RIGA TECHNICAL UNIVERSITY

Edgars KOVALS

ANALYSIS OF DYNAMICS OF FLOATING OBJECTS

Summary of Thesis

Direction: mechanical engineering
Sub-direction: mechanical engineering

Riga 2012

RIGA TECHNICAL UNIVERSITY
Faculty of Transport and Machinery
Institute of Mechanics

Edgars KOVALS

PhD sudent of doctoral studies plan “Engineering, mechanics and mechanical engineering (mechanical engineering sub-direction)”

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Summary of Thesis

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DOCTORAL THESIS
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PhD IN RIGA TECHNICAL UNIVERSITY

Thesis for acquiring of engineering (Engineering, Mechanics and Mechanical Engineering) PhD is defended on ………………….. at Mechanical Engineering faculty of Riga Technical university, Ezermalas street 6, audience ……

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CONFIRMATION

By this I confirm the present work and the scientific developments withing, being submitted for acquiring of engineering Phd (or other) in Riga Technical university, is solely written by me. The thesis has not been submitted in any other university for acquiration of academic degree.

Edgars Kovals …………………………….(Signature)

Date: ………………………

Doctoral thesis is written in latvian language, contains introduction, 6 chapters, conclusions, bibliography, 1 appendix, 165 illustrations and graphics, alltogether 129 pages. Bibliography contains 49 sources.

CONTENTS

GENERAL DESCRIPTION OF THE DOCTORAL DISSERTATION

The topicality of the theme

Propulsion systems are widely used to generate thrust for floating objects like ships, submarines and barges. A screw propeller since it was developed has always been the most popular propulsion system due the simplicity, low maintenance cost and rotary driving type complying with propulsion machinery. The given work is devoted to reveal new, alternative propulsion systems with biomimetic design. Offered systems are similar to fish tail and also use the same working principle.

In robot technique such propulsion systems are not widely investigated. The main obstacle for the application of the systems lies in their operation – the tail elements in the form of plate have a two-way oscillation movement (a screw propeller type engine operates only in one direction). Besides, the interaction of tail oscillation motions with water should be taken into consideration. It causes local swirls in every oscillation cycle.

First chapter provides an overview on propulsion system types, several propulsion system comparison and findings in the field. Several tasks were drawn – to develop mathematical models of biomimetic propulsion systems, and optimization of the models; to develop and patent working principles of robotized floating systems with variable area of interaction with the surrounding media; to develop new on principle 6 DOF mathematical model of a floating object with motion control and interaction with the surrounding media.

The following chapters hold developments of propulsion systems with a non-elastic fan. Several excitation types are used – harmonic excitation and adaptive excitation. The mathematical models are simulated in program MathCAD where also the optimization takes place. A parameter optimization method with a floating parameter was developed for use with MatCAD. A method is offered for floating robot movement modeling by dividing the object in 2 subsystems: calculation of propulsive thrust from the propulsion device; floating objects hull dynamics by the propulsive thrust.

A propulsion system with variable active work surface area is developed as a method of increasing efficiency. Mathematical model with various excitation systems simulation is done using MathCAD. The propulsion system with the variable active work surface area is also specifically viewed as navigational system with the ability to drive the thrust in any direction of the horizontal motion plane. A method of floating robot synthesis with variable active work surface area is given.

Following research reveals a three-dimensional 6 DOF floating object model with the impact of wind, current, waves and propulsive thrust. Appendix holds experimental results of air drag coefficient measured in a wind tunnel.

The proposed propulsion systems and methods, and models can be used as a theoretical and practical reference for further research development.

The aim and tasks of the dissertation

The aim of the dissertation is to synthesize the new type of propulsion systems of floating robots that are competitive with existing screw propeller type drive systems, even exceeding them in some aspects (silent movement, without characteristic noise, tail oscillation motion does not damage underwater fauna, have a maneuver ability, effectiveness etc).

The overview of literature allows drawing conclusion that the alternative biomimetic propulsion systems, their design are not in the scope of attention.

On the basis of the motion of fish shape objects are lateral motions of hull which wave-shape convexity moves axially its hull creating a positive push-off force against surrounding environment. The main objective of the dissertation is the design and simulation of different biomimetic propulsion systems.

Since the speed of motion of biomimetic objects is directly proportional to the speed of hull motion and inversely proportional to the hull, a part used in floating, ratio, these correlations are being taken into consideration creating the mathematic propulsion models of floating robots. Decreasing hull part of propulsion involved in floating, the shape of tail has considerable significance, and it directly influences a speed of motion.

A significant aspect of robot design and development is energy effectiveness that practically determines fuel autonomy or motion distances, and the control of robot as well. Thus, after the designing of models the aim of investigation is to optimize the propulsion operation of mathematic model adjusting optimal parameters with a focus on mechanical efficiency.

This aim has been achieved as follows:

Review of literature, review of the guidelines of fish type propulsion systems, examination of the fish type propulsion systems, floating types of fish, and carried out a comparison of propulsion systems;

- Review of significant investigations in the field;
- Defining of the aim and tasks of research;
- Designing of analytical models of propulsion systems;
- Creating of algorithm of mathematic model;
- Designing of mathematic models of propulsion systems:
    - The floating object model by harmonic excitation;
    - The floating object model by harmonic excitation and the optimization of parameters;
    - The floating object model by adaptive excitation;
    - The floating object model by adaptive excitation and the optimization of parameters;
    - The floating object model by harmonic excitation and the variable surface area;
    - The 6 DOF floating object with motion control and and interaction with the surrounding media;
- The synthesis of vibration robot by constant air flow excitation has been carried out;
- The methods for the motion control of propulsion systems with variable surface area have been worked out;
- The floating object model with the impact of surrounding environment;
- The synthesis of non-elastic propulsion systems with variable active work surface has been carried out.

The methodology used in the research

The methodological assumptions of the dissertation are based on the following research methods:

- The methods of dynamics analysis of classical mechanics systems in differential equation investigation;

- The computer modeling methods of hydrodynamics interaction between free surface flow and a free moving floating object using MathCAD;
- An optimal motion control method for finding, the motion control optimization method of floating object using Pontryagin's principle;
- A method of system parameters optimization for robotic mechanical systems investigation using moving parameter;
- An inverse method of algorithm for the optimal synthesis worked out by RTU;
- A decomposition method of fast and slow vibrations;
- An experimental method in a wind tunnel for identification motion resistance forms.

The scientific novelty and the results of the research raised for defence

The scientific novelty lies in the synthesis of analytical models of such new type of robot propulsion systems which are competitive with existing screw propeller type drive systems, even exceeding them in some aspects (silent movement, without characteristic noise, tail oscillation motion does not damage underwater fauna, have a maneuver ability, effectiveness etc). The overview of available literature sources allows drawing conclusion that the alternative biomimetic propulsion systems, their design are not in the scope of attention. The main objective of the dissertation is the design and simulation of different biomimetic propulsion systems which motion is based on lateral, periodical motions of hull (working area) creating a positive push-off force against surrounding environment.

A significant aspect of robot design and development is energy effectiveness that practically determines fuel autonomy or movement distances, and the control of robot as well. In research, after the designing of models, the parameters of mathematic models with a focus on mechanical efficiency have been optimized. A new algorithm of propulsion systems with variable active work surface has been designed.

The main results of research being raised for defence:

- The following mathematic models of propulsion systems have been designed:
  - The floating object model by harmonic excitation;
  - The floating object model by harmonic excitation and the optimization of parameters;
  - The floating object model by adaptive excitation;
  - The floating object model by adaptive excitation and the optimization of parameters;
  - The floating object model by harmonic excitation and the variable surface area;
  - The 6 DOF floating object with motion control and and interaction with the surrounding media;
- The synthesis of vibration robot with constant air flow excitation has been carried out;
- The methods of the motion control of propulsion systems with variable surface area have been worked out;
- The floating object model with the impact of surrounding environment has been designed;
- The synthesis of robotic propulsion systems with variable active work surface has been carried out.

Practical application

The practical application in the field of theory is connected with the development of new robotic systems, their optimization and synthesis. Thus, for instance, a system for floating robots screw propeller drive in different directions of the horizontal motion plane, modifying the control algorithm of interaction area in time and phase coordinates has been worked out. Additionally, a theory for motion decomposition has been improved by dividing a mathematic model in two parts – in fast and slow sub-models.

Participating in a research project financed by EU's Seventh Framework Program FILOSE (Robotic Fish Locomotion and Sensing) in RTU Research Laboratory of Nonlinear Phenomena of Vibrating Systems several single-fin and two-fin vibro-silencers have been developed. The cyclic changes of work surface area of fin were realized in silencers. (The patents LV 14034, LV 14077, LV 14237, LV 14289, a.o.) The application of proposed findings makes possible to divide effectively the energy supplied to by fin increasing the area which enhances motion of floating object forwards and simultaneously decreases energy loss. As a result, the work efficiency of fin motion operator will increase, and it will allow increase maximum motion speed of fish robot, and effectiveness as well

Working together with RTU Research Laboratory of Nonlinear Phenomena of Vibrating Systems, the experiments of floating objects in linear water basin have been carried out, thus the optimal parameters of system have been verified experimentally.

Together with RTU Research Laboratory of Nonlinear Phenomena of Vibrating Systems the practical recommendations for the development of floating constructions applicable to recreational facilities, designing of boats for fishermen and hunters, or for military purposes have been worked out.

The models of propulsion systems, methods and approaches suggested by the author provide a theoretical and practical foundation for further research of the particular object.

The structure of the dissertation

The dissertation consists of following parts: Annotation, Introduction, 1. Aim and Tasks of Dissertation, 2. Overview of Literature with 4 sub-chapters, 3. Design of model analysis Mathematical support with 4 sub-chapters, 4. Analysis and optimization offloating object models with 5 sub-chapters, 6. Floating object model with the impact of surrounding environment with 3 sub-chapters, Conclusions, Appendix, Bibliography.

The length of dissertation is 129 pages; the dissertation contains 165 figures and illustrations, 4 tables; bibliography contains 49 sources.

Participation in Conferences

1. „Vibration 2010", 12.-14.05.2010, Kurska 2010, Krievija;
2. Динамика виброударных (сильно нелинейных) систем "DYVIS-2009", москва – эвенигород 2009, июнь;
3. Vibration Problems ICOVP 2011, Prague, Check Republic 2011, September;
4. 2nd International Symposium RA'11 on Rare Attractors and Phenomena in Nonlinear Dynamics. Rīga, 2011.

List of publications

No	Title of Publication	Authors	Published
1	Vibration Devices with Variable Working Area of Head Interacting with Liquid or Air Medium	Jānis Vība, Vitālijs Beresņevičs, Māris Eiduks, Lauris Štāls, Edgars Kovals, Guntis Kuļikovskis, Semjons Cifanskis, Jean-Guy Fontaine	Vibration 2010" konferences rakstu krājumā, 12.-14.05.2010, Kurska 2010, Krievija, 35 – 45 lpp.
2	Fin Type Propulsive Devices with Varying Working Area of Vibrating Tail	Jānis Vība, Vitālijs Beresņevičs, Semjons Cifanskis, Bruno Grasmanis, Vladimirs Jakuševics, Māris Eiduks, Edgars Kovals, Maarja Kruusmaa	Journal of Vibroengineering. Volume 12, Issue 3. 278 – 286 lpp, ISSN 1392-8716. www.jve.lt
3	Robotic Fish Tail Motion Excitation by Adaptive Control	Guntis Kuļikovskis, Māris Ābele, Edgars Kovals, Igors Tipāns, Semjons Cifanskis, Maarja Kruusmaa, Jean-Guy Fontaine	Scientific Journal of Riga Technical University. 6. Series. 33. Volume. Transport and Engineering. RTU, Riga. 2010. 15 – 20 lpp.
4	Dynamics of Vibration Machine with Air Flow Excitation and Restrictions on Phase Coordinates	Jānis Vība, Vitālijs Beresņevičs, Lauris Štāls, Māris Eiduks, Edgars Kovals, Maarja Kruusmaa	Scientific Journal of Riga Technical University. 6. Series. 33. Volume. Transport and Engineering. RTU, Riga. 2010. 9 – 13 lpp.
5	Optimization of Vibrator Motion with Air Flow Excitation	Māris Eiduks, Lauris Štāls, Jānis Vība, Edgars Kovals, Atis Vilkājs	Journal of Vibroengineering. Volume 12, Issue 5. 34 – 41 lpp., ISSN 1392-8716. www.jve.lt
6	Floating Robot Motion Dynamics Analysis and Control Synthesis	Jānis Vība, Edgars Kovals, Guntis Kuļikovskis, Māris Eiduks, Jean-Guy Fontaine, William Megill	Kursk State Technical University. IX International scientific-technical. Conference. "VIBRATION – 2010. CONTROL VIBRATION. TECHNOLOGIES AND MACHINESVolume II: 226 – 233 lpp.
7	Motion of Two Degree of Freedom Vibrator with Air Flow Excitation	Lauris Štāls, Māris Eiduks, Jānis Vība, Edgars Kovals	Динамика виброударных (сильно нелинейных) систем "DYVIS-2009", москва – эвенигород 2009, июнь. 453-459 lpp

8	Vibration Devices with Variable Working Area of Head Interacting with Liquid or Air Medium	Jānis Vība, Vitālijs Beresņevičs, Māris Eiduks, Lauris Štāls, Edgars Kovals, Guntis Kuļikovskis, Semjons Cifanskis, Jean-Guy Fontaine	Kursk State Technical University. IX International scientific-technical. Conference. “VIBRATION – 2010. CONTROL VIBRATION. TECHNOLOGIES AND MACHINES. Volume II: 35 - 45 lpp.
9	Synthesis of Vibrator with Air or Water Flow Excitation	Jānis Vība, Lauris Štāls, Atis Vilkājs, Edgars Kovals	Solid State Phenomena Vols. 147-149. Switzerland: Trans Tech Publications, 462 – 467 lpp
10	Nonlinear Optimal Synthesis of the Vibrator with Flow Excitation	Jānis Vība, Lauris Štāls, Edgars Kovals, Atis Vilkājs	JVE Journal of Vibroengineering – Vilnius: ISSN 1392-8716, December 2008, 493 – 496 lpp
11			Rare attractors and rare phenomena in nonlinear dynamics. 2008., 8-12 september. Rīga, RTU, 2008. 131-137 lpp.
12	Motion dynamics analysis of a floating robot	E. Kovals, J. Viba, Guntis Kulikovskis, Maarja Kruusmaa, Paolo Fiorini, Jean – Guy Fontaine	Vibration Problems ICOVP 2011 Supplement. ISBN 9788073727598 510-515 lpp.
13	Fluid flow vibration excitation by the control of interaction surface	Maris Eiduks, Janis Viba, Lauris Shtals, Edgars Kovals	10th International Scientific Conference "Engineering for Rural Development" Proceedings, volume 10. Jelgava, 2011, 464-470 lpp.
14	Nonlinear Dynamics of Robot Fish Flexible Tail Motion	J. Viba, E. Kovals, I. Tipans, G. Kulikovskis, J.-G. Fontaine, M. Kruusmaa, W. Megill	2nd International Symposium RA'11 on Rare Attractors and Phenomena in Nonlinear Dynamics. Rīga, 2011, 177-187.lpp
15	Method for control of operating condition of hydrodynamic fin-type vibration propulsive device	J. Viba, S. Cifanskis, V. Jakushevich, O. Kononova, J.-G. Fontaine, E. Kovals	Patent LV 14055, Republic of Latvia, Int.Cl. B63 H1/00.

REVIEW OF THE CONTENTS OF THE DOCTORAL DISSERTATION

In our daily life, nature and technology, everything including man is surrounded by the environment where physical objects and bodies are constantly in contact with the mechanical environment. It is a constant and inevitable effect caused either by air or water. Interactions with local surrounding environment may seem disturbing and inexpedient, however both nature and man have also learnt to exploit the surrounding environment in their favour, for instance, flying and floating.

As a result of scientific progress considering commercial aspects a variety of well known solutions for propulsion systems has been adopted, for instance, aircraft propellers and ship screw propellers. It is related with specific construction features of industrially used propulsors, though basically the mechanical drive is of a rotary type. The direct combustion drives and intermediary electric drives are used. The most common ship propulsion systems (with a typical srew propeller) have the efficiency up to 70%, which is not bad, however nature is still far ahead of mankind in this field. On the other hand, the hydrodynamic efficiency of some fish severely exceeds 80%, which is a better result than the efficiencies of well known man made propulsion systems.

Natural propulsion systems compared to man made propulsion systems have both positive and negative aspects. Besides differences in efficiency, the noise is an essential factor. The noise levels radiated by man made propulsion systems exceed the number of times the noise levels of fish swimming. In addition, modern technologies have been so developed that they are able to recognize the operation of man made propulsion systems over distances of many kilometres, precisely determining their types, direction of motion and possible risk immediately sending danger signals. If new propulsion types similar to natural were launched in practice, the recognition of floating objects equiped with them would be made severely difficult, which would call for creating completely new generation monitoring systems.

From the above mentioned, it can be concluded that the features of natural propulsion systems have been insufficiently acquired so far because technological progress was mainly focused on propulsion systems of other types regardless of positive aspects of natural propulsion systems. Thus, the creation of propulsion systems similar to natural would be a significant step to the choice and development of propulsion systems for floating objects in future.

Scientific progress and the speed, power and size of modern computer systems allow to create control systems that realize simple neurophysiological functions of brain. Reverse engineering or searching a result via process towards start has the principle that a reason exists. Consequently, the fact that in nature living organisms having excellent swimming abilities exist proves the possibility of such systems. Presently, the development of biomimetic underwater robot programme requires that there be more effective, flexible, manoeuvrable, and stable means of transport capable to adapt as well as operate under complicated conditions. The most powerful force of development is the fact that modern underwater means of transport are intended for operating in still open water. For manoeuvring these means of transport use screw propellers and they have very limited manoeuvring possibilities. Biomimetic underwater means of trasport are mostly needed in the environments where manoeuvrability is good and the ability to cause thrust in different directions and a quick real time response control of sudden hydrodynamic events are obligatory. The application of such underwater robots that employ natural principles of motion can be found in many civil and military branches. A detailed summary is given in Table 1.

APPLICATION	Civil	Military
The determination of water quality and searching for pollution source	+	+
Searching damages of underwater pipes	+	
Searching fish populations and informing fishing vessels	+	
Checking underwater parts of ships without divers, evaluating the growth on ship hulls	+	+
The measurement of stream speeds at different depths	+	
Searching wrecks and non-exploded shells	+	+
Searching underwater mineral resources	+	
Bypassing protective nettings of submarines in harbours and other intelligent tasks		+
Tracking and exploring the underwater fauna	+	
Monitoring underwater geothermal and seismic processes	+	
The platform for carrying projectiles		+

Table 1. The application of biomimetic underwater robots in industry

The underlying principle of fish motion is constant muscle functioning. The fundamental principle of vertebrate swimming motion is sinusoidal undulations of the body, which means consecutive pulling the body in the S-shape. When moving, the fish sends wave oscilations through its body from head to tail (the caudal fin). Moving curves of the body cause the water pressure behind them. The balance of lateral force components occurs, so consequently, a positive thrust force is achieved. In order to stop it is enough to stay in the convex position. If oscilations are sent from tail to head, it is possible to achieve the negative direction of motion.

In swimming different body proportions can be involved. The amount of muscles used in swimming is clearly shown in Figure 1. In the fish family whose members mostly use motions of the body and caudal fin in swimming four hydrodynamic undulatory swimming types can be distinguished according to the amplitude of body lateral oscilations.

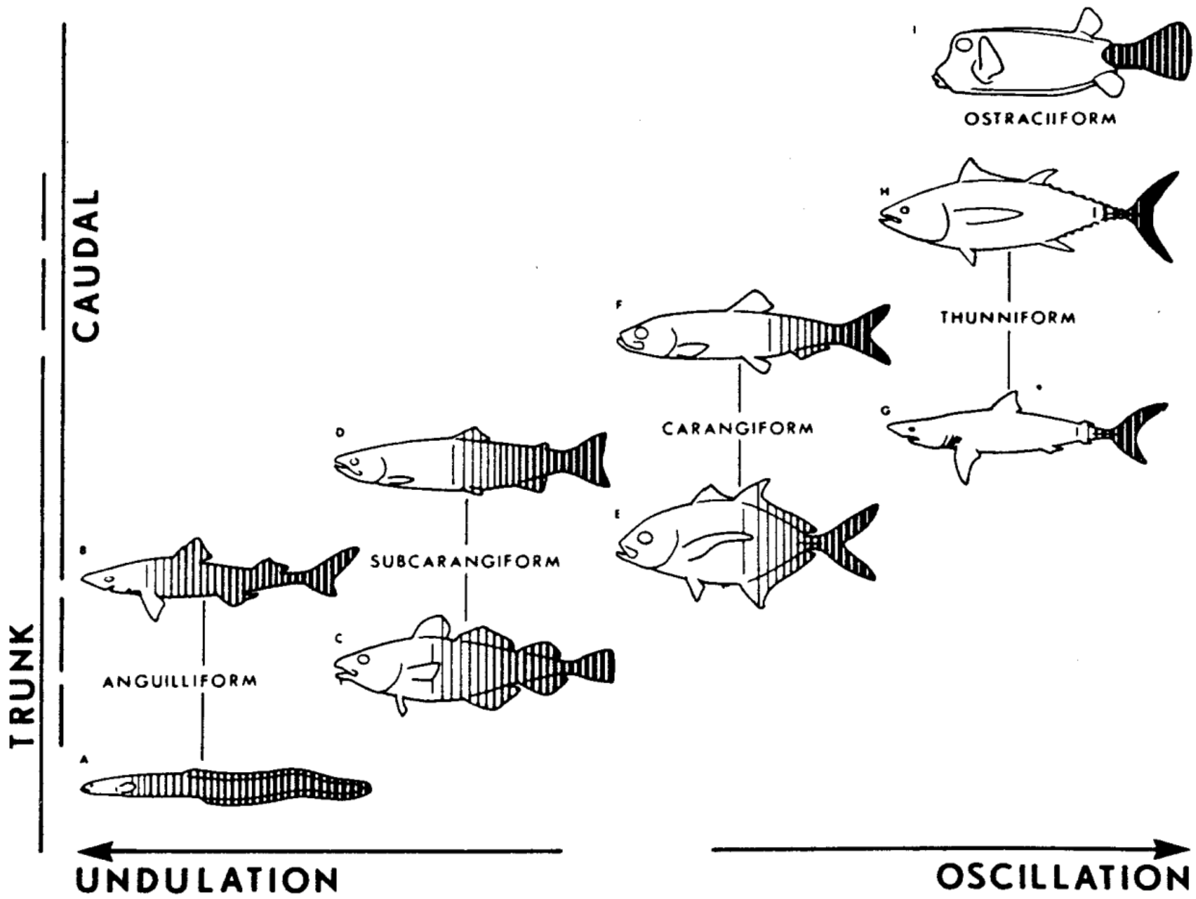

Figure 1. Types of fish propulsion systems

Sub-carangiform – for motion generation less amount of muscles is used; in the forming of undulatory motion, 1/3 - 2/3 of the fish total muscle mass is employed. It is common for fresh-water fish such as the salmon and trout. The fish that use this propulsion type can move faster, but with less manoeuvrability. The angle of head turning is much less, though no body point constantly moves along or parallelly swimming direction. The caudal fin is strong and big, yet flexible. It can be opened or shut in such a way that the fin surface changes within 10% in one wave. Interestingly, the caudal fin is not the main source of propulsion force. The surgical amputation of the caudal fin just a little decreases the swimming quality. It is otherwise considered that the big fin is necessary for sharp accelerations, quick turnings and manoeuvrability at high speeds.

Carangiform **-** for motion generation less than 1/3 of the fish total muscle mass is employed. It is common for the laterally squeezed fish. The lateral motion is mainly concentrated in the end of the body - the tail. For the fish of this propulsion type the caudal fin is rigid, often with deep cuts and extended lobes. Such a fin design allows to decrease the amount of water that has to be moved laterally, which, consequently, decreases the turbulence and viscous resistance without losing thrust force.

Oscillating swimming, when the caudal fin is moved as the pendulum, but the body remains relatively motionless, is characteristic of the fish that cannot create undulating waves due to their body features. They do not ususally have marked streamline shapes and cannot move fast.

The researches of bionic analogies began in the 60's of the 19th century and soon they became regular, systematic and huge. In the past years, due to the rapid development of computing machinery and control systems several significant discoveries have been made in the field of underwater robotics. These robot models have two parts of a tail section and the microprocessor based remote control system.

It must be mentioned that the author personally participated in the International Research Project FILOSE (Robotic Fish Locomotion and Sensing), which is the research project FP7-ICT-2007-3 STREP within 7th Framework Programme. The main aim of this project is to design a robot fish model that would be able to sense nuances of environmental streams, which would allow to correct a chosen swimming type.

For designing a simple swimming robot model with propulsion, two construction parts will be enough - the robot's basic hull and its propulsive part or the tail that is connected to the basic hull by a hinge joint. In this case, an absolute rectangular shaped, solid, and inflexible tail is used. The tail can oscillate around the hull in a certain diapason with the angle φ. Thrust force that occured moves the hull along the x-axis. Motion takes place under water, so in a homogeneous environment not considering influences of either streams or waves or wind.

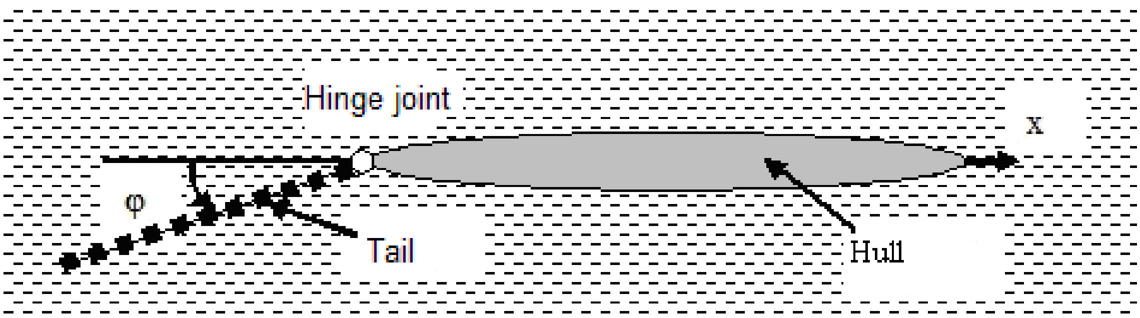

Figure 2. A simplified robot model

In order to compile the equation of all forces correctly according to Newton's second law, it is necessary to investigate in detail the forces acting on such an object. As mentioned above, for fish motion, it is necessary to create the hull lateral motions whose wavy convex moves axially along the hull by forming positive repulsive force against the local environment, whereas the sum of lateral forces occured equalizes without the resultant thrust force. These forces are clearly shown in Figure 2. When dividing normal forces along axes, side forces and thrust forces are obtained. Thrust forces summarize making the resultant thrust, but side forces equalize each other. Since side forces have opposite directions and they do not lie on one axis, the moment against the fish body occurs. This moment changes its direction in each period of motion. When observing motions of the swimming fish from above, an impression occurs that the fish turns a little in each period of motion. The moment mentioned above completely explains these motions. If the hull is big and heavy enough, the influence of lateral forces formed by tail motions against the hull is inessential, subsequently, for creating the mathematical model one degree of freedom is enough - the turning angle φ of the tail against the hull at the hinge joint (Figures 2 and 3).

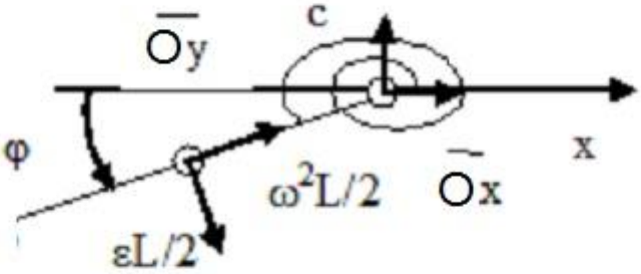

Figure 3. The tail's scheme

In order to ensure tail motions, two control reverse adapters are needed - for measuring displacement and velocity. For industrial control systems proportional-integral-derivative regulators (PID) are widely used [16]. The PID regulator tries to correct the difference between measurable variables and system settings by calculating the dynamics of the measurable variable and the displacement from system settings in time and accordingly giving a control and command to the system actuator whose operation influences the measurable variable in order to decrease the difference. Three constants are used in PID control - proportional, integral and derivative. When these constants are optimally adjusted, it is possible to obtain the optimized regulation of the system - with a focus on system response or stability. The system with a wrongly adjusted operation of the PID regulator does not guarantee its optimal operation. In this case harmonious excitation as a function of time is used. The harmonious excitation can be easily realized by a cyclic trigonometric function. The sine function is used, which assigns a positive or negative value depending on a value of time. In order to evaluate the tail's operation, it is necessary to know the reaction at the point Ox. If the average value of reaction of stable operation is positive (Ox>0), the tail pulls the object backwards. Contrary, If the average value of reaction of stable operation is negative (Ox<0), the tail pushes the object forward as it is prescribed.

When the fish is in motion, it has to overcome the resistance caused by the local environment. This resistance can be divided into several parts (Figure 4):

- friction force caused by pressure – related to the moved or displaced water mass;
- friction force caused by frictions – related to the surface features of the moving object;
- friction force caused by whirpools – water whirpools appearing during swimming also influence fish swimming.

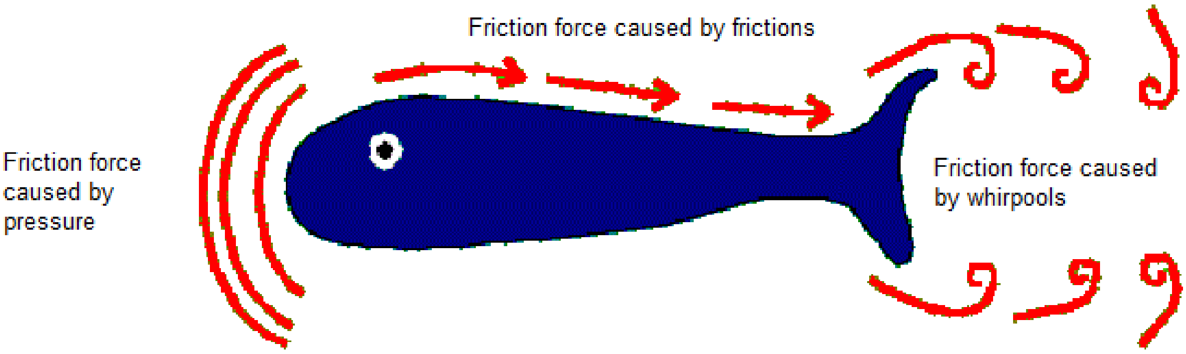

Figure 4. Forces caused by local environment affecting the body

As a result of different transformations, the reacton at the point *Ox* is mathematically obtained:

$$Ox = m \cdot \begin{Bmatrix} \dot{\varphi}^2 \cdot \frac{L}{2} \cdot \cos(\varphi) + \frac{1}{J_A} \cdot \\ \cdot \left[M(t) - c \cdot \varphi - b \cdot \dot{\varphi} + \left(-k_1 \cdot B \cdot sign(\dot{\varphi}) \cdot \dot{\varphi} \cdot \frac{L^4}{4} \right) \right] \cdot \frac{L}{2} \cdot \sin(\varphi) \end{Bmatrix} + k_1 \cdot B \cdot \sin(\varphi) \cdot sign(\varphi \cdot \dot{\varphi}) \cdot \dot{\varphi}^2 \cdot \frac{L^3}{3}$$

By transformation of the equation into mathematical simulation using the software MathCad, the following exposition is obtained:

$L := 0.5 \qquad m := 1 \qquad J0 := m \cdot \left(\frac{L}{2} \right)^2$

$M0 := 20 \qquad k := 4 \cdot \frac{\pi}{2} \qquad KT := 10000 \qquad B := 0.05 \qquad b := 5 \qquad c := 20$

$n := 0..70000 \qquad s := 0.000 \qquad t_n := n \cdot s$

$$\begin{pmatrix} \varphi_0 \\ \omega_0 \end{pmatrix} := \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

$$\begin{pmatrix} \varphi_{n+1} \\ \omega_{n+1} \end{pmatrix} := \begin{bmatrix} \varphi_n + s \cdot \omega_n \\ \omega_n + \frac{s}{J0} \cdot \left[M0 \cdot \sin(k \cdot t_n) - c \cdot \varphi_n - b \cdot \omega_n - \left[KT \cdot (\omega_n)^2 \cdot (\mathrm{sign}(\omega_n)) \cdot \frac{L^4}{4} \cdot B \right] \right] \end{bmatrix}$$

where:

L – the tail's length [m];

m – the tail's mass [kg];

J0 – the tail's moment of inertia [kgm^2];

M0, k, KT, B, b, c – constants;

n – the number of simulation steps;

s – the size of simulation steps;

The graphical simulation results can be obtained practically in unlimited combinations. The most significant of them are:

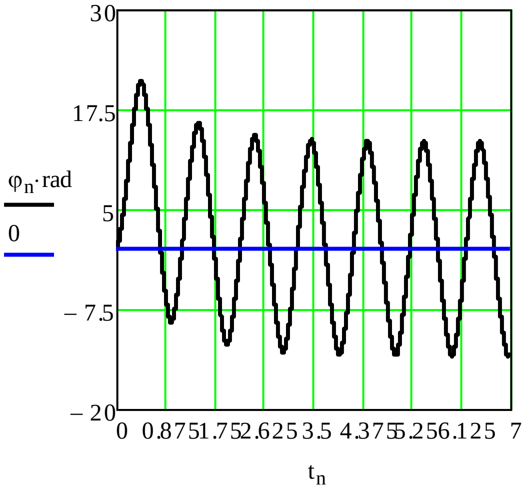

Figure 5. The tail's turning angle in time

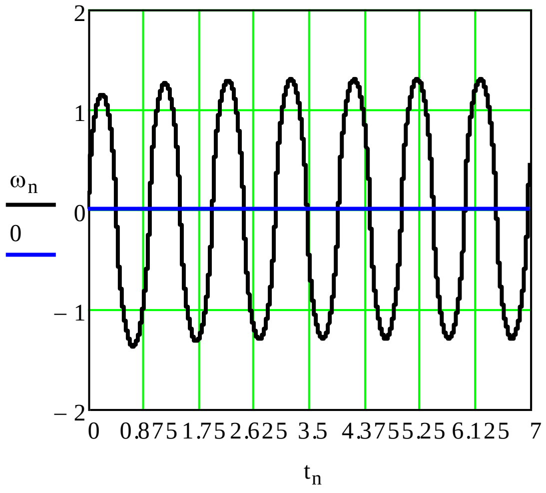

Figure 6. The tail's turning angular velocity in time

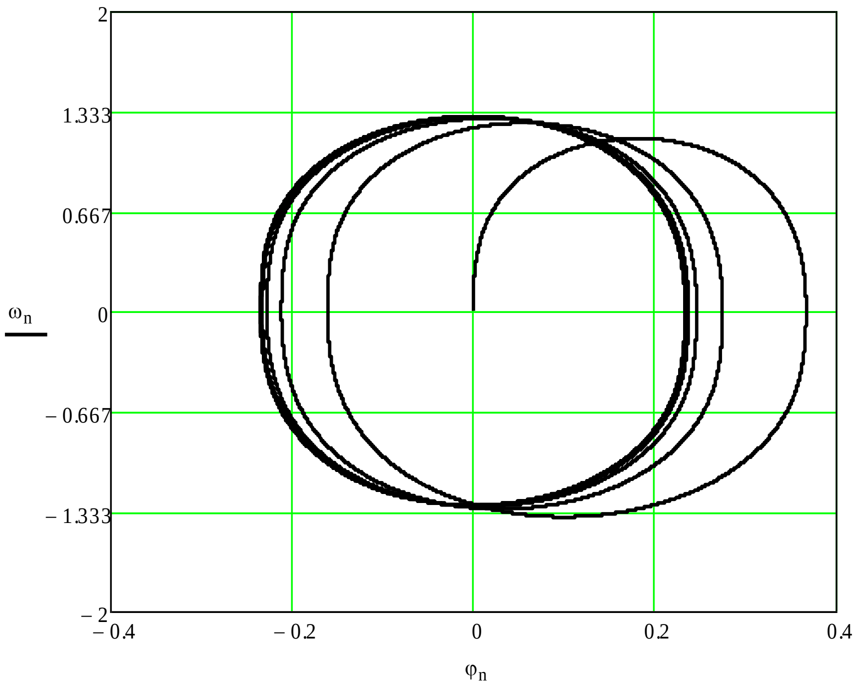

Figure 7. The tail's motion in the phase plane

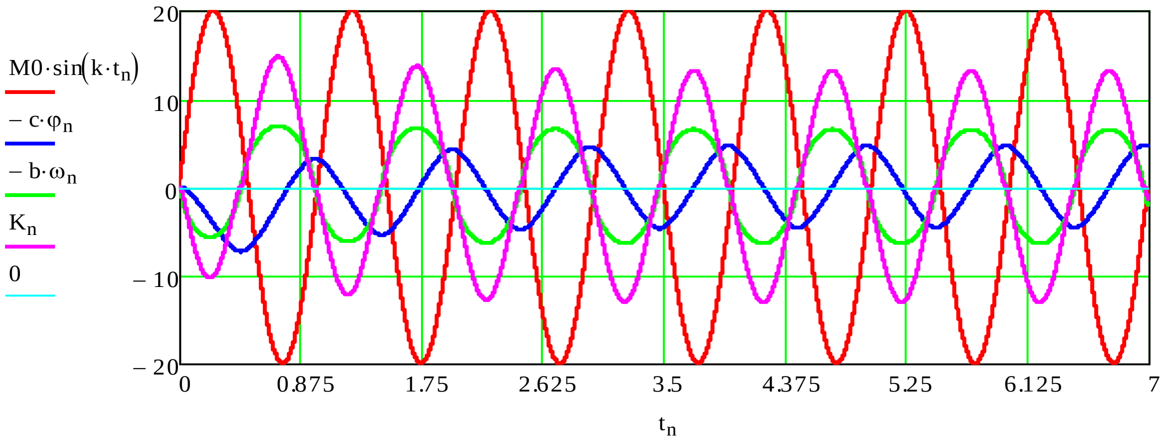

Figure 8. Forces affecting tail's motion in time

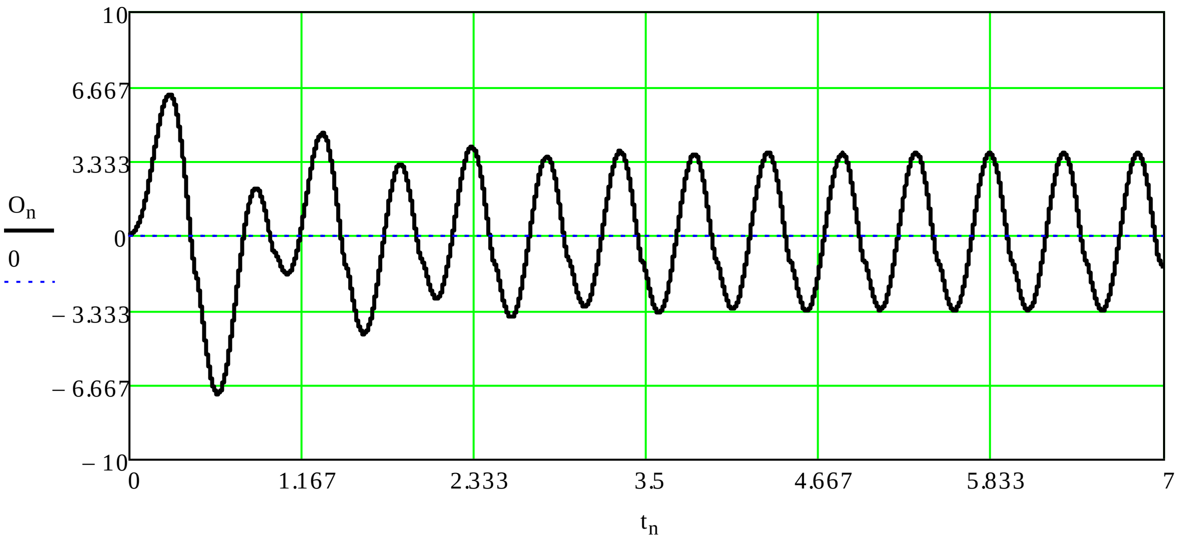

Figure 9. The reaction caused by the tail at the hinge joint

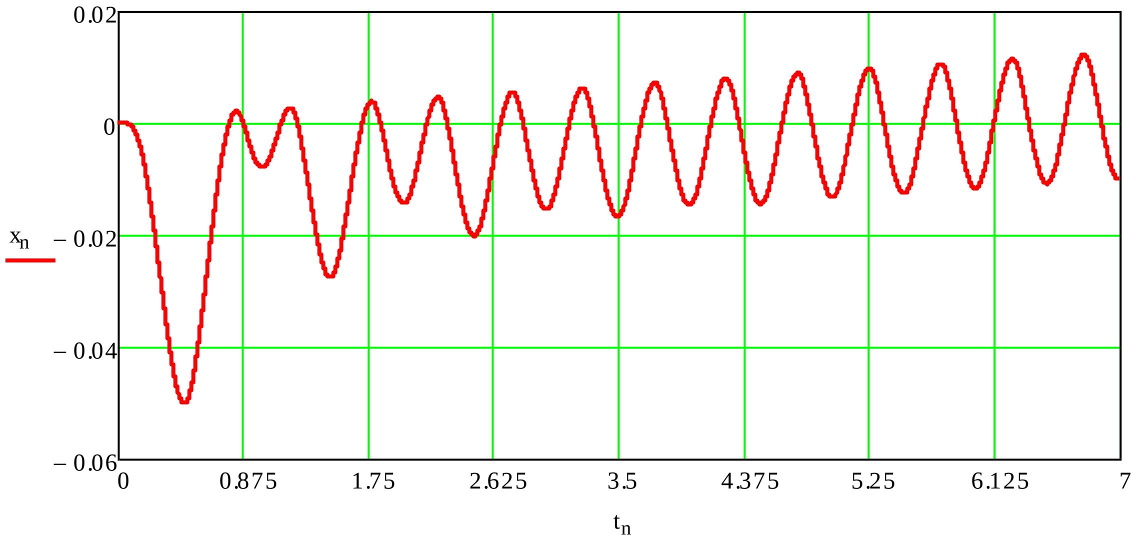

Figure 10. The body displacement in time

For optimisation the algorithm of three arguments for the linear variable is used. The offered optimisation method operates and is applicable to solving similar tasks. The obtained results for harmonious systems without surface area changes do not cherish hopes because the obtained system efficiences are very low. The model with adaptive control has a wide range of advantages in comparison to the harmonious excitation systems. The most essential of them is a response from the system as well as the constant force value during the whole operation period is regarded as an advantage. In this case, the applied adaptive control is a function of phase coordinates of the equation; for transformation of a response signal into operation, mathematically the *signum* function $sign(\varphi,\omega)$ is used, which assigns a positive or negative value depending on the value of scalar multiplication of arguments. The efficiency of the adaptive unoptimized model with similar parameters almost two times exceeds the efficiency of the optimized harmonious model. The main reason is the difference of motion velocities from the position "0" to the point of change and back. The model with adaptive excitation ensures a higher tail's velocity at pushback, thus creating a higher reactive impulse. By optimizing the rigidity of the spring, the model with adaptive excitation presented the efficiency of 30 times higher than the unoptimized model, which proves the great importance of optimisation for development of mechanical systems.

Better results were obtained for the mathematical model with a changing surface area of propulsion system. Initially, the aim of the research was to demonstrate the application opportunities for gas or liquid flow excitation in vibrotechniques. The dynamics of the vibromachine with the constant gas or liquid flow excitation was analysed. The main idea was to find the optimal control law according to which the surface of the working organ should be varied within certain limits. The optimisation criterion is time that is spent in order to move the machine's working organ from the starting position to the utmost state. For solving fast operation problems the Pontryagin's maximum principle was used. It was shown how the working surface area should assign boundary values under optimal control. Limitations were introduced in phase coordinates. A vibration excited robot with constant flow excitation was proposed.

Later, the fin-type propulsion system in water environment became a research object. The aim - to find the optimal control law for fin surface area change, which ensures the maximum efficiency of the propulsion system regarding thrust force occured. The problem was solved by using the Pontryagin's maximum principle. It was clarified that the surface area change could be realized with extreme values at the points of motion changes. The given method allows to increase the surface area of the propulsion system at the moments, when the effective motion or working motion occurs, and to decrease the surface area at the moments, when the swing occurs, thus decreasing water resistance forces. Due to this operation energy losses are decreased and efficiency of the system is increased. The algorithm of the surface area change is shown in Figure 11.

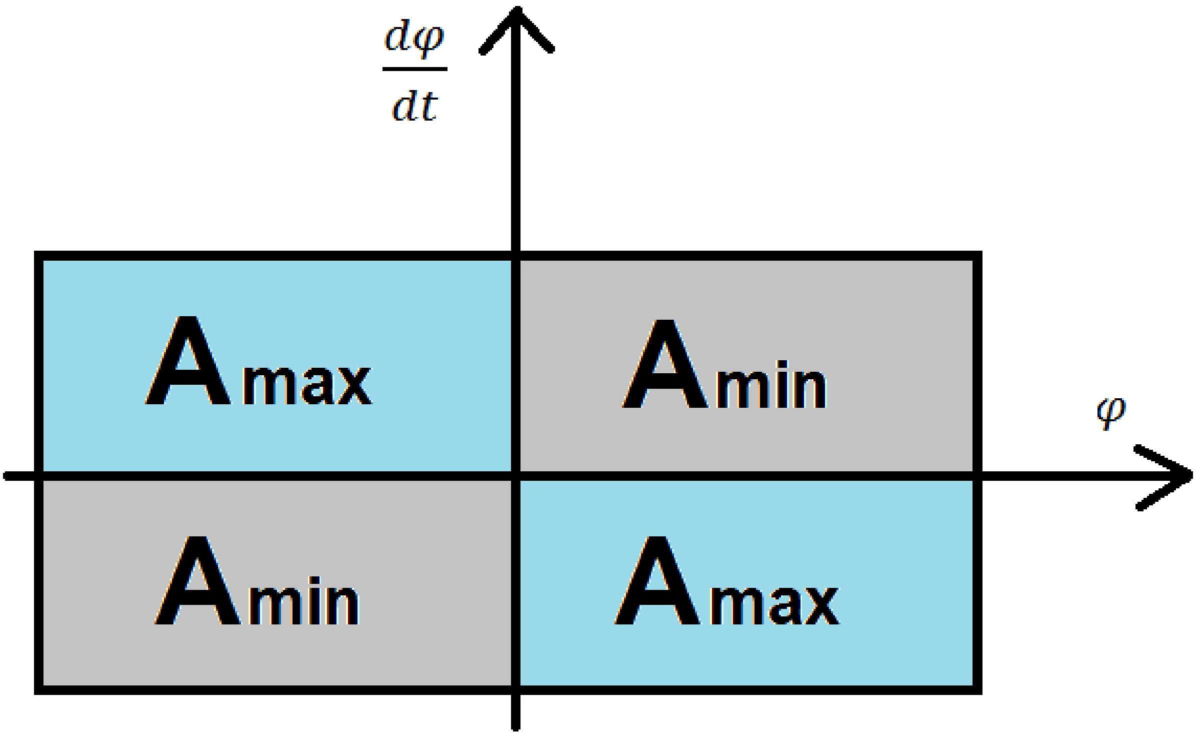

Figure 11. The algorithm of surface area change

In this case, the tail's varying area *A* is included in the position *Amax* from each utmost change of motion direction in order to gain an effective push-off force. In the tail's position "0", the area is switched to *Amin*, in order to decrease resistance forces of local environment while a new push-off force is prepared.

It is also clarified that the change of the effective working area A of the examined propulsion system offers a wide opportunity to robot control, which concerns not only ensuring of translation motion but also steering and reversing. By making corrections in the algorithm of area changes, it is possible to achieve the resultant reaction force at the hinge joint in all directions in the xy-plane. The synthesis method of the solid propulsion system with the area change has been discussed, which has been elaborated in the Research Project FILOSE (Robotic Fish Locomotion and Sensing) (project number 231495) within 7th Framework Programme of the European Commission.

The mathematical 3-dimensional model of the floating object considering the influence of local environment has been created, which could be used for the research in situations under real conditions. In the mathematical model, the following affecting forces of local environment and control are included:

- wind influence
- stream influence
- wave influence
- propulsion systems influence.

CONCLUSIONS

1. The overview of available literature sources allows drawing conclusion that the alternative biomimetic propulsion systems, their design are not in the scope of attention. The necessity of the development of such systems is obvious due to the shortcomings of existing propulsion systems mentioned in the dissertation.
2. The above mentioned overview of available literature revealed fish ability to provide lateral hull motions in bionic understanding. The wave-shape convexity of these models moves axially its hull creating a positive push-off force against surrounding environment, whereas a sum of created lateral forces would smooth out without resulting propulsive thrust.
3. Minimization of the hull part involved in propulsion leads to increased effect of tail shape. The shape of the tail directly affects locomotion speed. Since selection of optimal tail shape is not included in thesis goals, carangiform and sub-carangiform body types will are utilized.
4. Energetic efficiency determining fuel autonomy is of key importance in robot design and synthesis.
5. For the simulation of mechanical system models the program MathCad is advisable (the program used in research is 14.0.0.163 [build 701291152]). The features of the program MathCad are very suitable for such complex and resourse-consuming operations as numeral integration, working with matrices and graphical illustration of results.
6. The developed algorithm for simulation calculations is resilient enough to investigate an examined type system and similar mechanical systems; a discovered optimization method of parameter is a good approach to find an optimal value of parameter without additional calculations.
7. The optimization of parameter turned out to be necessary after obtaining the simulation results of the floating object model by harmonic excitation, for the results were not satisfying. Although, in optimization process the operation of model was improved, the results were not to take into account. Wherewith, we may conclude that the floating object model by harmonic excitation is capable to work only in relatively low efficiency zone.
8. The examined floating object model by adaptive excitation proved to be more effective than the floating object model by harmonic excitation, however, the performance of propulsion systems existing in nature was not reached. It may be caused by the fact that the examined models with firm, non-elastic tail are not able to provide lateral hull motions in bionic understanding. The wave-shape convexity of these models moves axially its hull creating a positive push-off force against surrounding environment, whereas a sum of created lateral forces would smooth out without resulting propulsive thrust.

9. The proposed propulsion system with variable active work surface area is more elastic system with the potential of practical aplicability. Using this system it is possible to reach not only significant working efficiency, but also provide floating object ability to maneuver in coordinates. Besides, the proposed model is able to operate with negative energy flow or to work as an energy generator. It is proved by a vibration robot by constant air flow excitation. The propulsion system with the active variable work surface has been worked out, and it served as the basis for obtaining patent No 14055.
10. Supposedly, the six degree of freedom model proposed in Chapter 6.3 with motion control and interaction of the surrounding ambience would serve as a model for calculations to investigate robot dynamics in real environmental conditions.
11. A new numeric method of a floating object control against the impact of wind, waves and current has been designed.
12. Theory of dynamic analysis of floating objects has been supplemented.
13. For synthesis of dynamic mechanical systems it is important to select suitable materials in order to obtain more precise mathematically proved desirable parameters. Certainly, the essential factor is friction/thrust ratios in relation to surrounding environment.
14. The appendix provides the results of experiments of various type objects obtained in the wind tunnel Armfield. In this case the attention should be drawn to cover material, for experiments proved that objects of identical shape with different cover materials showed different air flow resistance or drag coefficients. Moreover, a lower thrust ratio was observed to the object with a fuzzy cover comparing to the object with smooth cover.

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