byly vybrány rozměry mechanismu, které byly dále pomocí optimalizačních algoritmů měněny za účelem získání ergonomicky přijatelného tvaru dráhy řadící páky. Výsledkem práce bylo několik verzí modifikací rozměrů mechanismu řazení.

1 THE SHIFTING MECHANISMS IN GENERAL

Nowadays there is a wide offer of the trucks, which are intended to operate in the hardest terrain and climatic conditions. Customers decide with respect to price, high reliability and among others also to ergonomic features of a truck controlling. It is important for users that the vehicle manipulation and controlling are in harmony with operator's motions. If we achieve this harmony then the truck using seems to be intuitive and simple to the operator.

The shifting mechanism is also one of these controlling devices, which has to satisfy the ergonomic demands. This mechanism enables a driver to change gear ratios.

The mechanism can be actually based on three principles. We can use electronic components. So the shifting lever becomes a joystick. Unfortunately the electronic devices are in general highly sensitive to vibrations and humidity and also their reliability is low.

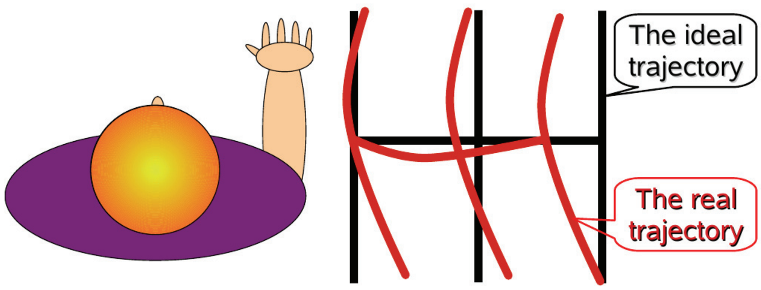

Fig. 1 Real and ideal shape of the shifting lever trajectory

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Or we can transfer the gearing impulses from the shifting lever to the gearbox by the wire strand. However there is a problem with an accuracy if the wire is pushed and also soil or sand can intrude between the line and guiding.

So none of the above described concepts cannot be used. We cannot avoid the usage of the classical rigid body mechanism. But these are structurally very complicated and there is also problem with a lack of room. It follows difficult design of the mechanism. We obtain curved lever trajectories, see figure above. In case of the real trajectory the driver can hardly find gearing points and there is also element of unconcetration and exhaustion due to this inconveniences. Consequently we have to optimize the trajectory of a shifting lever hand-grip in order to obtain the acceptable ergonomic trajectory see figure above.

Investigated shifting mechanism is supposed to be used in cars where the driver sits on the left hereinafter called the left-hand shifting mechanism.

2 THE LEFT-HAND SHIFTING MECHANISM

In order to deeply investigate and analyze mechanisms at first we have to create a kinematic scheme of a particular mechanism and appropriately describe the mechanism dimensions, see figures bellow.

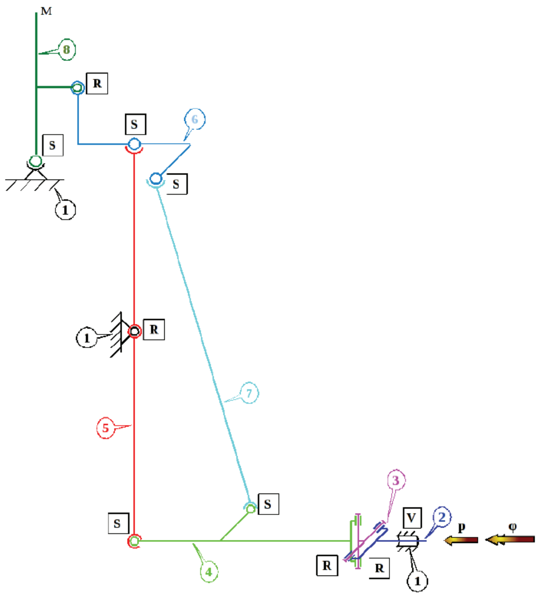

Fig. 2 Kinematic scheme of the right-hand shifting mechanism; joint symbols: S - spherical; R - rotational; V - cylindrical;

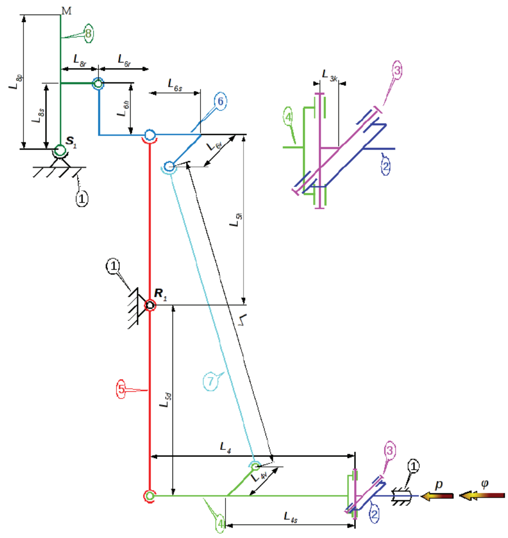

Fig. 3 The description of the mechanism dimensions

2.1 Mechanism Coordinates

The gearbox is controlled by the fork no. 2 (see figure no. 2). One can find two marked coordinates of this fork and those are shift (denoted by p) and rotating (denoted by φ) along and about the same axis. Let's call these the mechanism coordinates. Values of the mechanism coordinates and layout of gear ratios is shown in figure no. 4. For instance if a driver choses a second gear ratio the fork has to shift and rotate about certain distance and angle. Let's consider the ideal version of the shifting mechanism; if the shifting lever moves in the car driving direction (respective perpendicular to this direction) the fork shifts (respective rotates). In practice this two moves are not mutually independent and this independence results in the curved shifting tracks as was sketched in figure no. 1.

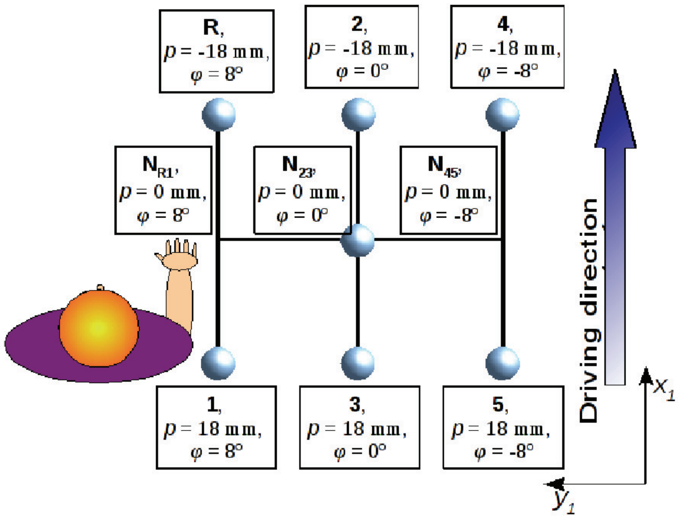

Fig. 4 Layout of the gear ratios

3 THE ANALYSIS OF THE LEFT-HAND MECHANISM

If the kinematic and the dimension scheme is created we can determine the fundamental mechanism properties. The mechanism is assembled from eight parts (including frame). Number of degrees of freedom is equal three of which two are the mechanism coordinates and one is undefined (undefined rotation of part no. 7 about its longitudinal axes). One can find three kinematic loops in in the scheme.

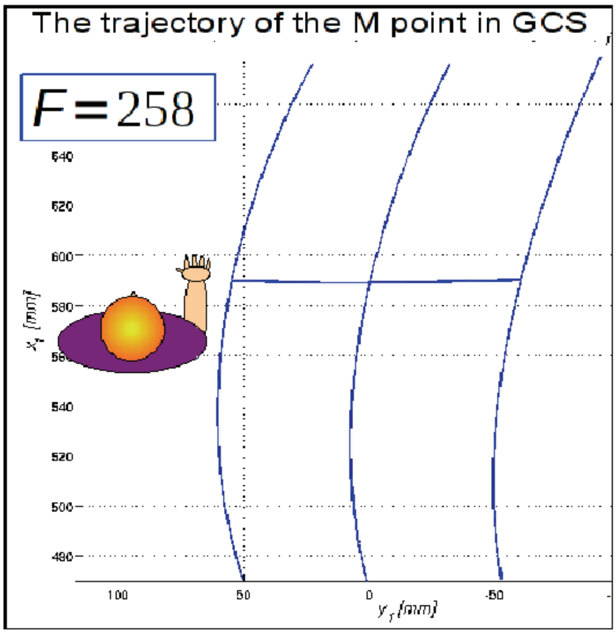

Fig. 5 The shape of the left-hand mechanism shifting tracks for the original concept

Once we know these basic specifications, we can construct a mathematical surrogate of the mechanism. The construction of mechanism mathematical surrogate (or the transmission function) is a long and complicated process, that is why it is not described in the paper in details. The transmission function has been created through the use of the transformation matrix method, see [3]. The function consists of a system of sixteen (number of loops multiplied by six) nonlinear equations, where sixteen unknowns represents coordinates of the particular joints (mostly angles of spherical joints). The system of nonlinear equations has been solved by the Gauss-Newton method. This method turned out to be the most efficiency and the fastest in comparing with Levenberg-Marquardt or „Trust-Region Dogleg“ methods. These methods did not even converged to a solution in some cases of mechanism positions.

If the transmission function is solved, we can plot the shifting tracks, see figure above. One can see, that the track shape is truly far from the optimum. So we have to optimize the mechanism dimensions in order to obtain better shaped tracks.

4 THE OPTIMIZATION OF THE LEFT-HAND MECHANISM

4.1 The Construction of the Objective Function

First step in the optimization process is to build up the objective function (denoted by *F*). This function quantifies desired properties so that the closer to the optimum shape the lowest value of the objective function. The author established two geometric features of each particular track (by the term track is meant the each vertical part of the trajectory). These features are the curvature and the scope denoted by d_r and s_r, see figure bellow. A value of the objective function for the original mechanism is noticed in figure 5.

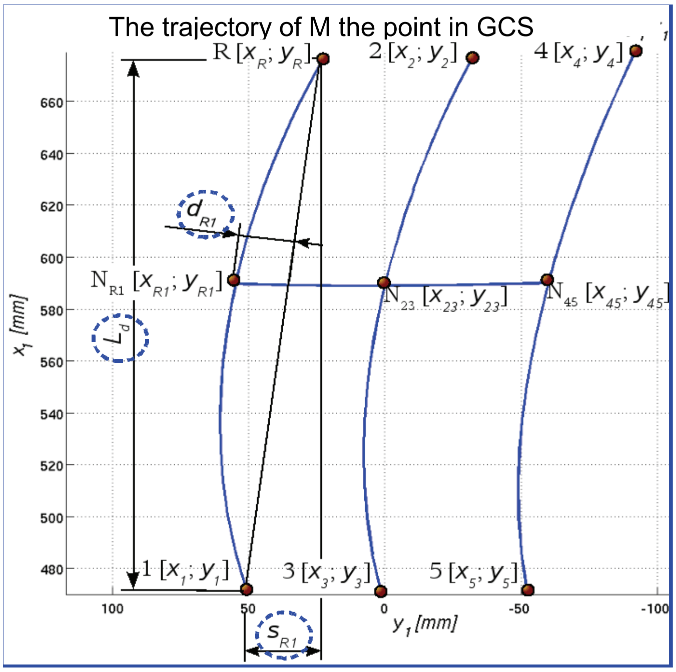

Fig. 6 Description of the geometric features of the shifting tracks

5.2 Identification of Design Parameters

If the objective function is established, we have to find the mechanism dimensions, which improve the shape of the tracks. These dimensions will be called hereinafter design parameters and these design parameters will be optimized.

The design parameters have been found by means of sensitivity analyses. In practice we chose one mechanism dimension and we observe an influence of dimension's change at the shifting tracks shape. If the change improves the shape then we consider this dimension as design parameter. By examining the mechanism, three design parameters have been selected. These are two distances and one angle of scope of rotational joint's axes, see figure bellow.

Two methods of unconstrained mathematical optimization have been used. These are Nelder-Mead method (also known as simplex method) and Broyden-Fletcher-Goldfarb-Shanno (BFGS) method.

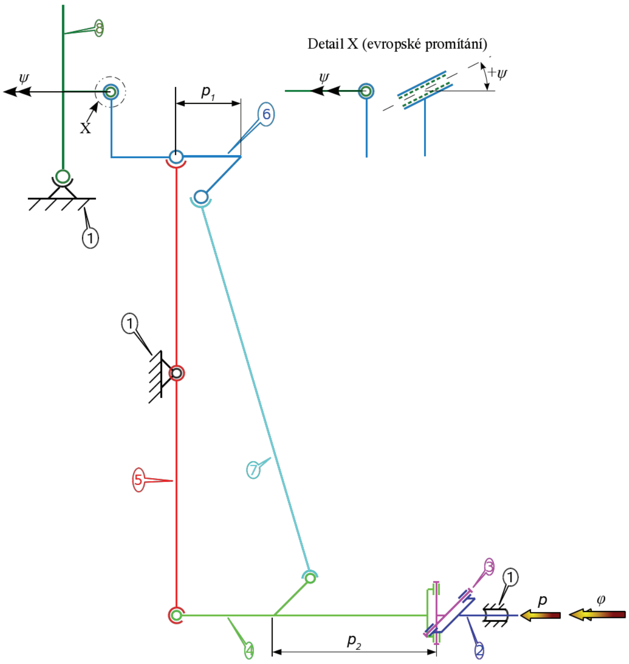

Fig. 7 Three design parameters of the mechanism

4.3 Nelder-Mead Method

This method is based on a construction of a simplex in space $\mathbb{R}^n$ (where n is number of the design parameters). Simply, simplex is the simplest object in the space which we can build up, for instance in two-dimension space the simplex becomes a triangle. The simplex is defined by the set of n+1 points (vertices). Roughly the principle of the method consists of the following steps:

0) Initial guess of the simplex (this step needs to be provided just at the beginning of the algorithm).
1) Evaluating the objective function values in vertices.
2) The algorithm compares the evaluated values. According to the comparing, the algorithm provides reflection, expansion, outside contraction, inside contraction or shrinkage of the simplex.

The algorithm was taken from [1]. In the figure bellow is shown how the method works in practice. The graph plots two-dimensional optimization process of the design parameters p_1 and p_2.

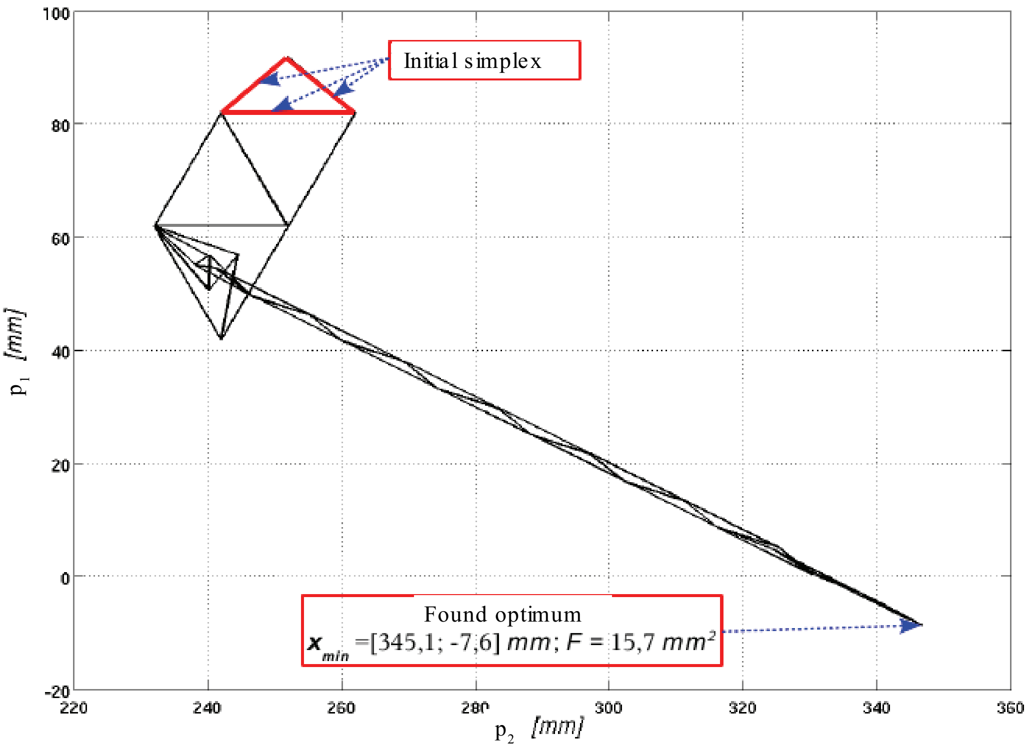

Fig. 8 Two-dimensional optimization process by the simplex method

In the figure bellow you can see the shape of the shifting tracks after three dimensional optimization by the simplex method (compare with figure no. 5)

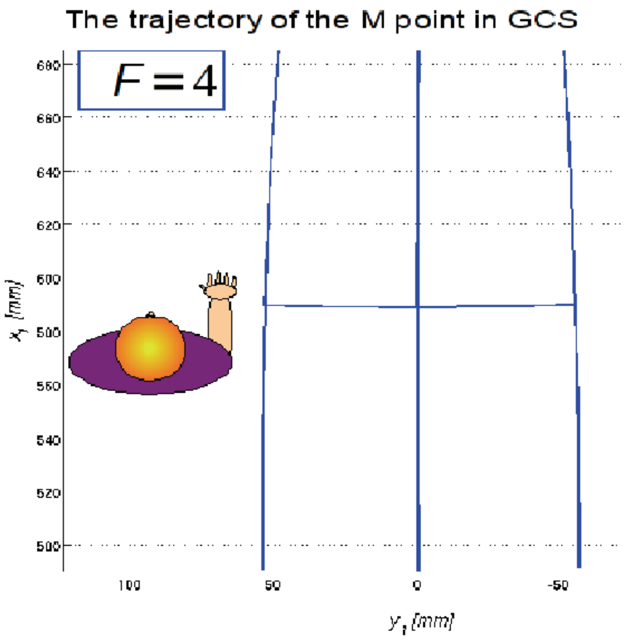

Fig. 9 The shape of the left-hand mechanism shifting tracks
for the optimized concept

4.4 The BFGS Method

This method belongs to the group of Quasi-Newton optimization methods. These methods approximate the objective function by so-called quadratic surrogate $m^{(k)}$: $\mathbb{R}^n \rightarrow \mathbb{R}$, given by the Taylor series:

$$F\left(x^{(k)}+p\right) \approx m^{(k)}(p) = F^{(k)} + \nabla F^{(k)T} \cdot p + \frac{1}{2} p^T \cdot B^{(k)} \cdot p. \qquad (1)$$

Where superscript *(k)* denotes a number of iteration, F is the objective function, $x^{(k)}$ is the current set of design parameters, p is searched increment of the design parameters so that these minimize the objective function, ∇F denotes a gradient of the objective function and finally B denotes Hessian matrix. Explicit formula for this matrix is

$$B^{(k)} = \begin{bmatrix} \frac{\partial^2 F^{(k)}}{\partial x_1^{(k)2}} & \frac{\partial^2 F^{(k)}}{\partial x_1^{(k)} \partial x_2^{(k)}} & \cdots & \frac{\partial^2 F_k}{\partial x_1^{(k)} \partial x_n^{(k)}} \\ \frac{\partial^2 F^{(k)}}{\partial x_2^{(k)} \partial x_1^{(k)}} & \ddots & & \frac{\partial^2 F^{(k)}}{\partial x_2^{(k)} \partial x_n^{(k)}} \\ \vdots & & & \vdots \\ \frac{\partial^2 F^{(k)}}{\partial x_n^{(k)} \partial x_1^{(k)}} & \frac{\partial^2 F^{(k)}}{\partial x_n^{(k)} \partial x_2^{(k)}} & \cdots & \frac{\partial^2 F^{(k)}}{\partial x_n^{(k)2}} \end{bmatrix}. \qquad (2)$$

Obviously it is not possible to explicitly evaluate the matrix in case of engineering problems, so we approximates the Hessian matrix by means of a history of optimization process, in other words we exploit former evaluations of the objective function to build up the matrix. There are several ways how to approximates the Hessian. In our case we used BFGS approximation formula, for more details about the algorithm and approximation formula see [2].

The usage of the BFGS method resulted in almost the same set of design parameters as the simplex method (see figure 9).

5 CONCLUSIONS

Six variants of dimension modifications have been proposed to the manufacturer. The company took into consideration an extent of changes and available space in the truck. Finally the chosen variant works well in operation.

Let us summarize the achieved results. Concerning solving of the transmission function (the mathematical surrogate of mechanism kinematics); the Gauss-Newton method turned out to be the most efficient and appropriate to solve the transmission function. In case of practical usage of the optimization algorithms; the simplex method appears much convenient to use (the method does not need any input parameters) and also the method is highly robust (it is possible to use it in case of any terrain of the objective function). On the other hand the BFGS method offers possibility of parallelization (could be worth it in case of large problems).

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