UDC 372.862:378.22:37.022:37.026.1:37.026.6:37.026.9

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APPLICATION OF JMODELICA.ORG TO TEACHING THE FUNDAMENTALS OF DYNAMICS OF FOUCAULT PENDULUM-LIKE GUIDED SYSTEMS TO ENGINEERING STUDENTS

Abstract. The present educational research is focused on the solution of didactic problem of an engineering-friendly description and explanation of the dynamics and control of Foucault pendulum-like systems, which have arisen from practical problems of boom crane dynamics in lifting-and-handling machinery and transport. An educational actuality of the present research is grounded on the absence of a proper description and explanation of this topic in available textbooks and scientific articles in the fields of classical mechanics, control engineering, transport, lifting-and-handling machinery, engineering education, mechanical engineering education, and classical mechanics education. Among learning tools this article uses the following educational techniques: Modelica-assisted simulation with acausal equation-based freeware computer system JModelica.org with Optimica extension, physical simulation techniques, allegoric fairy tale analogy, didactic transposition method and a complex of individual Modelica-enhanced students' computational assignments. The proposed educational approach provides a broadening of students' ideas concerning the applicability of abstract physical concepts to the theory and practice of freeware-assisted mechanical engineering education of undergraduate and graduate students majoring in dynamics and control of guided lifting-and-handling machinery. Research finding, concepts and ideas of this research have found a practical educational application through the formulation of practical computational problems of term design works, planning of MSc degree students' works, and freeware-enhanced curriculum of Donbass State Engineering Academy, Kramatorsk, Ukraine.

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Keywords: Foucault pendulum-like system; mechanical engineering education; JModelica.org & Optimica freeware; crane arm guided rotation; open-loop load swaying control problem; acausal programming.

1. INTRODUCTION

1.1. Problem posing and educational background of the present research

The solution of applied problems of crane dynamics [1, 5, 9, 14, 17-18, 20, 26-28, 33, 35, 37] requires mechanical engineering students to study the motion of lifted load both in inertial and non-inertial frames of reference.

The absolute load trajectory in Figure 1, derived by the authors of the present research using a simple physical simulation-based experiment, strongly indicates the appearance of swaying of the transportable load during rotational motion of the crane arm, where the transferable load is attached to the crane arm with a cable (Figure 3). The experimental swaying of a light-emitting diode (LED) is visually observable in Figure 1 in the form of the zig-zag-shaped absolute LED's path with additional inflection points on the absolute trajectory. The physical cause of the visually observable load swaying in Figure 1 is the action of Coriolis inertia force on the moving LED-model of load.

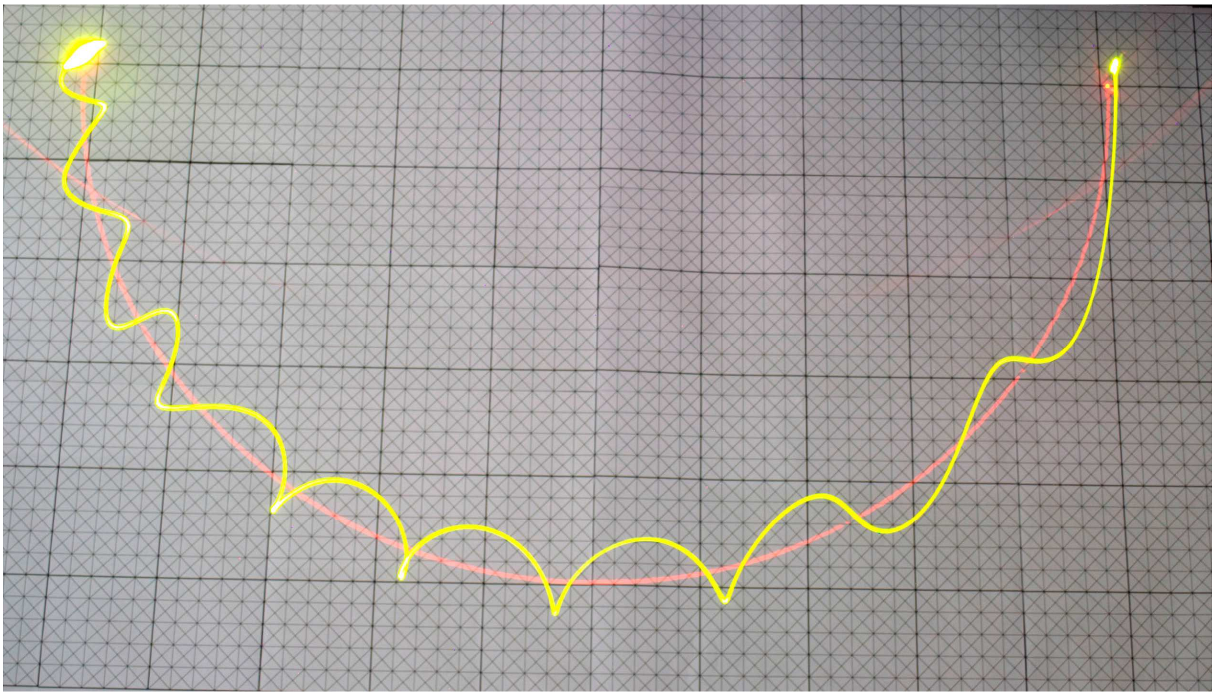

Figure 1. Educational physical simulation-based experiment, illustrating influence of Coriolis effects on the shape of an absolute LED's yellow zig-zag-shaped trajectory

Special attention is given to the direct geometric analogy between swaying of a transportable load M with respect to the non-inertial frame of reference B ($O_1x_1y_1z_1$), associated with the rotating crane arm BD (Figure 3) and swaying of the Foucault pendulum with respect to the Earth-associated non-inertial frame of reference. This geometric analogy means that the mechanical system "rotating crane arm DB – cable BM – transferable load M" is a Foucault pendulum-like system (Figure 3). Therefore, Foucault pendulum-like systems are important not only for physicists but for the specialists in crane dynamics and control. However there is a lack of applied didactic educational research, focused on the application of theories of Foucault pendulum-like systems to the formulation and solution of practical problems, which arise in mechanical engineering education.

It is important to note that the majority of researchers in the field of boom crane dynamics and control (Sakawa et al. (1980) [33], Terashima et al. (2007) [35], Uchiyama et al. (2013) [37]) have not properly addressed Coriolis effects associated with crane arm rotation. At the same time authors-derived experimental Figure 1 clearly shows the appearance of Coriolis effects and the importance of proper accounting for these effects for proper engineering analysis of payload swaying during crane arm-assisted transportation (Figure 3).

There is a large quantity of research in the dynamics of classical Foucault pendulum-like systems in known publications [2-4, 6-8, 10-13, 15-16, 19-21, 23-25, 29-30, 32, 34, 36, 38-39]. However, the majority of this research is rather abstract and mathematically difficult for applied didactic purposes. Therefore the educational application of available research [2-4, 6-8, 10-13, 15-16, 19-21, 23-25, 29-30, 32, 34, 36, 38-39] is rather restrictive in mechanical engineering education due to mathematical complexity and the weak connection with practical problems of lifting-and-handling machinery (Figure 3).

At the same time the applied didactic problems of engineering education of students with a major in transport require the introduction and comprehensive explanation of guided Foucault pendulum-like systems of a non-classic type because almost in every problem of lifting-and-handling machinery crane arm rotation is non-uniform (Figure 3).

Moreover, the level of mathematical knowledge of engineering students is insufficient for proper understanding of most theoretical articles concerning dynamics of Foucault pendulum-like systems. Therefore an engineering-friendly and understandable explanation of Foucault pendulum-like dynamic systems, sufficient for practical students' applications of new knowledge is the aim and scope of the present research.

1.2. The state of the art concerning teaching of Foucault pendulum-like systems

Foucault pendulum-like systems play an important role in many practical problems of physics, mechanics and mechanical engineering. These dynamic systems play a key role in gyroscope theory, guidance and navigation, celestial mechanics, astronomy, geodesy, particle physics, mathematical physics etc. However, despite the wide field of physics applications, Foucault pendulum-like dynamic systems have not been properly addressed in the well-known physics textbooks.

A classical textbook in Mechanics by Landau et al. (1976) addresses inertia force related problems in Chapter 39, pp. 126 – 130 [19]. However, it is really hard for students to understand the origin and the structure of Lagrangian (39.6), which contains the velocity $[\mathbf{\Omega}, \mathbf{r}]$, associated with the rotational translational velocity component. A short definition of the Coriolis force was provided on p. 128 [19] in the form of a comment on the term $2 \bullet m \bullet [\mathbf{V}, \mathbf{\Omega}]$ of equation (39.7) for the relative acceleration. Landau et al.'s method of approach to an explanation of the dynamics of relative motion for physicists in [19] is based on formal mathematical techniques without an explanation of the physical meaning of the proposed mathematical transformations. A formal and quick introduction of the Coriolis inertia force in [19] was done with no explanation of the causes and origins of this force and without notes concerning differences between Coriolis force and other forces in classical mechanics. On pp. 129 – 130 of [19] Landau et al. (1976) have shown a problem which briefly illustrates the Foucault pendulum problem. The system of differential equations, which describes the motion of a Foucault pendulum, was provided on p. 129 of [19] with no derivation nor explanation. Landau et al. (1976) have not shown the trajectory of the Foucault pendulum and have not explained the starlike shape of the Foucault pendulum trajectory.

It is necessary to note that there was no mention of Foucault pendulum-like systems in mature and popular physics textbooks by Feynman et al. (1977) and Kittel et al. (1965).

At the same time there are a lot of scientific publications, which address the dynamics of Foucault pendulum-like systems.

Condurache et al. (2008) have studied the motion of a Foucault pendulum in the central gravity field with respect to the non-inertial Earth-associated reference frame [7]. However highly rigorous Condurache et al.'s research has prevented an educational application to students' study and self-study of the dynamics of Foucault pendulum-like systems by undergraduate mechanical engineering students by the complex vector & tensor-based language of derivation and explanation of the governing equations. Undoubtedly the exact vector solution of the mechanical problem of motion of a Foucault pendulum system in [7] is very general and scientifically important but is rather abstract and very difficult for undergraduate students with majors in physics and engineering.

It is necessary to note that known descriptions and explanations of Foucault pendulum-like system dynamics in [2-4, 6-8, 10-13, 15-16, 19-21, 23-25, 29-30, 32, 34, 36, 38-39] are focused on the motion of mainly classical Foucault systems. However, applied engineering transportation problems of dynamics, automation and control in lifting-and-handling machinery require analysis of little known non-classic guided Foucault pendulum-like systems. This shortcoming of the earlier research forms the scientific and educational focus of the present original didactic research.

1.3. Aims and scopes of the present research

The above mentioned literature review has shown that technical and educational aspects of the nonlinear control problem of payload swaying during guided crane boom non-uniform slewing, taking nonlinear Coriolis effects and complex two-part structure of minimized functional (or performance index) J into account, has not been properly addressed in previous known educational and scientific research [1-39].

This fact outlines and confirms the prime novelty and relevance of the present research, which is focused on the implementation of didactic transposition techniques in the case of the education of technical university students in inertia forces and guided Foucault pendulum-like systems with the application of a mature a causal modeling computational freeware JModelica.org for equation-based numerical solution of open loop optimal control nonlinear problem for minimization of the two-part functional (performance index) with an emphasis on Coriolis force-influence effects on relative and absolute trajectories of payload motion.

The principal goal of the present research is the formulation of an original didactic concept of engineering-friendly study of selected topics in mechanical engineering education of graduate students in the fields of guided crane boom dynamics optimization and mechanics-based optimal control theory of lifting-and-handling machinery through the classical mechanics-based formulation, dynamic posing and JModelica.org freeware-based numerical solution of an open loop optimal control nonlinear problem of payload swaying during crane boom guided non-uniform slewing with proper accounting of nonlinear Coriolis effects and for taking into account the complex two-part structure of the minimized functional (or performance index) J.

The object of this research is an accurate determination of compulsory educational changes within undergraduate and graduate curriculum, formulation of novel didactic transposition-based educational approach to the formation of an engineering-friendly new curriculum in crane dynamics, associated with development of novel freeware-based computer codes, which results in significant improvement in the quality of mechanical engineering education for students, majoring in control engineering and transport through

JModelica.org-assisted visualization of the dynamic processes of payload swaying along the Coriolis force-influenced and performance-index J shaped payload trajectory during crane boom guided slewing for an open loop crane boom control strategy and for different numerical values of control parameters q_1 and q_2 of minimized functional $J = J(q_1, q_2)$.

The subject of this research is focused on the general trends of a combined application of didactic transposition techniques and the proper principles of anthropological theory of education to improvement of engineering curriculum through advanced student-friendly explanation of dynamics and control of Foucault pendulum-like guided systems like a "slewing crane arm – swaying load" to graduate students in lifting-and-handling machinery through the widest outline of peculiarities of open loop optimal control JModelica.org-derived relative and absolute trajectories of a swaying payload with respect to the unknown non-uniform law of crane boom slewing, the form of two-part minimized functional $J = J(q_1, q_2)$ for different numerical values of control parameters q_1 and q_2 of minimized performance index $J = J(q_1, q_2)$, and nonlinear Coriolis effects during payload swaying motion.

2. THEORETICAL STUDIES

2.1. Concerning creativity in mechanical engineering

Discussions concerning the proportions of creativity and craft in the science and engineering academic activity of undergraduate students, graduate students, engineers, PhD researchers and faculty are as eternal in the academic environment as pendulum-related problems among mechanics and mechanical engineering communities are.

Very often the successful accomplishment of computational routine in the process of education in engineering and science requires the use of standard template-based approaches for the solution of typical problems. However, a craft-based application of existing templates is a true indicator of the professionalism and qualification of an implementer, which guarantees the sustainability and consistency of educational activity. The successful solution of these typical problems requires solver to have a large amount of preliminary specialized knowledge. However the process of a craft-based solution is like a computer-assisted algorithm with strictly prescribed order and number of consequent operations. Existing elementary and higher mathematics textbooks contain many of these algorithms, mandatory for learners, which surely shape a qualified craft in learners. It is important to note that despite the complicated and laborious solution process, the solution routine for the majority of these problems contains no creativity elements.

It is a very complex and difficult educational assignment to teach students creative thinking, focused on the development of the student's ability to think beyond the template to find his or her own alternative solution of the computational problem. In most cases, it is people who are able to think creatively who make true progress in science and technology. It is obvious that a student's creativity development is really impossible without diligence and hard work in solving individual home assignments. It is a common problem in the STEM teaching practice when a student is fluent with studied material but becomes puzzled if the lecturer asks this student a non-trivial question, which requires additional thought. This problem is usually caused by an insufficient awareness of the studied material due to the formal solution of a limited, insufficient quantity of relevant examples and problems. This example means that it is impossible to discuss the problems of students' creativity formation without individual solutions of large quantities of thematically-connected examples, problems, and computational assignments. The growth of the student's interest in the studied discipline is closely associated with growth in the number of individually solved problems. Therefore the student's solution of dozens of relevant problems is a necessary but nonsufficient condition for youth creativity development. The quantity of individually-solved problems for creativity development should be at least 10 times more than the standard problem requires. Generally, the successful formation of a student's interest and the further development of creativity are impossible unless both lecturer and student expend more time and effort outside of class. This fact demands a high level of devotion by instructor and student as well as an extensive use of computer-assisted computations. Another important element of creativity education is the demonstration of non-standard approaches to the solution of complex problems.

It is also possible to enhance the understanding of the problems in the studied subject area through the use of additional mathematical formalism and concepts like matrices, vector and tensor analysis techniques, quaternion calculus, graphs, fractals etc. It is quite possible to ensure the growth of STEM-related creativity through the enhancement of the mathematical culture of students by switching from 2D to 3D computational problems and introducing additional degrees of freedom to the studied mechanical or electro-mechanical systems.

The authors believe that, as a first approach to an approximate measure of a student's creativity, the maximum lecturers' grades with no principal differences between ranges [0..5], [0..12] or [0..100] grades may be used. At the second level the measure of students' creativity may be associated with individual research activity, reflected by scientific metrics of such vendors as Scopus and Web of Science Core Collection.

Today it is a common practice to solve a large number of computational problems using computers that have developed over the last few decades with rapidly growing computer hardware and variety of specialized software. Using modern computational software enables a researcher to become partially free from mathematical routine, making more time available for possible creativity.

It is important to note that in previous decades the elements of mathematical creativity were associated with the development of effective and efficient algorithms, which enabled a researcher to solve quite complex problems while computer hardware and software were still quite weak. The lack of memory and low speed of early computers and the standard programming techniques that were used resulted in frequent failures and numerous problems for researchers who tried to make a direct implementation of standard computational methods with very weak results. Sophisticated and creative old computational techniques and early computers were used for the solution of such problems as effective matrix inversion algorithms or linear equation solution algorithms using sparse coefficient matrix structure, etc. Today the quick growth in computational power and speed of modern computers allows researchers to switch from the highly creative approach to the sustainable and successful craft-based scientific programming routine. This trend results in shifting mathematical creativity into other research directions.

Today researcher creativity becomes extremely important at the stage of understanding the problem and strongly depends on the scholar's ability to make a proper mathematical description of the complex physical or social process. The formulation of a computational problem depends on the nature and quantity of hypotheses which are the basis of the researcher's approach. It is important to note that a researcher's creativity at the formulation stage of a computational problem is based on his or her ability to select the essential factors which strongly influence the simulated process and discard the unessential factors. It is very hard to apply known mechanics techniques to a rapid formulation of new mechanical problems "on the fly" using available methods of mechanical engineering (e.g. using Lagrangian formalism). It is also a very important assignment to make an accurate engineering-friendly linearization of derived equations, which is grounded on the application of a small parameter method or perturbation method to the posed non-linear problem. Linearization quite often provides an engineering-acceptable accuracy, which is reasonable for restricted ranges of model variables and parameters. The most important fact is the fulfillment of engineering requirement that used linearization should not lead to significant discrepancy between the simplified model, non-linear formulation and available experimental results. Therefore an accurate and reasonable linearization has elements of creativity because it ensures identification and visualization of new phenomena, features and general trends within the studied engineering problem.

The interrelation between creativity and ethics in R&D activity should not cause a violation of academic integrity. Ethics issues are closely associated with creativity questions in the establishment of priorities of scientific findings, obtained by different researchers and research groups. The priority problem is especially important for cases of simultaneous publication of the scientific works where publication dates are close.

It was earlier mentioned that today the sphere of creativity in computational science is shifted to the questions of accurate formulation and well-posing of the studied problem. A research supervisor usually distances his/her students, PhD-candidates and PhD-students from these complex questions of problem posing. Unfortunately this supervisor's habits may often restrict and eliminate the current and future development of creativity of young researchers.

As an example of this the authors would like to recall the fact that many persons who successfully defended their Master's and PhD degrees but were never engaged in details and complexities of proper formulation of the posed problems quite often become very unenterprising and passive in further individual R&D activity. This research shiftlessness prevents development of creativity and craft and severely affects academic integrity and sustainability.

2.2. Concerning didactic transposition pedagogical technique

Didactic transposition is one of the basic components of modern pedagogy [40-47]. Didactic transposition ensures the process of transformation of the engineering disciplines from R&D-related scientific dialect into simple educational language or the transition of engineering disciplines for scientists into engineering disciplines for students [40-47]. The problem of correct, proper and student-friendly transformation and simplification of complex engineering problems into something easily understandable for students without learning material corruption in the process is the most important methodological problem in this educational process. Emergence, growth and development of didactic transposition were the pedagogical answer to modern demands and requirements of educational systems, resulting in a change from a behaviorism to a constructivism philosophy. The philosophical idea of constructivism application to education is grounded on the absolute impossibility to transmit complex comprehensive knowledge to a student. Instead, this educational constructivism is focused on the creation of conditions which will facilitate the process of students' learning. Constructivism a priori assumes preference of students' position. Constructivism disregards the obvious imperfections and limits of the student's knowledge, mind and viewpoint.

Constructivism is grounded on ideas developed by Piaget (1950/1973), who studied the generation of new constructed knowledge as a result of resolution of conflicts between a structure of a subject, who studies new things (technical student-cognizer) and the surrounding reality [40]. A constructivism philosophy implies that the aim of cognition is the formation of complex constructs and models of reality, which correspond to the phenomena of environmental reality, society, and social realm. Didactic transposition enables the adaptation of a student as a subject of cognition (student-knower) to modern conditions, which allows the effective solution of practical problems of the modern educational process and curriculum.

The authors believe that true education assumes an active formation of new knowledge through the process of intellectually-practical activity of a student developing solutions of complex real-life engineering problems and situations. It is a very important educational assignment to develop the internal structure of a student's learning mind as a subject who is able to grow into a true student-knower or a student-cognizer. New knowledge itself, which gets a student into a technical university, is only a way of possible solution of existing contradictions and inconsistencies. This means that pure knowledge itself, which was not used to resolve real practical contradictions and conflicts, has no special importance and is negotiable. In the abstract and pure form, generalized theoretical knowledge is rather useless and harmful for technical students because it gives learners a false sense of a high level education but keeps students enthralled by dogmatism. The most important is the formation of a student's ability to derive optimal solutions of specific practical assignments, which are highly dynamic, requiring multi-step re-thinking of complex engineering or social problems.

It is possible to ensure a successful engagement of technical university students in scientific and engineering R&D-related activity by finding the measure of concordance between the volume of available knowledge and a student's experience. This can be done with a new system of theoretical knowledge, which can help learner to solve real practical problems. According to the constructivism philosophy the role and functions of a teacher in the pedagogical processes have changed. Teachers are strongly encouraged to transition from a lecturer who provides learners with a body of knowledge into a curriculum developer, organizer of educational processes, and creator of learning environments. The teacher, of course, is busy with the activation of the student's practical scientific activity.

A university teacher creates conditions for intensification of the mental capacity and intelligence of students by the development and formulation of real problem-based practical assignments. This student activity improves self-assurance, enhances confidence in personal success in problem solving, and provides the possibility for more academic freedom and responsibility, rather than becoming narrow-minded within the borders of restricted available knowledge and algorithms. A theoretical background for this educational approach is generally grounded on the didactic transposition pedagogical technique, which was developed by French researcher Chevallard (1985) and became the background of anthropological didactics theory [41].

The aims and scope of the proposed article are focused on educational research of topical problems, basic theoretical preconditions and development strategy of didactic transposition for the case of mechanical engineering education of graduate students in transport and lifting-and-handling machinery. The present study is focused on the identification of the role of pedagogical discourse in socially-enhanced development of engineering-friendly knowledge. The proposed article provides analysis of possible productive collaborations of didactic transposition theory with other theories of engineering and scientific education and possible critical perspectives of a complex multi-level educational study. The scientific novelty of the present research article consists in the fact that for the first time a study of didactic transposition was made in the field of university-level mechanical engineering education of graduate students in lifting-and-handling machinery and transport for the problem of guided dynamics of Foucault-pendulum like system.

The basic theses of didactic transposition theory are as follows [41]:

In the first thesis Chevallard (1985) explains the principal difference between STEM-related disciplines in the fields of Engineering, Computing & Technology and social sciences like STEM education, engineering didactics and socio-cultural studies of engineers and engineering [41]. The first Chevallard thesis (1985) emphasizes that dynamic non-linear social systems "teacher-students" are "anthropological systems", which are always human-related and human-containing dynamic social systems [41].

In the second thesis Chevallard (1985) clarifies that conversion of scientific knowledge for educational purposes at university and college levels with further widest knowledge dissemination is not simply adaptation or simplification of specific specialized knowledge but is the process of subsequent transformation [41]. The process of conversion of scientific knowledge into STEM-educational knowledge for teaching and learning purposes requires the following two stages for successful completion [41]. The first stage of didactic transposition is an external transposition at the level of formal curriculum, education programs, textbooks, and teaching guides [41]. The second stage is an internal transposition, when a new innovative curriculum has been really and truly implemented into auditory or classroom students' activity [41]. In this case a teacher transfers educational program or instructional content from one discursive practice into another and has to manage with proper explanation of scientific knowledge, taking into account a current specific discursive situation [41].

Bosch and Gascón (2006) have defined the aim of the theory of didactic transposition as the description and explanation of knowledge transformation from scientific-based knowledge generation into educational usage in instructional practice [42].

Chevallard's research (1985) was focused on identification of social factors, which influence two fundamental processes of didactic transposition [41]. Chevallard's work (1985) also addressed the subject of didactic discourse variations in different curricula and educational programs taking into account the individual peculiarities of students and the current communicational context [41]. Further, Chevallard (1985) addressed the duality of didactic transposition starting from a scientific discourse to an educational one and vice versa [41]. Duality of didactic transposition was shown to determine the exercise and adjustment of an analytical way to study educational practices for teaching and learning different disciplines in different curricula and pedagogical situations [41]. Chevallard (1985) has assumed the need for social recognition and legitimization of didactic discourse [41]. The didactic discourse itself assumes the identification and establishment of gnoseological, epistemological, and pedagogical foundations of some specific theoretical questions, range of applied questions, practical engineering problems, specialized topics in a non-standard industrial situation etc [41]. The educational discourse determines the complexities in the study of the didactic transformation of scientific codes, possible representation of a specific studied topic as an anthropological system, and identification of obstructive factors, which complicate the understanding of specific topics [41].

The ideas of didactic transposition are very topical within the modern pedagogical discourse in an engineering university. Modern researchers in science education Wozniak et al (2010) assume that the meaning of didactic transposition theory is in expansion of analysis of "didactic phenomena" and in the possibility to analyze the fundamental restrictions of local and global educational systems [43]. Moreover, Wozniak et al (2010) have explained that didactic transposition theory shows the mandatory and compulsory interconnection of mathematical knowledge with learning institutional practice within which these "didactic phenomena" appear, develop, find educational usage, and are disseminated in curricula, taught and studied by students [43].

Kang & Kilpatrick (1992) supposed that it was Chevallard's contribution in identification and outline of earlier hidden mechanism of generation and assembly of knowledge [44]. Factually Chevallard has shown how it is possible to create new effective didactic transpositions, which will use advantages of society in the best possible way [44].

Tiberiu-Octavian (2015) has shown the distinctive features of localized reconstruction of contents within didactic transposition as well as the fundamental difference between discursive strategy and argumentation [45]. Tiberiu-Octavian (2015) also proved that didactic language, which is mediated by a computer, is a generalization within an educational process [45]. They also noted that reconstruction of educational content is displaced to an axiomatic background of curriculum paradigms [45]. This displacement of pedagogical reconstruction was explained by Tiberiu-Octavian (2015) by the fact that a change of a paradigm causes a change of architecture in a didactic language in order to convey to a student's auditory system the scientific content, which is revealed and reconstituted by didactic transposition [45].

Klisinska (2009) has studied the fundamental preconditions of didactic transposition in the course of mathematical analysis and made the corresponding thematisation and conversion of computing theory within a determined body of mathematical knowledge [46].

Didactic transposition has found large-scale educational implementation in different subject areas and has initiated extended research studies in related fields of didactics and education theory in the early 21st century [47]. However, a number of researchers like Bosch and Gascon (2006) [42] and Beitone et al (2013) [47] have numerous doubts and criticism of didactic transposition theory because it is impossible to identify a clear body of scientific knowledge and there are numerous complications with a proper representation of many fields of knowledge as a single integrated system [42, 47].

The present research article is focused on the implementation of didactic transposition techniques in the case of the education of technical university students in inertia forces and guided Foucault pendulum-like systems. The authors of this work have proposed an original didactic concept of engineering-friendly study of selected topics in mechanical engineering education of graduate students in the fields of guided crane boom dynamics optimization and mechanics-based optimal control theory of lifting-and-handling machinery. The final stage of educational transformation using didactic transposition techniques have provided real possibilities of an accurate determination of compulsory changes within educational engineering with specialized groups of graduate students at Donbass State Engineering Academy (Kramatorsk, Ukraine), majoring in control engineering and transport. A novel didactic transposition-based educational approach, reported in the present article, has found a successful educational application in the formation of an engineering-friendly new curriculum in crane dynamics, development of freeware-based computer codes, which resulted in significant improvement in the quality of mechanical engineering education. A successful description of nonlinear crane dynamics using the proposed approach is grounded on a combined application of didactic transposition techniques and the proper principles of anthropological theory of education, which led to the successful solution of applied engineering problems.

2.3. Concerning reduction of teaching hours

A disturbing trend has been established in mechanical engineering education, wherein full time students majoring in lifting-and-handling machinery are receiving a decreasing number of hours in classroom study of theoretical mechanics. This trend can be illustrated with an example of a gradual reduction of instructor-led teaching hours at Donbass State Engineering Academy, Kramatorsk, Ukraine over the last 46 years. In 1970, students had 180 hours of classroom study in the complete spectrum of classical mechanics (statics, kinematics & dynamics). In 2016 students had only 83 hours (Figure 2). This reduction of teaching hours resulted in the complete elimination from lectures and practical classes of such topics as spherical motion in rigid body kinematics, theory of vibration for systems with two degrees of freedom in dynamics, impact theory in dynamics. Absence of these topics badly affects the whole curriculum in classical mechanics for undergraduate students in mechanical engineering and makes the proper study of dynamics of Foucault pendulum-like systems extremely difficult.

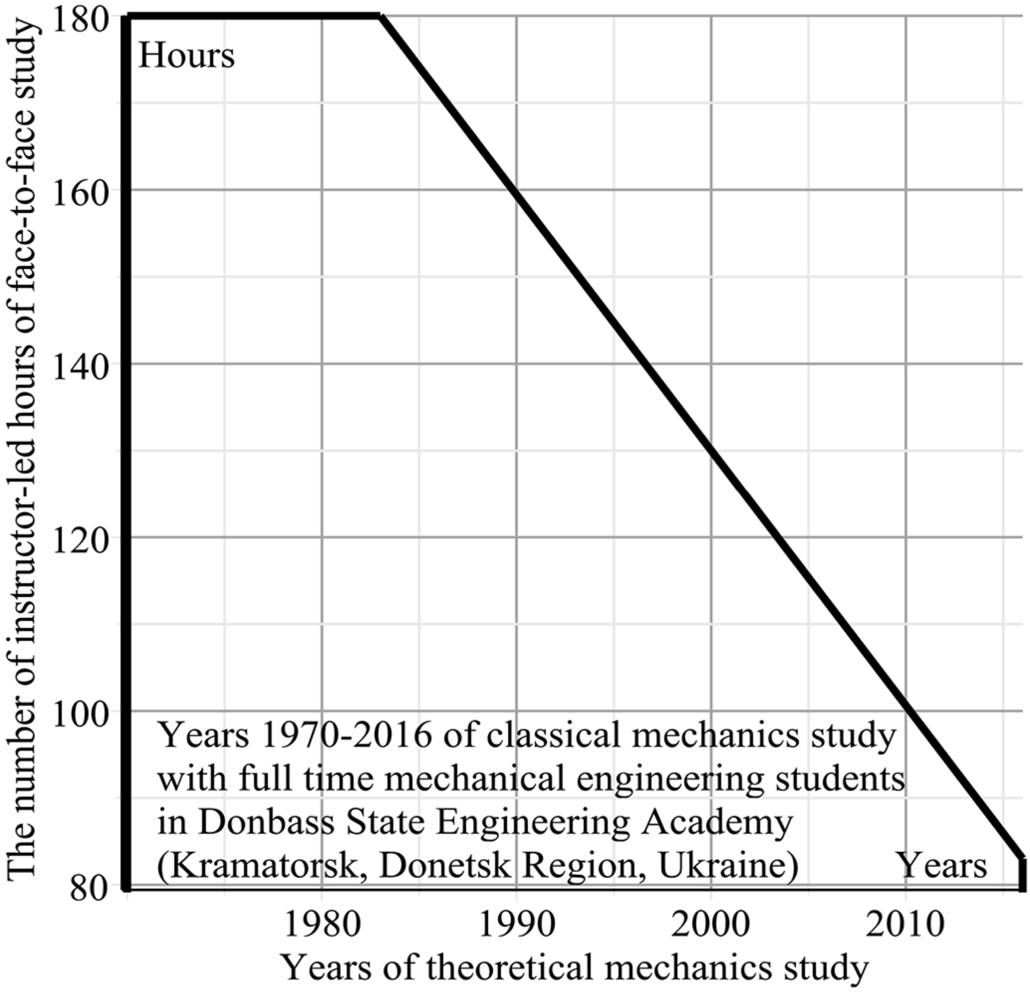

Figure 2. Linearly decreasing time profile for lowering quantity of classroom-based hours in classical (theoretical) mechanics for the range of years [1970…2016]

The above mentioned topics in classical mechanics were moved to students' self-study and to special disciplines of student's free choice as a result of the Bologna Process implementation. Moreover, these advanced topics in theoretical mechanics have even been eliminated from the educational curriculum of senior graduate students in transport. As result, undergraduate, graduate, and PhD students in lifting-and-handling machinery cannot personally complete, pose and solve differential equations of motion for even the simplest mechanical systems.

2.4. Concerning issues with students' understanding of inertia forces and Foucault pendulum-like systems

It is difficult to properly present to students even the most fundamental concepts of dynamic effects in physics and engineering caused by the appearance of Coriolis inertia forces $\mathbf{\Phi}_{\mathbf{cor}}$. Rigorous and clear explanation of dynamics of Foucault pendulum-like systems in lifting-and-handling machinery is simply absent from all known mechanical engineering textbooks (Figure 3).

Even hard working and attentive undergraduate students have numerous questions and make serious errors both with practical computations of absolute values and with determining the correct direction of the vectors of Coriolis accelerations $\mathbf{a}_{\mathbf{cor}}$ and Coriolis inertia forces

$\mathbf{\Phi_{cor}}$. For example, when a lecturer encourages engineering students to calculate the values of Coriolis acceleration $\mathbf{a_{cor}}$ and Coriolis inertia force $\mathbf{\Phi_{cor}}$ for a mathematical conical pendulum with a fixed pivot center with respect to rotating Earth E, many students jump to errors and instead of working with pendulum angular velocity $\boldsymbol{\omega}$, they focus on the angular velocity of Earth rotation $\boldsymbol{\omega}_E$. The causes of such typical errors are often associated with earlier fragmentary students' memories of some physical geography concepts, where all global Coriolis effects are really caused by Earth diurnal rotation.

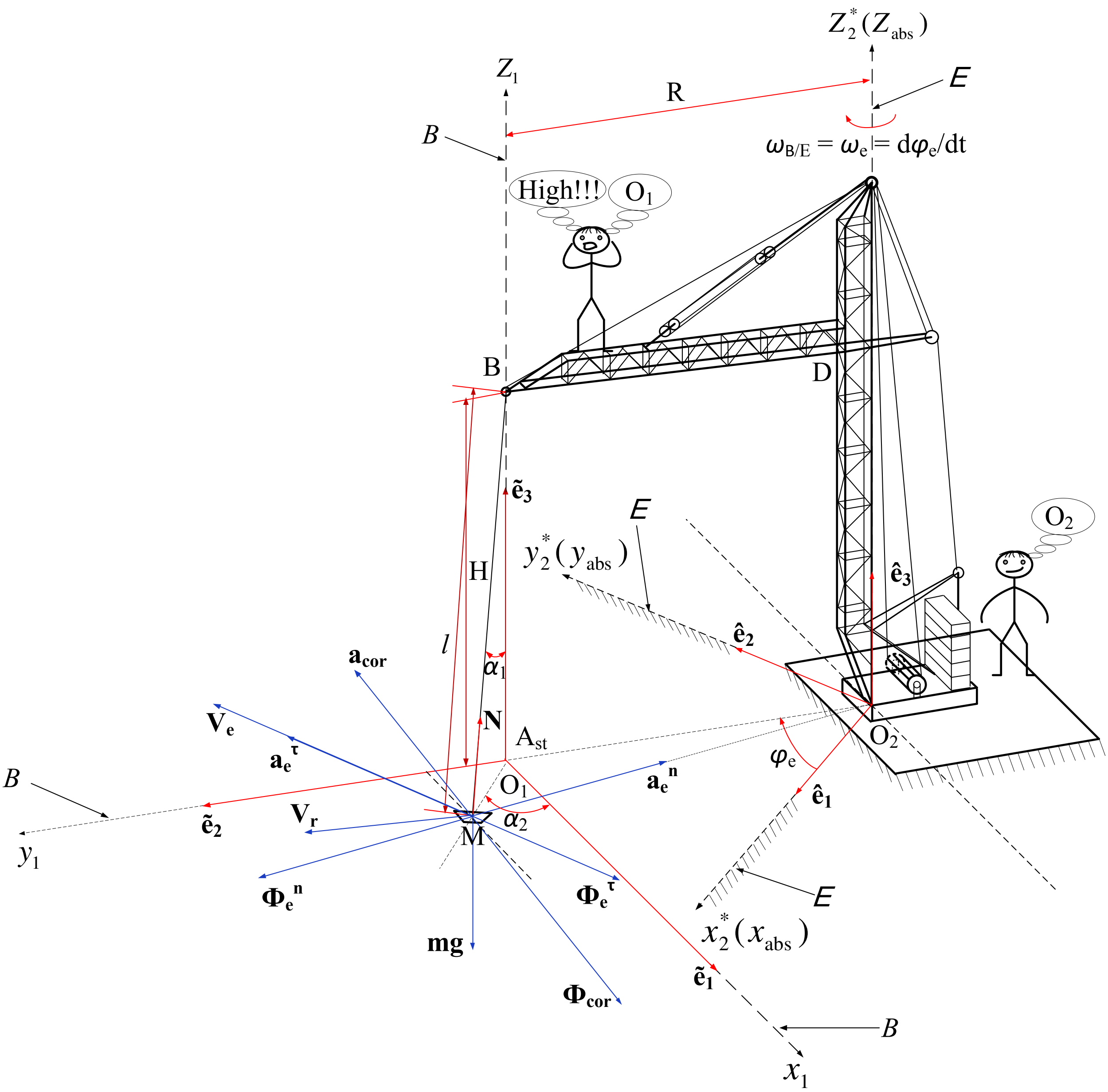

Figure 3. Computational scheme, illustrating concepts of Foucault pendulum-like systems in mechanical engineering problems of boom crane dynamics and control

For a proper explanation of further concepts a lecturer has to introduce some additional terminology concerning Foucault pendulum-like systems (Figure 3).

The first lecturer's definition is about the system of ordinary differential equations, which approximately determines a so-called "classic" Foucault pendulum-like system of boom crane dynamics for uniformly rotating crane arm BD in the following terms of Figure 3:

$$\begin{cases} \left(\frac{d^2(x(t))}{dt^2}\right)-\left(\omega_e^2-\left(\frac{g}{l}\right)\right)\cdot(x(t))-2\cdot\omega_e\cdot\left(\frac{d(y(t))}{dt}\right)=0; \quad (1.1) \\ \left(\frac{d^2(y(t))}{dt^2}\right)-\left(\omega_e^2-\left(\frac{g}{l}\right)\right)\cdot(y(t))+2\cdot\omega_e\cdot\left(\frac{d(x(t))}{dt}\right)=0, \quad (1.2) \end{cases} \tag{1}$$

where the lecturer notes that angular velocity of crane arm BD $\omega_e = \omega_{BD} = const$ is constant, $x(t) = x_1(t)$ and $y(t) \approx y_1(t)$ are the relative load's M coordinates with respect to the non-inertial frame of reference B ($O_1x_1y_1z_1$), associated with the rotating crane arm BD (Figure 3).

The second lecturer's definition is about the system of ordinary differential equations, which determines a so-called "non-classic" Foucault pendulum-like system of boom crane dynamics for a non-uniformly rotating crane arm BD in the following terms of Figure 3:

$$\begin{cases} m\cdot\left(\frac{d^2(x_1(t))}{dt^2}\right)=m\cdot\left(\left(\frac{d^2(\varphi_e(t))}{dt^2}\right)\cdot(R+y_1(t))\right)+m\cdot\left(\left(\left(\frac{d(\varphi_e(t))}{dt}\right)^2\right)\cdot(x_1(t))\right)+ \\ \quad +2\cdot m\cdot\left(\left(\frac{d(\varphi_e(t))}{dt}\right)\cdot\left(\frac{d(y_1(t))}{dt}\right)\right)-(\lambda(t))\cdot\left(\frac{x_1(t)}{l}\right); \quad (2.1) \\ m\cdot\left(\frac{d^2(y_1(t))}{dt^2}\right)=(-1)\cdot m\cdot\left(\left(\frac{d^2(\varphi_e(t))}{dt^2}\right)\cdot(x_1(t))\right)+m\cdot\left(\left(\left(\frac{d(\varphi_e(t))}{dt}\right)^2\right)\cdot(R+y_1(t))\right)- \\ \quad -2\cdot m\cdot\left(\left(\frac{d(\varphi_e(t))}{dt}\right)\cdot\left(\frac{d(x_1(t))}{dt}\right)\right)-(\lambda(t))\cdot\left(\frac{y_1(t)}{l}\right); \quad (2.2) \\ m\cdot\left(\frac{d^2(z_1(t))}{dt^2}\right)=(-1)\cdot m\cdot g-(\lambda(t))\cdot\left(\frac{z_1(t)-l}{l}\right); \quad (2.3) \\ \left(\frac{d^2(\varphi_e(t))}{dt^2}\right)=(-1)\cdot\left(\frac{1}{T_\varphi}\right)\cdot\left(\frac{d(\varphi_e(t))}{dt}\right)+\left(\frac{K_\varphi}{T_\varphi}\right)\cdot(u(t)); \quad (2.4) \\ N(t)=\lambda(t)=\left(\frac{x_1(t)}{l}\right)\cdot\left[m\cdot\left(\left(\frac{d^2(\varphi_e(t))}{dt^2}\right)\cdot(R+y_1(t))\right)+m\cdot\left(\left(\left(\frac{d(\varphi_e(t))}{dt}\right)^2\right)\cdot(x_1(t))\right)+\right. \\ \quad \left.+2\cdot m\cdot\left(\left(\frac{d(\varphi_e(t))}{dt}\right)\cdot\left(\frac{d(y_1(t))}{dt}\right)\right)-m\cdot\left(\frac{d^2(x_1(t))}{dt^2}\right)\right]+ \\ \quad +\left(\frac{y_1(t)}{l}\right)\cdot\left[(-1)\cdot m\cdot\left(\left(\frac{d^2(\varphi_e(t))}{dt^2}\right)\cdot(x_1(t))\right)+m\cdot\left(\left(\left(\frac{d(\varphi_e(t))}{dt}\right)^2\right)\cdot(R+y_1(t))\right)-\right. \\ \quad \left.-2\cdot m\cdot\left(\left(\frac{d(\varphi_e(t))}{dt}\right)\cdot\left(\frac{d(x_1(t))}{dt}\right)\right)-m\cdot\left(\frac{d^2(y_1(t))}{dt^2}\right)\right]- \\ \quad -\left(\frac{z_1(t)-l}{l}\right)\cdot\left[m\cdot g+m\cdot\left(\frac{d^2(z_1(t))}{dt^2}\right)\right], \quad (2.5) \end{cases} \tag{2}$$

where the lecturer explains to students that $\omega_e = \omega_{BD} = var_1$ is the variable angular velocity of the crane arm; the variable angular acceleration of crane arm $\varepsilon_e = \varepsilon_{BD} = var_2 = f\,(u(t), T_\varphi, K_\varphi)$

depends on the electrical drive known control voltage u(t) and the electromechanical drive's constants (T_φ, K_φ); R = BD is the length of the crane's boom; l = BM is the length of the cable BM; m is the mass of load M; g is gravity acceleration; $\lambda(t) = N(t)$ is the internal force of the cable tension; the first $x_1(t)$, the second $y_1(t)$, and the third $z_1(t)$ components are the three relative load's M coordinates in the non-inertial rotating frame of reference B ($O_1x_1y_1z_1$), associated with rotating crane arm BD (Figure 3).

The third lecturer's definition is about the extended system of differential equations (2)-(3), where system (2)-(3) determines a so-called "non-classic" guided Foucault pendulum-like system of boom crane dynamics with open loop control in Figure 3:

$$\begin{cases} J = Q_1 \cdot t_f + Q_2 \cdot \int\limits_0^{t_f} \left(x_1^2(t) + y_1^2(t) + z_1^2(t)\right) dt; & (3.1) \\ x_1(0) = 0;\ y_1(0) = 0;\ z_1(0) = 0;\ \varphi_e(0) = 0; & (3.2) \\ \left(\dfrac{d(x_1(0))}{dt}\right) = 0; \left(\dfrac{d(y_1(0))}{dt}\right) = 0; \left(\dfrac{d(z_1(0))}{dt}\right) = 0; \left(\dfrac{d(\varphi_e(0))}{dt}\right) = 0; & (3.3) \\ x_1(t_f) = 0;\ y_1(t_f) = 0;\ z_1(t_f) = 0;\ \varphi_e(t_f) = 0; & (3.4) \\ \left(\dfrac{d(x_1(t_f))}{dt}\right) = 0; \left(\dfrac{d(y_1(t_f))}{dt}\right) = 0; \left(\dfrac{d(z_1(t_f))}{dt}\right) = 0; \left(\dfrac{d(\varphi_e(t_f))}{dt}\right) = 0; & (3.5) \\ |u(t)| \le u_{\max}; \left|\dfrac{d(\varphi_e(t))}{dt}\right| \le \omega_{\max}, & (3.6) \end{cases} \quad (3)$$

where J is the minimized functional or performance index with weighting coefficients q_1, q_2, $u(t)$ is an unknown control function, which minimizes the performance index J, subjected to constraints (2)-(3), and t_f is the final time of rotation of crane arm BD in Figure 3.

2.5. Concerning students' issues with solution of systems of differential equations (1)-(3)

With no clear understanding of even ordinary differential equations (ODEs) of motion and mechanics techniques of their derivation, students are regularly busily searching for the best "clever" software like OpenModelica, Dymola, MapleSim, Wolfram SystemModeler etc, which can solve students' mechanical problems in an implicit way. However, unmodified and thoughtless use of the above mentioned software without any preliminary knowledge of theoretical mechanics leads to serious errors with implicit numerical simulation of system dynamics.

There is no doubt that students' study of numerical techniques is a very important component of mechanical engineering education. The application of numerical methods enables the possibility for visualization of results, which are derived in the solution of mechanical problems. Visualization makes it possible to determine the relation of the derived numerical results to initial and terminal conditions of the problem and to draw conclusions concerning relation of the mechanical model to the real process it should describe.

However, there are other complexities involved in the practical application of numerical techniques. First, existing complexities are associated with the algorithmic presentation that requires writing computer codes with algorithmic languages, and debugging code is a quite long process. Secondly, there is a large variety of different numerical techniques which can solve the same engineering problem. This presents the student with the problem of making the proper choice of the most suitable numeric technique for solving the problem with the necessary degree of accuracy and with sufficient rate of numerical solution.

Many computer mathematics codes have been created to overcome of the above mentioned difficulties. Among freeware codes the most popular programs are Maxima, Sage, SciLab & XCos, Octave, JModelica.org & Optimica etc. Among commercial systems the most popular programs are MathCad, Maple, Wolfram Mathematica, Magma, MatLab. Among all these commercial and freeware codes JModelica.org [17-18, 22, 28, 48-61] is the most attractive choice for successful mechanical engineering education. Advances in JModelica.org-enhanced engineering education have been confirmed by recent works of Larsson and Braun (2008) [48], Seabra and Machado (2009) [49], Åkesson et al (2010) [50], Zhao et al. (2011) [51], YuXiang et al. (2011) [52], Jianfeng et al. (2012) [53], Zimmer (2012) [54], Martin-Villalba et al. (2012-2013) [55-56], Winkler and Lie (2013) [57], Palensky et al. (2014) [58], Yanshan et al. (2015) [59], Magnusson and Åkesson (2015) [60], Wetter et al. (2016) [61], Kostikov et al. (2017) [17-18], and Perig et al. (2017) [28].

It has been clearly shown in numerous recent studies [17-18, 22, 28, 48-61] that JModelica.org freeware with Optimica extension is an accurate, growing, simple, student-friendly, sustainable and powerful learning tool, which is suitable for implementation in undergraduate, graduate and postgraduate curricula for successful university education.

JModelica.org [17-18, 22, 28, 48-61] has three main educational advantages: no cost, cross-platform code type, and providing the possibility for acausal programming. Acausality is the most important advantage, because it provides possibility for programming at equation level. In fact, acausality makes it possible for the student to focus on the mechanical and physical aspects of the problem without being distracted by particular details associated with mathematical routine and the proper choice of numerical technique and algorithmic presentation. As a result, the student has more time for dealing with mechanics, which improves the quality of mechanical engineering education.

2.6. Concerning issues with posing and solution of optimization problems in mechanical engineering

Problems of multi-criteria choice (3) have arisen in many applied research areas [1, 17-18, 31, 33]. Choice multicriteriality means that it is necessary to analyze all possible solutions of the posed problem (2)-(3) and to select an option which simultaneously satisfies several mandatory requirements (3). In most cases it is impossible to build a solution which is simultaneously optimal according to the several criteria (3). As result, in practical cases, it is necessary to derive a compromise solution, which is not optimal according to all criteria, but practically is satisfactory for the fulfillment of all requirements. The present research is focused on the study of one such problem (2)-(3) which is aimed at finding a control which provides boom crane-assisted payload transportation from starting to final position with minimal time and minimal payload swaying (3). In order to solve this transportation problem (2)-(3), an optimal control problem (3) was posed for an objective function, which contains two components with weighting coefficients (3). The first term of the objective function (3) determines the time t_f of payload transportation. The second term determines the value of payload swaying during crane boom-assisted transportation (3). It is possible to give priority to one or another selection method for choice of objective function by varying the values of weighting coefficients in (3).

It is possible to use the terminology of game theory for the interpretation of optimal control for minimization of a two-term functional (3). We will assume the first player to be the first term in the minimized functional (3), which corresponds to the minimization of load transportation time during load displacement by a guided crane arm. We will assume a second player to be the second term in the minimized functional (3), which corresponds to the value of payload swaying during arm-assisted load transportation. Both players in (3) have antagonistic opposite goals because the winning of one means the failure of the other.

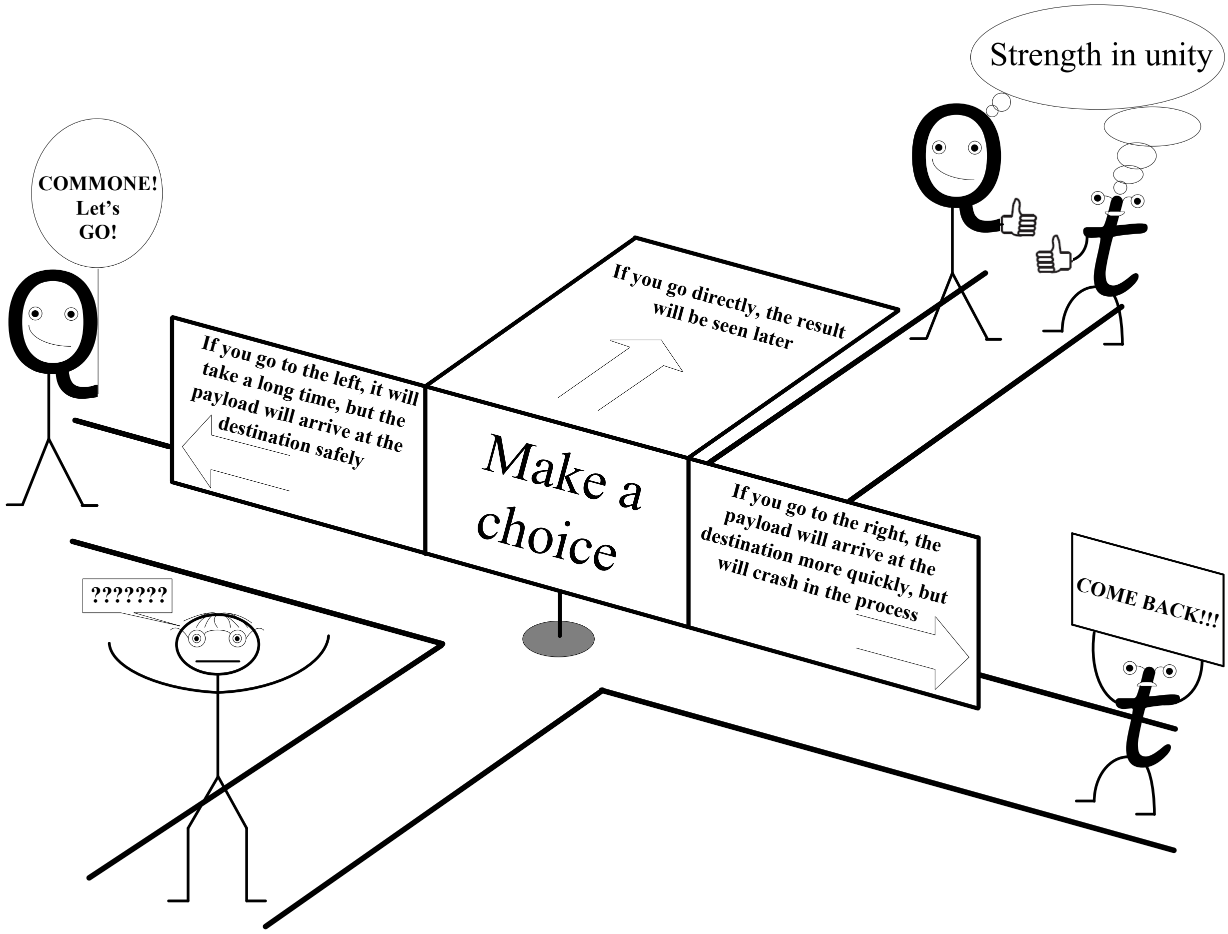

Figure 4. Allegoric crossroad for a guided non-classic Foucault pendulum-like system, which corresponds a structure of a two-component minimized functional J = q1•T1 + q2•T2 [s]

As result it is necessary to find a strategy which would provide a compromise decision. It is possible to show inconsistency of the goals in the following form of a minimized functional $J = q_1 \bullet T_1 + q_2 \bullet T_2$ [s] in (3), where parameter q_1 corresponds to the value of the first factor T_1 (load displacement time) and parameter q_2 corresponds to the value of the second factor T_2 (load swaying value). It is obvious that a compromise solution corresponds to the values of q_1, q_2, located in the range of $0 < q_1; q_2 < 1$ (Figures 5 – 7). End-point values of q_1, q_2, i.e. 0 & 1 correspond to the minimization of one component without taking another component into account. So points 0 & 1 are the points of alternate victories of the opponents, i.e. the point of “conflict of interest”. It is possible to interpret the admissible values of q_1 & q_2 as a Pareto set. In the solution of problems of this type it is necessary to eliminate variants, which does not lead to optimality. In our case we should eliminate the values of 0 & 1 from the range of allowable values of q_1 & q_2. It is also obvious that the solution of the problem requires the imposition of additional limitations on load swaying and load transportation time [1, 17-18, 31, 33]. The left-hand road in Figure 5 corresponds to $q_1 = 0$ & $q_2 = 1$, the right-hand road in Figure 6 corresponds to $q_1 = 1$ & $q_2 = 0$ and the direct road in Figure 7 corresponds to $q_1 = q_2 = 0.75$.

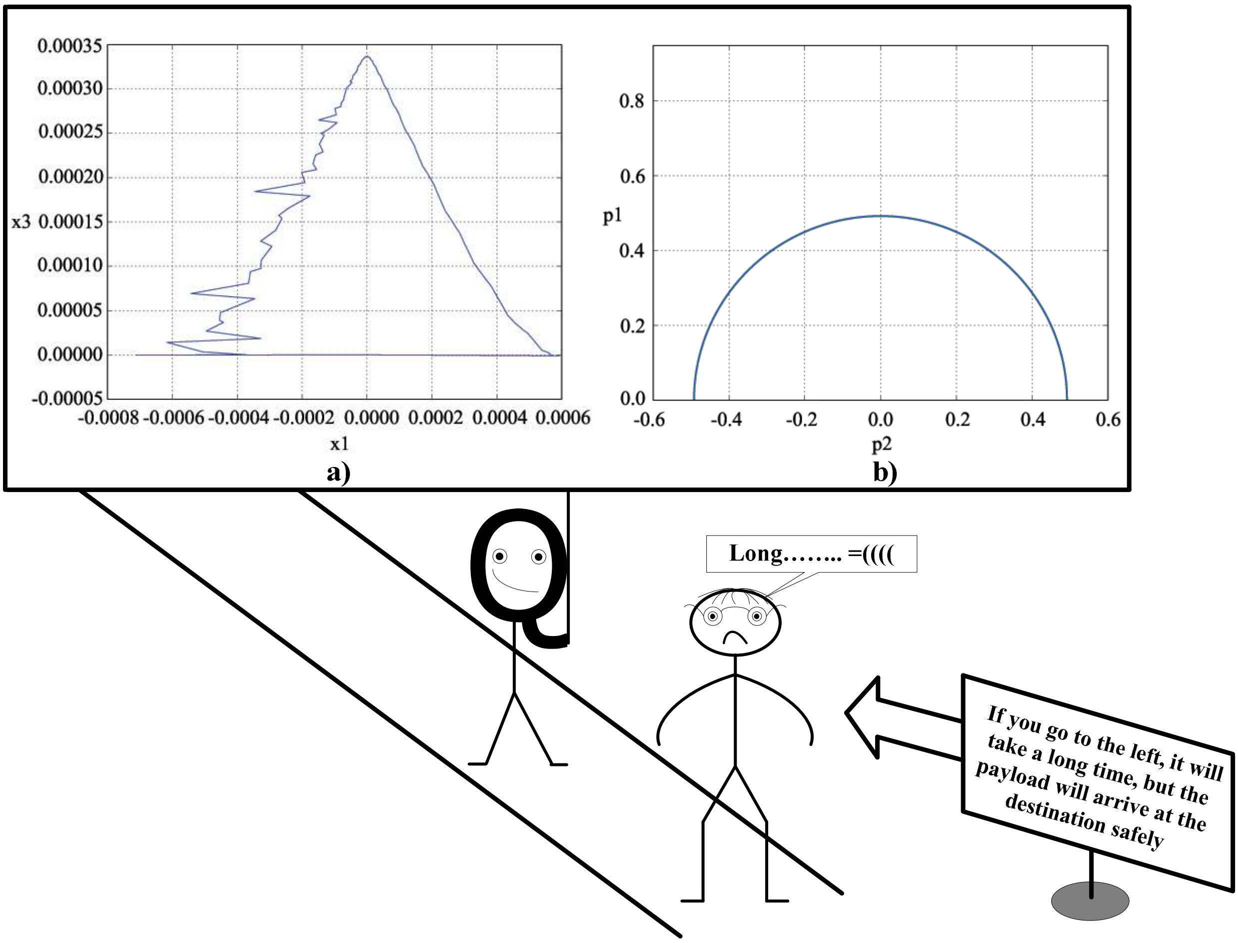

Figure 5. Allegoric left-hand road with absolute (b) and relative (a) load paths for the values of coefficients q1 = 0; q2 = 1, where left road's description is "If you go to the left, it will take a long time, but the payload will arrive at the destination safely"

3. RESEARCH RESULTS

3.1. Concerning fairytale analogy for explanation of optimization problem (2)-(3)

It is useful and effective to improve the quality of engineering education by re-addressing of this optimization problem with an introduction of the elements of a serious game.

It is possible to provide an enhanced students-friendly explanation of this transportation problem through an introduction of such learning tool as a fairytale analogy. Educationally saying the problem of selection of weighting coefficients was interpreted in this work as a choice of the proper road of a wayfarer, which stays at the crossroads (Figure 4). The three possible roads are shown in Figures 4 – 7 which correspond to the structure of a two-component minimized functional (3.1).

The road to the left for the traveler in Figure 5 with description "If you go to the left, it will take a long time, but the payload will arrive at the destination safely" means that we prefer a choice of minimal payload swaying and we consider payload transportation time as a subordinate parameter. However the payload transportation time for this road may be too large to be practically acceptable.

The road to the right for the traveler in Figure 6 with description “If you go to the right, the payload will arrive at the destination more quickly, but will crash in the process” means that we prefer a choice with quick boom-assisted payload delivery but with uncontrollable payload swaying in the process of fast transportation. So the choice of the right-hand road is also unacceptable because it may cause payload damage or occupational injuries to operating personnel.

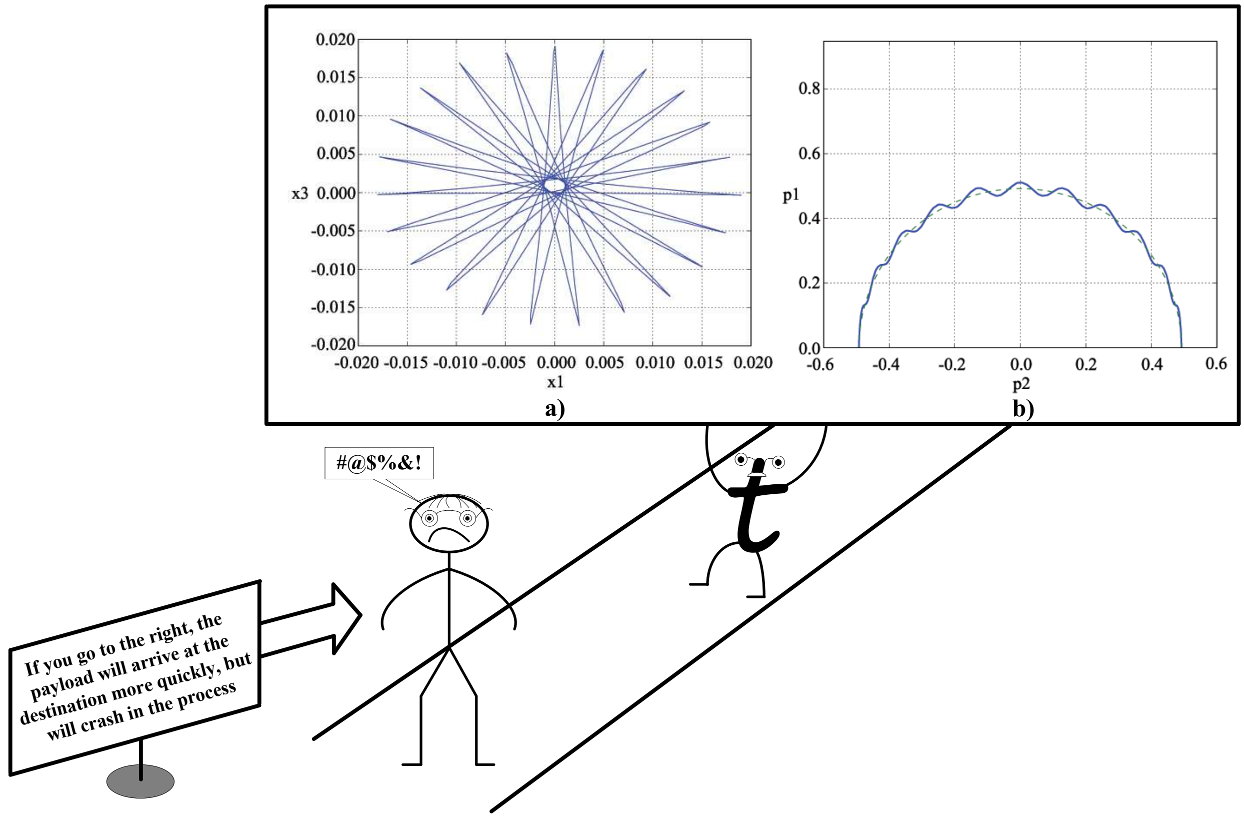

Figure 6. Allegoric right-hand road with absolute (b) and relative (a) load paths for the values of coefficients q1 = 1; q2 = 0, where right’s road description is “If you go to the right, the payload will arrive at the destination more quickly, but will crash in the process”

The straight road in Figure 7 with description “If you go directly, the result will be seen later” is the shortest and the most preferable route to the goal. The choice of the direct road is the preferable selection when the value of payload swaying is within a reasonable range and payload transportation time is acceptable. The direct road case corresponds to practical wisdom concerning the inappropriateness of going to extremes and the fact that a reasonable compromise lies somewhere in between those extremes. It has been found that an explanation of new computational material can be significantly aided by drawing analogies with life experiences which provide a better introduction to new concepts for mechanical engineering students.

The determination of control function which minimizes a two-component functional with a constraint set (2)-(3), is a sound example of a necessity in a graduate engineering education. First, this problem has a many-sided nature, which requires students to be acquainted with a range of advanced highly-specialized disciplines. These include numerical techniques for solution of Boundary Value Problems (BVPs) for Ordinary Differential

Equations (ODEs), theory of Differential-Algebraic Equations (DAEs), calculus of variations, optimal control, differential geometry, topology, function theory, and functional analysis.

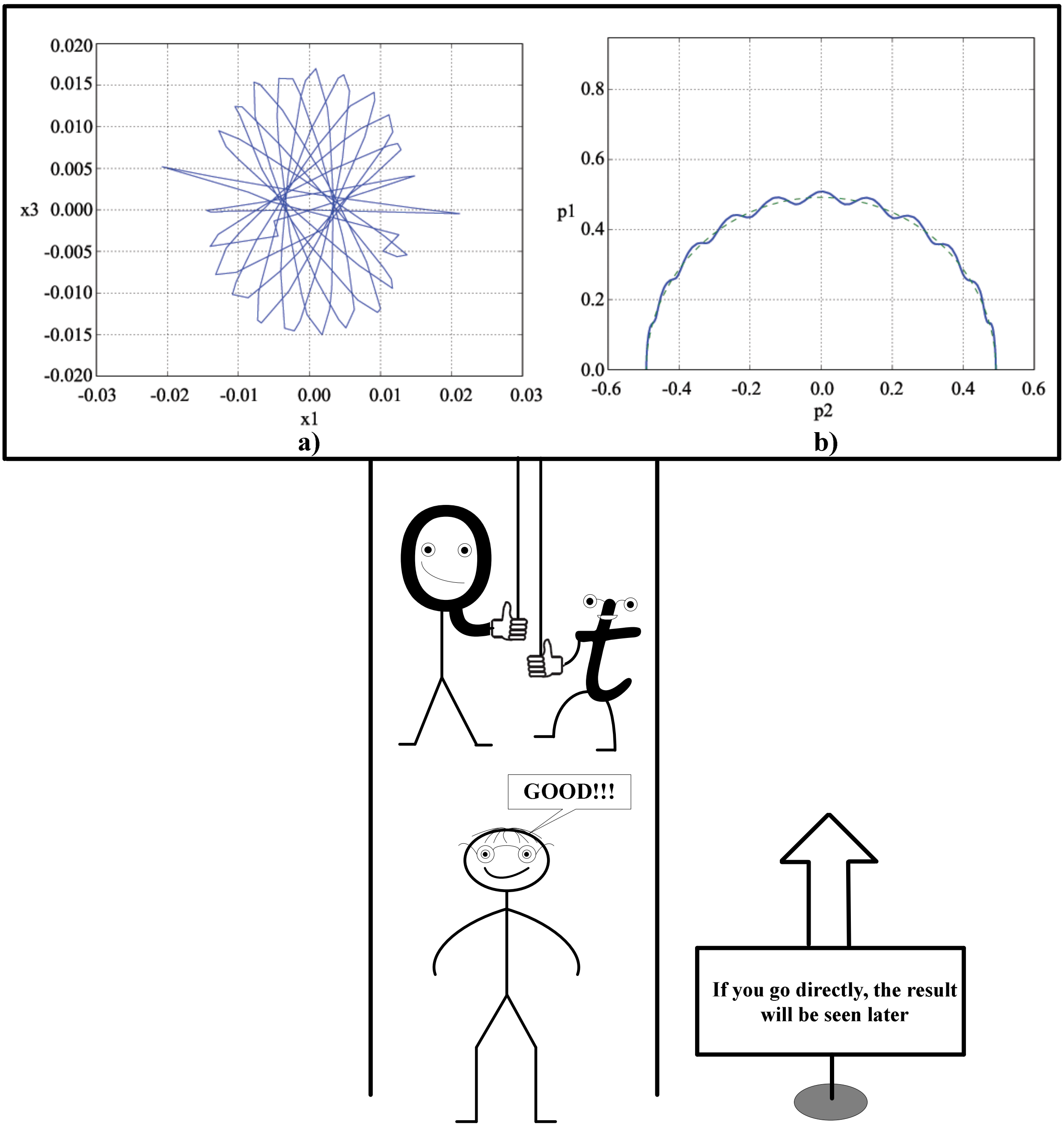

Figure 7. Allegoric direct road with absolute (b) and relative (a) load paths for the values of coefficients q1 = 0.75; q2 = 0.75, where direct road's description is "If you go directly, the result will be seen later"

In particular, the derivation of optimal control requires the application of Pontryagin's maximum principle, which is based on the rule that optimal control is an extremum of the corresponding Hamiltonian. After the derivation of an optimal control we get a BVP for the determination of phase variables, where the BVP solution requires students to have a preliminary knowledge of numerical methods for solution of BVPs for ODEs. An example of the problem of minimization of a two-component functional shows students how it is possible to use segmental knowledge from a variety of disciplines to solve specific practical engineering problems. A primary practical focus on educational analysis of complex applied optimization problems is very important for a successful professional education because the student learns the need for studying new things beyond his/her specific discipline. Students usually wonder “Why do I need to study ODEs and DAEs?”, “Where I can apply these numerical methods and techniques of analytical mechanics in my everyday life?”, “Is variational calculus useful for me in my practical activity?” etc. Educational demonstration of numerical solutions of optimization problems gives a visible answer to the above mentioned students’ questions.

The posed optimization problem (2)-(3) is a very complex one. Therefore it is necessary to spend a lot of educational time and effort to provide a step-by-step outline of its numerical solution. It is useful, for educational purposes, to apply JModelica.org freeware. JModelica.org together with the Optimica extension provides students with the ability to write the posing of an optimal control problem in a form which is very similar to the mathematical formulation of the problem and to derive an algorithm-free complex numerical solution of the problem. Despite the disrespectful attitude of students majoring in computer sciences toward mechanics-related problems of lifting-and-handling machinery, the lecturer is encouraged to emphasize that it is possible to consider the problem of minimization of a two-component functional as a problem of decision-making. Decision-making is based on determination of control, which can result in the achievement of alternative competing goals, which is an important element in the education of specialists in the field of system analysis. The JModelica.org-enhanced crane arm-assisted payload transportation problem is extremely useful for mathematically weak students with a lack of understanding of optimal control theory and numerical optimization techniques. Application of the JModelica.org & Optimica-based approach enables a student to overcome the mathematical barrier and provides every student with a powerful learning tool for the solution of complex applied engineering problems. Thus, it is possible to make a comparison with an automobile. An automobile has a complex interior arrangement and though not all motor-car enthusiasts are acquainted with the operating principles and internal design of automobiles all of them can be drivers and operate a car. The same is true when not all students know the required auxiliary disciplines but the use of the JModelica.org educational tool provides them with the possibility of achieving an educational goal and solving applied engineering problems, which may be useful in their practical activity. The volume of knowledge required for students to acquire JModelica.org & Optimica is much lower than the knowledge level of a researcher who solves this problem with the standard algorithmic methods.

3.2. Discussion

1. Practical crane dynamics problems of lifting-and-handling machinery and transport (Figure 3) require engineering students and educators to pose and solve dynamic optimization problems (2)-(3), which are unusual for classic Foucault pendulum-like systems (1). Lack of educational and engineering studies into dynamics and control of Foucault pendulum-like systems (2)-(3) highlights the relevance and the importance of the present original research. Theory and practice of mechanical engineering education for students majoring in transport requires an educational explanation of guided Foucault pendulum-like dynamic systems (2)-(3), which have arisen from applied problems of boom crane dynamics. Educational derivation of analytical solution of the classic Foucault pendulum problem (1) requires students’ preliminary knowledge of complex variable theory. However, calculus of complex variables is often beyond the program of a restrictive higher mathematics course for transport students. Moreover, an educational solution of a guided dynamic problem for a Foucault

pendulum-like non-classic system with open loop control (2)-(3) may be only numerical, and not analytical. Educational derivation of numerical solutions for a non-classic Foucault pendulum-like system (2)-(3) in the present research (Figures 4 – 7) was made using of JModelica.org freeware with Optimica extension. Engineering and educational innovation of the proposed approach is based on a wide availability for students authors'-proposed *.py and *.mop files for JModelica.org & Optimica freeware.

2. The authors believe that JModelica.org & Optimica freeware is an effective and innovative student-friendly learning tool with widest educational applications to teaching of dynamics and control (2)-(3). The proposed educational approach provides a visually-enhanced better understanding of the material and the broad reproducibility of the numerical results, derived through the use of JModelica.org freeware. From a transportation standpoint Modelica-enhanced numerical solution enabled the determination of optimal control which ensures load transportation with minimum travel time, minimum load swaying, and a zero-value of final payload velocity (3). Modelica-derived plots for the relative and absolute trajectories of payload in Figures 5 – 7 enable easy visual analysis of the numerical solution of (2)-(3) with a corresponding physical interpretation of the results. Computational Figures 4 – 6 show that in the process of control, the derived control function has a constant value at the major time interval with the exception of the last natural period, at which the control function reaches the required value necessary for optimization purposes (Figure 7).

3. The routine of successful engineering education (1)-(3) is analogous to training of a neural network. Neural network education is based on achieving a necessary neuronet output signal with a change of values of weighting coefficients of input signals (synapses). The same occurs here in Figures 5 – 7 when we achieve the necessary desired shape of an absolute trajectory of the payload through the change of weighting coefficients q_1 and q_2 in the minimized functional (3) $J = q_1 \bullet T_1 + q_2 \bullet T_2$ [s]. Therefore students are highly encouraged to install home JModelica.org freeware and computationally study the methodology and a sense of optimization ideas through individual variation of J's (3) coefficients q_1 and q_2 in their copies of *.py and *.mop files. Individual student variation of the values of q_1 and q_2 corresponds to the mandatory individual assignments and the corresponding student's report may be also treated as a learning tool. Additional enhancement of students' motivation and learning interest was provided with an introduction of an allegoric fairy tale analogy in Figures 4 – 7.

4. The authors' educational approach introduces the following elements of engineering-friendly creativity, which have to be accurately learned by students:

4a) The rational choice of the kind of minimized functional J, which enables simultaneous taking into account of the value of payload swaying and system's optimum performance, where J is shown as the end of every road in Figures 4 – 7 and derived results, which correspond to optimized J values are marked as A) & B) in Figures 5 – 7.

4b) The rational selection of control variable $u(t)$ by targeted variation of which it is possible to minimize the functional J, where $u(t)$ is shown as each specific road in Figures 4 – 7.

4c) The rational choice of the phase variables, which determine the state of the dynamic system.

4d) Originality of the author-proposed dynamic model (2), which is formulated in Cartesian coordinates, where the dynamic system (2) is interpreted as the crossroad itself, was shown in Figure 4.

4. CONCLUSIONS

I. The proposed allegoric interpretation of a formulated optimal control problem (2)-(3) using Figures 4 – 7 allows the following visual student-friendly interpretation. A wayfarer, who stays at the crossroad in Figure 4, is the symbol of a boom crane operator, who controls the process of a boom-assisted payload transportation. A crow, who sits on a stone at the crossroad in Figure 4, is the symbol of an external disturbance, which can have a positive or negative external influence on the system “slewing crane arm – transported payload”. The crossroad itself in Figure 4 is the symbol of the studied dynamic system “guided rotating crane boom – swaying payload”. Every specific road to the left (Figures 4 – 5), to the right (Figures 4, 6) or direct road (Figures 4, 7) is a symbol of a control variable u(t) in the systems (2)-(3). The minimized functional J in the present allegoric interpretation is the set of three final destinations, which are located at the end of the roads in Figures 4 – 7, and are marked as A) & B) in Figures 5 – 7. Visibility and availability of the proposed explanation and description of educational material (1)-(3) is provided with wide use of JModelica.org & Optimica freeware (Figures 5 – 7). The individuality of a students’ engineering education is provided with individual installation of this freeware to students’ computers.

II. An applied didactic methodology for describing and explanation the mathematically-complex problems of dynamics and control of guided Foucault Pendulum-like crane boom systems (2)-(3) has been developed, proposed, implemented and verified as an education process of Donbass State Engineering Academy, Kramatorsk, Ukraine. Modelica-enhanced visualization of numerical solutions in Figures 5 – 7 enables the proper formulation of practical problems of term design work and MSc degree students’ work.

ACKNOWLEDGEMENT

Authors thank “anonymous” referees for their valuable notes and suggestions.

ADDITIONAL POINTS. HIGHLIGHTS

New didactic explanation of the dynamics and control of Foucault pendulum-like systems was proposed.

Research uses Modelica-assisted simulation with freeware code JModelica.org & Optimica extension.

Modelica-enhanced educational approach is experimentally verified with physical simulation.

Allegoric fairy tale analogy was proposed and outlined.

A complex of individual Modelica-enhanced students’ computational assignments was developed.

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Text of the article was accepted by Editorial Team 30.10.2017

ЗАСТОСУВАННЯ JMODELICA.ORG ДЛЯ НАВЧАННЯ СТУДЕНТІВ ТЕХНІЧНИХ ВИШІВ ОСНОВАМ ДИНАМІКИ ФУКО-ПОДІБНИХ КЕРОВАНИХ СИСТЕМ

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Анотація. Представлене навчальне дослідження зосереджено на розв'язанні дидактичної задачі доступного для інженерів опису і роз'яснення динаміки s керування Фуко-подібними маятниковими системами, які виникають з практичних задач динаміки стрілових кранів у підіймально-транспортному машинобудуванні і транспорті. Навчальна значимість представленого дослідження ґрунтується на відсутності належного опису й витлумачення цієї теми у відомих підручниках і наукових публікаціях у сферах класичної механіки, інженерії керованих систем, транспорту, підіймально-транспортного машинобудування, інженерної освіти, викладання інженерної механіки і викладання класичної механіки. Серед освітніх інструментів представлена стаття використовує такі педагогічні інструменти: Modelica-основане моделювання в рамках застосування акаузального відкритого програмного забезпечення JModelica.org із розширенням Optimica, методи фізичного моделювання, алегоричну казкову аналогію, метод дидактичної транспозиції і комплекс індивідуальних студентських завдань при використанні обчислювальних можливостей мови Modelica. Запропонований навчальний підхід забезпечує розширення студентських уявлень відносно можливостей застосування абстрактних фізичних концепцій до теорії і практики викладання інженерної механіки для студентів молодших і старших курсів, які спеціалізуються у сферах динаміки і керування піднімально-транспортними машинами, в рамках широкого використання відкритого програмного забезпечення. Результати дослідження, концепції та методики представленої роботи знайшли практичне навчальне застосування шляхом формулювання практичних розрахунково-графічних завдань, постановки завдань для курсового і дипломного проектування у навчальних програмах студентів бакалаврату і магістратури Донбаської державної машинобудівної академії, Краматорськ, Україна.

Ключові слова: Фуко-подібні системи; викладання інженерної механіки; JModelica.org та Optimica відкрите програмне забезпечення; кероване обертання стріли крану; задача керування розгойдуванням вантажу з розімкненим контуром регулювання; акаузальне програмування.

ПРИМЕНЕНИЕ JMODELICA.ORG ДЛЯ ОБУЧЕНИЯ СТУДЕНТОВ ТЕХНИЧЕСКИХ ВУЗОВ ОСНОВАМ ДИНАМИКИ ФУКО-ПОДОБНЫХ УПРАВЛЯЕМЫХ СИСТЕМ

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Аннотация. Представленное образовательное исследование сосредоточено на решении дидактической задачи доступного для инженеров описания и разъяснения динамики и управления Фуко-подобными маятниковыми системами, которые возникают из практических задач динамики стреловых кранов в подъёмно-транспортном машиностроении и транспорте. Образовательная значимость представленного исследования основывается на отсутствии надлежащего описания и истолкования данной темы в известных учебниках и научных публикациях в сферах классической механики, инженерии управляемых систем, транспорта, подъёмно-транспортного машиностроения, инженерного образования, преподавания инженерной механики и преподавания классической механики. Среди образовательных инструментов данная статья использует следующие педагогические инструменты: Modelica-основанное моделирование в рамках применения акаузального открытого программного обеспечения JModelica.org с расширением Optimica, методы физического моделирования, аллегорическую сказочную аналогию, метод дидактической транспозиции и комплекс индивидуальных студенческих заданий при использовании вычислительных возможностей языка Modelica. Предложенный образовательный подход обеспечивает расширение студенческих представлений относительно применимости абстрактных физических концепций к теории и практике преподавания инженерной механики для младшекурсников и старшекурсников, специализирующихся в сферах динамики и управления подъёмно-транспортными машинами, в рамках широкого использования открытого программного обеспечения. Результаты исследования, концепции и методики данного исследования нашли практическое образовательное применение посредством формулировки практических расчетно-графических заданий, постановке заданий для курсового и дипломного проектирования в учебных программах студентов бакалаврата и магистратуры Донбасской государственной машиностроительной академии, Краматорск, Украина.

Ключевые слова: Фуко-подобные системы; преподавание инженерной механики; JModelica.org и Optimica открытое программное обеспечение; управляемое вращение стрелы крана; задача управления раскачиванием груза с разомкнутым контуром регулирования; акаузальное программирование.

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