Considerations over the Mechanisms that Provide Snake-like Locomotion

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1. INTRODUCTION

The biomechanisms, which provide dragging locomotion mechanisms. The structure of these mechanisms must be in concordance with the studied biomechanisms structure and the specific character of reproduce locomotion. The mechanisms that can provide dragging locomotion can be considered as an assembly made of the following base structural modules: dragging kinematic chain (DKC) based on a substratum through a support device (SD), driving motor (DM) and the motion transmission and transforming mechanism (MTTM). To solve the kinematic analysis of these mechanisms we implement two computational algorithms. To elaborate these algorithms we have considered the structure of these mechanisms and the specific character of snakes’ locomotion. For exemplification, we present the kinematic analysis for one mechanism that mimics snakes locomotion. This mechanism includes one dragging kinematic chain (DKC) that is built with dragging elementary chain (DEC) type \( R_z \). We also present the results of the experimental research regarding mechanisms for dragging locomotion. This research had the purpose to validate the principle of dragging locomotion like a snake and the theoretical calculation principles. Two experimental mechanisms for dragging locomotion similar to snake were conceived and realized. Satisfactory rapprochement between the theoretical and experimental results was established as a result of this research.

Abstract: In this paper we approach the structure, the kinematics and two experimental models of dragging locomotion mechanisms. The structure of these mechanisms must be in concordance with the studied biomechanisms structure and the specific character of reproduce locomotion. The mechanisms that can provide dragging locomotion can be considered as an assembly made of the following base structural modules: dragging kinematic chain (DKC) based on a substratum through a support device (SD), driving motor (DM) and the motion transmission and transforming mechanism (MTTM). To solve the kinematic analysis of these mechanisms we implement two computational algorithms. To elaborate these algorithms we have considered the structure of these mechanisms and the specific character of snakes’ locomotion. For exemplification, we present the kinematic analysis for one mechanism that mimics snakes locomotion. This mechanism includes one dragging kinematic chain (DKC) that is built with dragging elementary chain (DEC) type \( R_z \). We also present the results of the experimental research regarding mechanisms for dragging locomotion. This research had the purpose to validate the principle of dragging locomotion like a snake and the theoretical calculation principles. Two experimental mechanisms for dragging locomotion similar to snake were conceived and realized. Satisfactory rapprochement between the theoretical and experimental results was established as a result of this research.

1. INTRODUCTION

The biomechanisms, which provide dragging locomotion, could be included in the category of biologic structures type vertebral column. Such a structure is formed by serial connection of some reduce length elements through elastic entities which allow relatively reduced angular displacements. The constitutive elements can be rigid, in this case being named vertebrae (in the case of vertebrates) or flexible, the worm’s case, being named segments.

The functions of these structures are:
- spatial sustaining and guidance – vertebral column in vertebrates’ case;
- spatial guidance and sustaining – giraffe’s neck;
- spatial guidance – insects’ antennas, scorpion’s tail;
- dragging locomotion – snakes, worms, etc.

2. THE STRUCTURE OF BIOMECHANISMS FOR DRAGGING DISPLACEMENTS

The structure of such biomechanism presents a large variety due to the huge number of species that use this type of locomotion [1]. For this reason we will limit only to the apodeu’ study, whose natural locomotion is dragging. From all apodeus we have chosen, in this paper, snakes due to their performances in dragging locomotion.

The snakes do not present a real locomotion system. Body specific movements provide their displacement.

As concerning the skeleton (fig. 1) [9], only the endoskeleton is present, presenting a deep position inside the body. Only the axial skeleton can be remarked: skull, vertebral column and ribs.

![Fig. 1](image)

The vertebral column is formed from a large number of vertebrae (160-400). The amount of bending which can take place between any two adjacent vertebrae is about 25 deg from side to side and 25-31 deg in the vertical plane, some 13 deg of ventral and 12-18 deg of dorsal flexion being possible [2]. The muscles of the trunk and tail, which do all the locomotion work, are remarkably complicated.
3. STRUCTURE OF THE MECHANISMS THAT PROVIDE DRAGGING LOCOMOTION

The mechanisms that provide dragging locomotion can be considered as an assembly made of the following base structural modules [5], [6]: dragging kinematic chain (DKC) based on a substratum through a support device (SD), driving motor (DM) and the motion transmission and transforming mechanism (MTTM).

The function of DKC is to provide the ensemble of the liberty of movements, imposed by dragging locomotion. DKC is a fundamental kinematic chain, made of rotation and/or translation couples. The problem is that we have to find also in the case of DKC some elementary identical structures of which repeating to result the entire DKC. These elementary structures will be named dragging elementary chains (DEC). 63 types of DEC-s have been created. In [5] we present the obtained alternatives. For exemplification we present some DEC with three liberty degrees (table 1) and with four liberty degrees (table 2).

The driving motor destination is, of course, that of generating movement. The destination of MTTM is that of transmitting the movement produced by the motor to the driving kinematic joint. The role of the supporting device (SD) is to provide the contact between the mechanism and the surface of support. For a snake, this contact is provided by the scales situated on its ventral sides and for the earthworms by the tegument of the segments [1]. From the technical point of view, the SD can be replaced by wheels, caterpillars, skis or sets of needles. These elements need not be motors, the propulsion force being generated by the specific movements of the DKC. In this case unidirectional wheels and caterpillars and passive needles can be used.

4. THE KINEMATIC ANALYSIS OF MECHANISMS THAT PROVIDE SNAKE-LIKE LOCOMOTION

One considers in Figure 2 a mechanism that mimics snake's locomotion. This mechanism includes one dragging kinematic chain (DKC) that is built with one dragging elementary chain (DEC) with indefinite type. One knows the geometry of links and the kinematic parameter's variation in driving joints. As a result, one knows the order of connection with the base for the mechanism links. In Figure 2 one considers the n+1 links articulate to the base in contact point Dn+1, on right side in advance direction.

The computational algorithm for the kinematic analysis of this mechanism it is presented in Figure 3 [4].

As one shows, this algorithm can be use to the kinematic analysis of any snake-like locomotion mechanism. An alternative for this algorithm is presented in Figure 4. This last algorithm is less exactly than the previous, for speeds and accelerations calculus because of the approximations of interpolation. At same time, the algorithms of Figure 4 present the advantage of one improved calculus speed in comparison with the first algorithm. In the case of the mechanisms that mimic snake's locomotion, which include a large number of elements, the calculus speed is decisive.

Further on, for exemplification, we present the kinematic analysis for one mechanism that mimics snakes locomotion.

One considers the mechanism presented in Figure 5. This planar mechanism includes six identical elements jointed through five rotating joints. In accordance with the systematization proposed in [5], this mechanism
includes one dragging kinematic chain (DKC) that is built with dragging elementary chain (DEC) type Rz.

According to the Figure 6, the passing between frames B and A is ensured with matrix ABA, the passing between frames B and C is ensured with matrix A12, a.s.o.

The matrices AjD, j=2, 3, 4, 5, 6 have the expression:

$$[AjD] = \begin{bmatrix}
1 & 0 & 0 & 0 \\
11 \cdot \cos(ajd) - 12 \cdot \sin(ajd) \cdot \cos(ajd) & - \sin(ajd) \\
11 \cdot \sin(ajd) + 12 \cdot \cos(ajd) \cdot \sin(ajd) & \cos(ajd) \\
0 & 0 & 0 & 1
\end{bmatrix}$$

(1)

where:

- Ajd - the rotating angle between the frame attached to the element j in extreme point placed in laterally, right side and the frame attached to the same element in median point.

For the positional analysis of this mechanism we use the relations presented in [5], [3]. The positions of the frames attached to each element, in relation with the fixed reference frame are taken from matrices A, B, ..., D6, D6.

To solve the kinematic analysis of this mechanism we use an algorithm similar to the last presented algorithm. One knows the initial positions for the mechanism points A, B, ..., S6, D6 in relation with the fixed reference frame, the elements lengths AB=BC=...=FG=0,175m, BS2 = BD2 = ... = FD6 = l2 = 0,110 m, the angles values a12=-9°, a23=-3°, a34=3°, a45=9°, a56=15°.

The matrices AjS, j=2, 3, 4, 5, 6 have the expression:

$$[AjS] = \begin{bmatrix}
1 & 0 & 0 & 0 \\
11 \cdot \cos(ajs) + 12 \cdot \sin(ajs) \cdot \cos(ajs) & - \sin(ajs) \\
11 \cdot \sin(ajs) - 12 \cdot \cos(ajs) \cdot \sin(ajs) & \cos(ajs) \\
0 & 0 & 0 & 1
\end{bmatrix}$$

(2)

For the positional analysis of this mechanism we use the relations presented in [5], [3]. The positions of the frames attached to each element, in relation with the fixed reference frame are taken from matrices A, B, ..., D6. To understand the calculus algorithm we present in Figure 6 the matrices scheme that ensures the passing among the frames attached to the mechanism elements.
where:
- \( \text{ajs} \) - the rotating angle between the frame attached to the element \( j \) in extreme point laterally placed, left side and the frame attached to the same element in median point.

For start position, the angles values are known. For the other positions the values must be calculated. In Figure 5 we consider the segment \( S6D6 \) perpendicular on segment \( FG \).

For the positional analysis of this mechanism, we must know the kinematic parameters variation in driving joints. In this paper, we consider a parabolically variation of the parameters in driving joints \( a_{12}, a_{23}, ..., a_{56} \) (see Figure 7). On the basis of Figure 7 result the order for jointed to base of the mechanism elements.

Based on the calculus scheme in Figure 6 and using MATLAB 4.0 software package, we implemented a software program. With this program we calculate the trajectories and the positions of anyone mechanisms' points.

For initial position, presented in Figure 5, with the previous initial values and for diagrams presented in Figure 7, we obtain:
- in Figure 8 the trajectories of the points A, B, ...D6, for one working cycle;
- the trajectories of the points A (Fig.9), B (Fig.10), C (Fig.11), D, E, F and G, for three working cycles;
- the trajectories of the points S3 (Fig.12), S4 (Fig.13) and S5, for three working cycles;
- the trajectories of the points D2 (Fig.14), D3 (Fig.15) and D5, for three working cycles.

The numerical values of the mechanism point’s positions were registered and used further on like input data in another program. With this program, based on polynomial interpolation, we calculate and plot the velocities and accelerations diagrams. Some of the obtained results are presented in Figure 16.
5. EXPERIMENTAL MODELS OF MECHANISMS THAT ENSURE DRAGGING LOCOMOTION

To validate the theoretical principles previously stated, were conceived and realized two experimental models that ensure dragging locomotion similar to snake [7].

First experimental model is presented in Figure 17. The two component elements can perform relative oscillation with amplitude of 30°. The mechanism is actuated by means of an electrical motor for the wind screen cleaner of the OLTCIT automobile. To obtain the oscillation angle of 30°, lengths of equalizer and lever were modified.
Based on the first experimental model was conceived and realized the second one, of which layout is presented in Figure 18.

As it can be observed, locomotion structure is made of six modules, five of them identical, and one extreme, shorter. The five identical modules have mounted on them the operation motors. The structure has a length, with collinear elements, of 1080 mm and a weight of 9.350 kg.

On the first and on the last element were mounted counter-weights that increase the pressing force on extreme "legs". It was attempted that pressing force on earth "leg" to be approximately the same to realize equal friction forces with the soil. Motion was made with 12 V DC motors from the windscreen cleaner of DACIA automobile. Details regarding construction and operation of this mechanism are presented in [5] and [7].

To realize the locomotion of structure there is necessary that between the elements of the structure to be an oscillation movement. Achievement of this movement of oscillation was made by inversion of the rotating direction of motors, inverting the sense of feeding current at the extreme position of angular stroke.

6. PROGRAM OF EXPERIMENTAL RESEARCH

To study working of the mechanism that ensure snake like locomotion several experiments were carried out [8]. These experiments consisted in displacement of the experimental model on different type of plane surfaces:
- surface with textile support (fig. 18);
- synthetic carpet (fig. 19);
- wood plank (fig. 20);
- melamine surface;
- mosaic surface;

To visualize the marks made by mechanism, maize and corn flour were spread on the displacement surface. Although, to make necessary measurements, on the support surfaces was traced a square network. As a result of these experiments, the first finding was that through the oscillation movements of elements, one reported to the other, structure can move ahead. This finding represents, in fact, validation of the proposed locomotion principle.

During locomotion, median axis of mechanism is a curve (in fact a fractured line that may be approximated to a curve) of which curve radius depends of the oscillation angles between the elements and of the friction forces between the elements and the support.

Influence of the friction forces over the behaviour of mechanism during locomotion is decisive. As a result of the experiments it was establishes that on slippery surfaces (melamine, mosaic) the amplitude of the movements of elements is high and the mechanism is not advancing, in these case friction forces being small. In case of rugged surfaces (carpet, wood) when friction forces are high, amplitude is small and structure is advancing slowly. On the surfaces with textile support, when friction forces are smaller than in the before mentioned case, the mechanism is displacing with higher speed, movements of the elements being more ample.

All the experiments were shoot. To shoot, a video camera type PANASONIC VHS-C, PAL system with 25 frames/sec. was used. The images recorded on magnetic tape were studied on a color monitor though a video player having the possibility to reproduce images frame by frame. Same of the images were processed on computer trough a Movie Machine Pro. processor. On the obtained images, using the square network made on the support surface, were measured the angles between the elements and the coordinates of the points of the
mechanism. Then, the experimentally obtained values were compared with the values theoretically obtained.

7. INTERPRETATION OF THE OBTAINED RESULTS

To compare the experimental results with theoretical results it was used a set of images (for example see figure 21) in which successive positions of the mechanism on a plane surface whit textile support are presented.

Shooting was made with a speed of 25 frames/sec. Videotape was rewinded frame by frame and each fourth frame was held. Thus, time between the helded images is 4/25 seconds. On the images obtained in this way, with a protractor, were measured the angles between the axis of the elements. Based on these values by mean of a program realized in MATLAB programming media, variation diagrams of the angles of leading joints were traced, diagrams presented in Figure 22.

Although, reported to the presented systems of axis, were measured by mean of a rule the coordinates of points A, B, ..., G and, tacking into account the scale of images (approximately 1/166 [m]/[mm]) values were obtained.

To establish the theoretical values of the coordinates of the points alone mentioned a calculation program presented in was used.

As input data the real lengths of elements were used: AB=0.178m, BC=0.174m, CD=0.176m, DE=0.174m, EF=0.174m, FG=0.175m, BD2=...=FS6=l2=0.1m.

Based on the diagrams of figure 22 and following to the analysis of the set of images, order of lateral points of elements considered to base was established: D5, S4, (on two intervals) S6, D2, D4, S5, D3, D6, S2. Initial coordinates of point D5 were measured on the first image xD5=0.726m, yD5=-0.098m.

Following the analysis of the computer using the above mentioned data, resulted the values of the coordinates of points A, B, ..., G varying with time.

Based on these values several diagrams were obtained (see figures 23, ...,27) which are comparatively presented variation in time of coordinates of points A, B, ..., G, experimentally respective theoretically obtained.

Analyzing the values of the diagrams presented in alone figures, some conclusions are arising:
- during a cycle, theoretical values of the abscissa of points A, B, ..., G increase faster than experimental values;
- during a cycle, maximum deviation of theoretical values of abscissa of points A, B, ..., G compared to the experimental values have the values 1.58% for xG, 1.37% for xF, 2.31% for xE, 2.64 for xD, 4.89% for xC, 6.33% for xB, 21.8% for xA;
-increase of the value of maximal deviation of abscissa of point G (point of the front of the mechanism) towards point A (point of the back) may be on the account of the measuring errors of these lengths. These errors are due to the fact that, during shooting, video camera was placed over the front element of the mechanism;

-in case of variation of ordinates of analyzed points, errors of theoretical values compared to the experimental ones, are much higher than in case of abscissa. However it is to emphasize the fact that in case of yG, yE, yD an even yC diagrams, theoretical curves have the looking like those of experimental curves;

-large differences between theoretical and experimental diagrams, in case yF, yB on yA must be due to the friction forces between the elements of the mechanism and substratum. These forces, of which variations are not known, determine changing of points of mechanism considered to base.

Based on the obtained results, was made a liveliness program in TURBO PASCAL, that allows visualization of the movements of mechanism on the display. Thus, for the theoretical values of the coordinates of the mechanism resulted the positions of the medium axis of figure 28.

As it might be found, displacement of theoretical mechanism is a like displacement of the experimental one.

Some explanations must be given regarding the deviations between the theoretical and experimental values of the coordinates of the mechanism:
- at the beginning for measurements were used images of mechanism shoot at lapse of time of 5/25 sec. Computer program adapted at the data obtained based on these images led to theoretical values much different than the experimental one;
- to continue, study of the film was tacked back and were selected successive images at lapse of time of 4/25 sec. This time the differences were smaller but carriage of the theoretical and experimental curves were very different;
- finally were used images at a larger scale (with almost double resolution) such way that experimental
measurements were more accurate, obtaining the above mentioned results.

8. CONCLUSIONS

The mechanisms presented in this paper reproduce the macroscopic structure of dragging locomotion biomechanisms. These mechanisms are able to provide snakes-like locomotion.

The aim of this research was to validate the principle of dragging locomotion similar to snakes and the theoretical principles of kinematics calculus of analyzed mechanisms.

As we shown, to reach the proposed aims, were conceived and realized two experimental models of mechanisms that ensure dragging locomotion similar to snakes.

By mean of these experimental models some aspects related to the kinematics and structure of mechanisms able to displace similar to snakes were clarified.

All experiments were shoot with a video camera. Consequently to the analysis of film were selected a serial of images that were processed on computer and finally, reproduced on printer. On the images obtained in this way were made measurements related with the position of the points of the mechanism and of the angles of elements. For the same sequence of displacement of mechanism using a calculation program presented before adapted to the concrete condition of the analyzed mechanism were determined the positions of the same points. Finally experimentally obtained values were compared with the values obtained theoretically.

As a result of these comparisons it was established a satisfactory approach of the theoretical. Experimental results could be more precise by fitting the mechanism with some active position transducers and by using a command system led by a computer.

In spite of the mentioned minuses, we consider that the results of the experimental research validated the results of the theoretical research presented by this work.

REFERENCES

[4] Iordachita, I., Considerations over the Kinematics of Mechanisms that Provide Snake-like Locomotion. XXIIth Yugoslav Congress of Theoretical and Applied Mechanics, YUCTAM’97, Vrnjacka Banja, Yugoslavia, 1997;
### Table 1 (partial)

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