USING GEOGEBRA SOFTWARE IN THE TEACHING OF OSCILLATORY MOTIONS

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Abstract. In this paper we present methods for creating interactive visual models, useful in the study of oscillatory motion. The teaching approach we propose is interdisciplinary and based on constructivist learning principles. We present ways in which students can build dynamic models and simulations using GeoGebra educational software. The aim is to form competencies in the area of Science, Mathematics and Technology. Within the proposed activities, the student will use and strengthen not just the knowledge of Physics, but also of Mathematics and Information Technology.

Key words: GeoGebra, oscillatory motion, modelling, interdisciplinary learning.

1. INTRODUCTION

The formation of basic competencies in Mathematics, Science and Technology is one of the priorities of current education policies. The shortages of qualified personnel in the field of Science, Technology, Engineering and Mathematics (STEM) involve the need to increase the motivation of young people to pursue careers in these fields [1]. Interdisciplinary approaches, creating learning situations similar to those the students will meet later in their professional activity, became mainstays in organising teaching activities. In this article, we present ways in which capabilities of the GeoGebra educational software can be exploited for the creation of mathematical and computerized models, dynamic and interactive, useful in the study of the oscillatory motions, to support in-depth understanding of the studied physical processes. The teaching approach is constructivist, students being guided to build themselves these models. The students have the opportunity to use and enhance their knowledge of Mathematics, Information Technology and Physics, in an integrated interdisciplinary educational process.

Understanding different aspects characteristic for oscillatory motion can be supported through the use of various educational softwares. Simulations and dynamic models of oscillatory phenomena can be achieved using Flash [2, 3], and the resulting applications can be made available online. There are also frequently used spreadsheets created in Excel [4], soft which highlights the correlations between physical laws expressed in mathematical language and their graphical representations. A less used work environment in Physics lessons is the educational software GeoGebra, which combines the advantages of interactive simulations made in Flash with the mathematical facilities of spreadsheets. This software, available free for educational purposes, allows the creation of dynamic, interactive models and simulations, even by students, without requiring programming skills. The knowledge of Mathematics at high school level and the ability to use a software application with a graphical user interface are enough. The models created by students under the guidance of the teacher, can be shared by *GeoGebra Tube* and can be accessed online. The advantage of using GeoGebra comes from the ease of obtaining the wanted models and simulations, forming simultaneously competence in Mathematics, Sciences and Information Technology, through a unified approach. The interdisciplinary approach is a necessity in order to prepare students for scientific modeling complex tasks required in the STEM professions. Preparing teachers of Mathematics, Science and Information Technology to address interdisciplinary topics should be considered a priority, given that the current textbooks and lessons include very few such applications [5].

1.1. LEARNING BY BUILDING MODELS

Forming the correct mental representations of physical systems and processes is essential for the training of students' competences in science. Although the modeling activity is an indispensable component in the work of scientific research, it is too little used by students in the study of Physics [6]. Involving students in the scientific modeling game [7] can stimulate creativity, facilitating the formation of connections between the knowledge acquired in various disciplines of study. Combining the study of Mathematics and Physics with the use of Information Technologies provides the optimal context in which students can build models and simulations of physical phenomena studied [8–14].

Computer models have a special position amongst various other types of models that may be used in the learning process [15–17]. They can provide a high degree of interactivity, allowing selective views, focusing successively on different components and features of the considered systems. At the same time, through the involvement of students in the construction of these models, using the existing information technology, is favoured the formation of computational thinking [18], one of the important components in the education of young people in the 21st

century, in particular those who will opt for a career in Science, Technology, Engineering and Mathematics.

1.2. BUILDING INTERACTIVE MODELS IN GEOGEBRA

The GeoGebra educational software combines the features of a Dynamic Geometry System (DGS) with those of a Computer Algebra System (CAS). It allows multiple representations and highlights links between Algebra and Geometry [19]. GeoGebra presents simultaneously and synchronized in two separate panels, both algebraic and the geometric representation of various mathematical concepts studied.

Over the years, GeoGebra has been enhanced by the contribution of large teams of programmers, so it can be used as well for the development of models and simulations of physical phenomena, or to formulate real-life problems [20–22]. GeoGebra allows the creation of interactive worksheets that can be uploaded to www.geogebratube.org, being then accessible to anyone, anywhere. GeoGebra is a valuable teaching resource available as Open Source, which can support in-depth understanding of scientific concepts. Unfortunately, the huge potential of the application is too little harnessed by an effective use in the classroom.

Informing practitioner teachers about the capabilities of the GeoGebra software, training teachers to use this software and the development of appropriate educational content are the objectives of GeoGebra user communities, existing at this time in dozens of countries.

The teaching strategies based on integrating the GeoGebra software in learning aim to develop students' abilities to solve problems, develop critical thinking, form an adequate attitude to scientific knowledge, confidence in the usefulness and applicability of mathematical and scientific knowledge in solving real life problems.

Interactive applets created with GeoGebra will provide a more accurate representation of the physical phenomena than static images or textual descriptions, facilitating in-depth understanding of abstract scientific concepts. Applets can be run in any browser, simulating real-world experiments and allowing the modification of the parameters that characterize the system. The student will be challenged to make predictions about the evolution of the system and then verify their reasoning's correctness.

2. ELASTIC PENDULUM – MODELING IN GEOGEBRA

The construction of visual and dynamic models of the elastic pendulum can be performed in GeoGebra, through the combined use of graphic and algebraic representation. We present several ways, in a methodical approach from simple to

complex, for the representation of the horizontal and vertical elastic pendulum, to simulate simple or compound oscillatory motions. The developed models will enable understanding the effect of modifying the system parameters' values both for simple oscillatory motion and the motion obtained by the composition of parallel or perpendicular harmonic oscillations.

2.1. SIMULATING THE OSCILLATORY MOVEMENT OF A SPRING

For the graphical and dynamic construction of a first model of an elastic horizontal pendulum, we use four independent numeric variables a, b, n, m, with the following meanings:
- the points $A(a,0)$ and $B(b,0)$ represent the extremities of the spring;
- n is the number of turns of the spring (positive integer);
- m is the radius of a loop of the spring (positive rational number)).

The spring's image will be created using a function of the form:

$$f(x) = m \sin(px + q). \tag{1}$$

The value of parameter p will be determined by imposing the condition that between points A and B to be exactly n periods (n turns of the spring), and the parameter q will be determined by imposing the condition that the graph of the function f, given by relation (1), contains the point A. Thus, the equalities

$$b - a = n \cdot \frac{2\pi}{p} \quad \text{and} \quad f(a) = 0 \tag{2}$$

lead us to:

$$p = \frac{2n\pi}{b-a}, \text{ respectively } q = -pa. \tag{3}$$

Considering the relations (1) and (3), in the input bar of GeoGebra we introduce successively the following commands:

a = 0   (creating a variable a, with initial value 0);
A = (a,0)   (represent point $A(a, 0)$ in the graph panel);
b = 5   (creating a variable b, with initial value 5);
B = (b,0)   (represent point $B(b,0)$ in the graph panel);
n = 5   (creating a variable n, with initial value 5);
m = 0.5   (creating a variable m, with initial value 0.5);
p = 2 n π / (b–a)   (defines the graphic parameter p);
q = − p a   (defines the graphic parameter q);
Curve[u, m sin(q + p u), u, a, b]   (plot a sinusoid with amplitude m, between points A and B, containing n periods).

Each of the independent variables *a*, *b*, *n*, *m* is associated with a slider, which allows us to change their values through the graphic panel of the application. The associated sliders can be seen simply by selecting the visibility buttons on the algebraic panel of the app. The result is shown in Fig. 1.
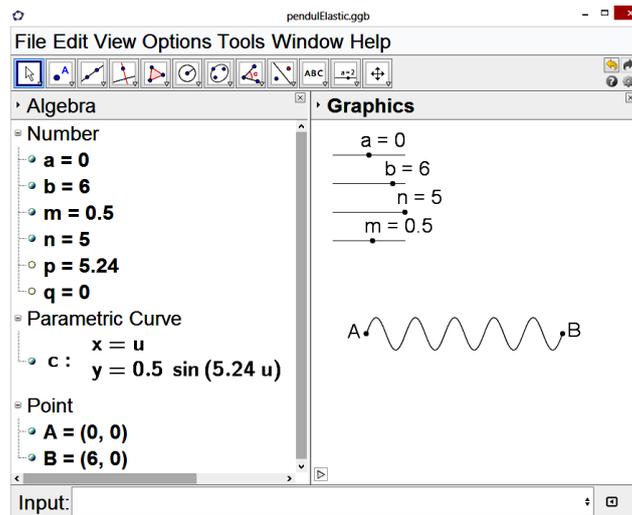

Fig. 1 – The graphic representation of the spring. The colored versions can be accessed at http://www.infim.ro/rrp/.

In the *Properties* window of the variable *b* we will set its extreme values and we start the animation for this variable, in oscillating style (Fig. 2). As a result, point *B*(*b*,0) will start an oscillatory movement and the sinusoidal *AB* will deform properly.
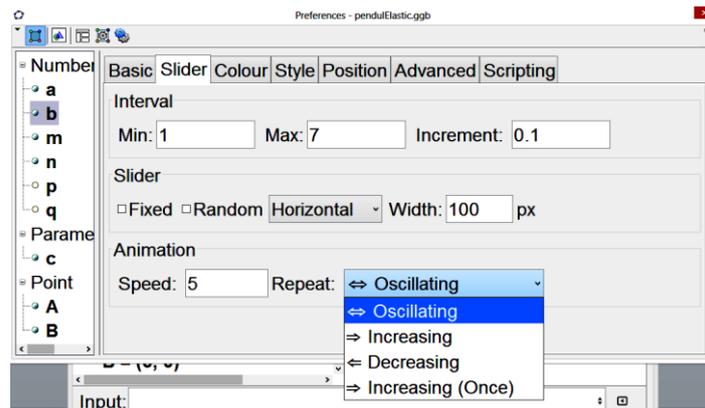

Fig. 2 – Setting animation parameters. The colored versions can be accessed at http://www.infim.ro/rrp/.

2.2. HARMONIC OSCILLATORY MOTION SIMULATION

The movement of end *B* of the spring in the above construction is oscillatory but is not harmonic, the velocity of the point *B* remains constant in absolute value and changes its sense. In order to achieve a harmonic oscillatory motion, we introduce point *D* as an auxiliary element. This point will run uniformly on a circle with radius equal to the amplitude of the oscillation, and the abscissa of the mobile extremity *B* of the spring will be, by definition, equal to the abscissa of the mobile point *D* on the circle.

We introduce two new independent variables, *l* and *r*, representing the length of the nondeformed spring and the oscillation amplitude, and then we will display the sliders associated with these variables. Using these sliders, the values of the independent variables *l* and *r* can be modified from the graphic panel of the app. Point *A* will remain fixed, with abscissa $a = 0$.

In the input bar we will introduce successively the following commands:

l = 4   (creates variable *l*, the length of undeformed spring);
r = 3   (creates variable *r*, representing the amplitude of the
                      oscillation);
C = (1 , 0)   (creates point *C (l, 0),* the equilibrium position for the extremity
                      B of the spring);
d = Circle[C, r]   (creates circle *d* with center at *C* and radius *r*);
D = Point[d]   (creates a point *D* on the circle *d*);
b = x(D)   (variable *b* takes dynamically the abscissa of point *D*).

We start the animation on the circle *d* for the point *D* and we see that point *B* moves along with it (Fig. 3). The auxiliary ellements, the circle *d* and the points *C* and *D*, may finally be set to invisible by unchecking their associated visibility buttons in the algebraic panel of the application.

For consistency of graphical representation, we impose the condition $1 \leq r \leq l-1$. In order to achieve the full representation of a horizontal elastic pendulum (Fig. 4), we introduce two new variables *h* and *w*, representing the height and width of a rectangular body, attached to the mobile extremity *B* of the spring and we will build the rectangle with these dimensions, by entering successively the following commands: E = (x(B), y(B) + h / 2); F = (x(B), y(B) − h / 2); G = (x(B)+w, y(B)+h/2); H = (x(B)+w, y(B)–h/2); Polygon[E, G, H, F].

Once we choose a convenient visual representation, the place of the graphic parameters can be taken by the physical parameters of the pendulum: the mass of the attached body and the elasticity constant of the spring. The running speed of the auxiliary point *D* on the circle will be set in the *Properties* window through the relation $\omega = \sqrt{k/m}$.
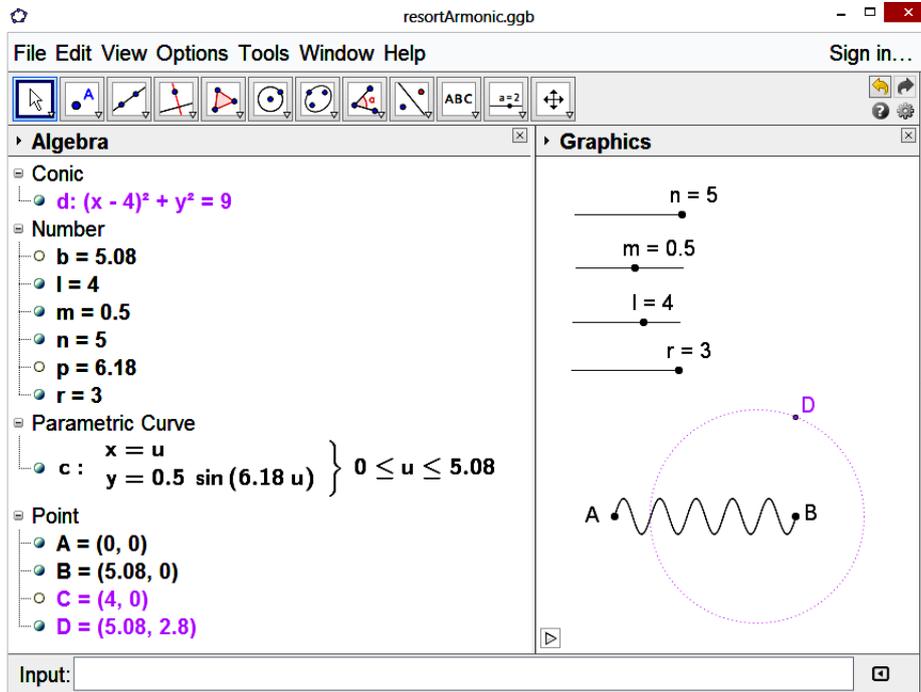
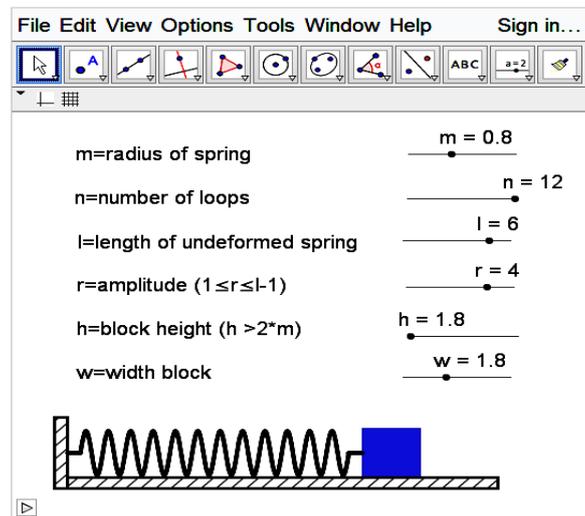Fig. 3 – The simulation of harmonic oscillatory movement. The colored versions can be accessed at http://www.infim.ro/rrp/.

Fig. 4 – The horizontal elastic pendulum. The colored versions can be accessed at http://www.infim.ro/rrp/.

2.3. COMPOSITION OF PERPENDICULAR OSCILLATIONS

An interesting application that can be created with GeoGebra using mathematical knowledge of students is the simulation of the motion of a material point D subjected simultaneously to two elastic forces on perpendicular directions. To visualize the movement of point D and its trajectory, we introduce in the input bar the following commands:

Command/ Range of values	Significance
a = 2, 1≤a≤4	The amplitude of the oscillation parallel to Ox axis
b = 2, 1≤b≤4	The amplitude of the oscillation parallel to Oy axis
u = 2, u∈[1,20]∩ℕ	Angular frequence of the oscillation parallel to Ox
v = 3, v∈[1,20]∩ℕ	Angular frequence of the oscillation parallel to Oy
f = 0, f∈[−5,5]	The initial phase of the oscillation parallel to Ox
g = 0, g∈[−5.5]	The initial phase of the oscillation parallel to Oy
t = 0, t∈[0,2π]	Time parameter for the generated motion
D = (a cos(ut+f), b cos(vt+g))	The position of point D at time t
Curve [a cos(ut+f), b cos(vt+g), t, 0, 2π]	Display the trajectory of point D

In order to simplify this representation, the pulsations values u and v are integers, such that a common period of the composed oscillations to be $T = 2\pi$, a common multiple of the periods of the two oscillations, $2\pi/u$, respectively $2\pi/v$.
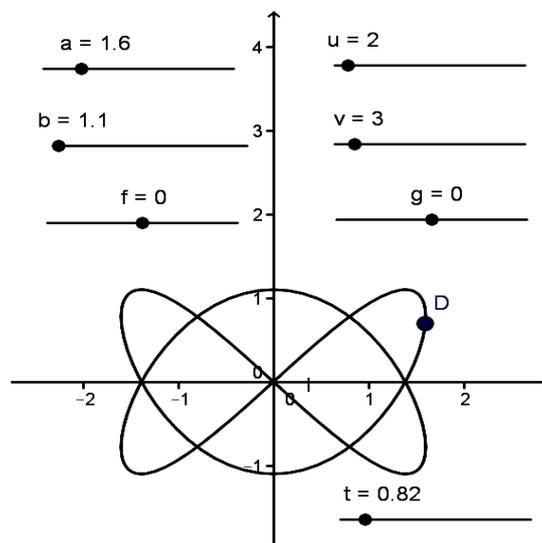

Fig. 5 – Composition of perpendicular oscillations. The colored versions can be accessed at http://www.infim.ro/rrp/.

By setting the range of values for the variable t in the interval $[0, 2\pi]$ it is achieved the closure of the Lissajoux curve (Fig. 6), and when the animation of point D is started, the curve will be covered completely and fluently.

Using sliders associated with variables a, b, u, v, f and g, we can change amplitudes, angular frequencies and initial phases of the two oscillations which are composed and we can see the effect on the shape of the generated trajectory. We will also represent graphically the two springs, acting with elastic forces parallel to the coordinate axes. The ends of the springs are fixed points $A(a1, 0)$, $a1 = -a - 2$, for the spring with elastic force acting parallel to the y-axis and $B(0, b1)$, $b1 = -b - 2$, for the spring with elastic force acting parallel to the x-axis. Point D will be attached to the mobile ends of the two springs. We define the following variables required for the graphical representation of the springs:

n1 = 10	(number of turns of the first spring);
n2 = 10	(number of turns of the second spring);
r1 = AD	(variable length of the first spring);
r2 = BD	(variable length of the second spring);
p1 = 2 n1 π / r1	(parameter p of the first spring);
q1 = − p1 a1	(parameter q of the first spring);
p2 = 2 n2 π / r2	(parameter p of the second spring);
q2 = − p2 b1	(parameter q of the second spring).

To the horizontal sinusoidal representing the spring with fixed end point A, with the parametric equations

$$\begin{cases} x = s \\ y = m \sin(p1\ s + q1) \end{cases}, \ s \in [a1, a1 + r1], \tag{4}$$

we will apply a rotation with the center A and the angle

$$\theta_1 = atan\left(\frac{yD - yA}{xD - xA}\right), \tag{5}$$

such that the mobile end of the spring will move along with point D.

The equation with matrices of this rotation is:

$$\begin{pmatrix} x1 - xA \\ y1 - yA \end{pmatrix} = \begin{pmatrix} \cos\theta1 & -\sin\theta1 \\ \sin\theta1 & \cos\theta1 \end{pmatrix} \begin{pmatrix} x - xA \\ y - yA \end{pmatrix}, \tag{6}$$

such that, considering the relations (4) and (6), we will obtain the parametric equations of the sinusoid rotated with angle $\theta1$:

$$\begin{cases} x1 = xA + (s - xA)\cos\theta1 - (m\sin(p1\ s + q1) - yA)\sin\theta1 \\ y1 = yA + (s - xA)\sin\theta1 + (m\sin(p1\ s + q1) - yA)\cos\theta1 \end{cases}. \tag{7}$$

Similarly, to the vertical sinusoidal representing the spring with fixed end in point B, with the parametric equations

$$\begin{cases} x = m \sin(p2\,s + q2) \\ \quad\quad y = s \end{cases}, \; s \in [b1, b1 + r2]$$ (8)

we will apply a rotation with the center B and the angle

$$\theta_2 = atan\left(-\frac{xD - xB}{yD - yB}\right),$$ (9)

such that the mobile end of the second spring also moves along with point D. Considering the relations (6) and (8), the parametric equations of the second sinusoidal rotated with angle $\theta 2$ are:

$$\begin{cases} x1 = xB + (m \sin(p2\,s + q2) - xB) \cos\theta2 \; - (s - yB) \sin\theta2 \\ y1 = yB + (m \sin(p2\,s + q2) - xB) \sin\theta2 + (s - yB)\cos\theta2 \end{cases}.$$ (10)
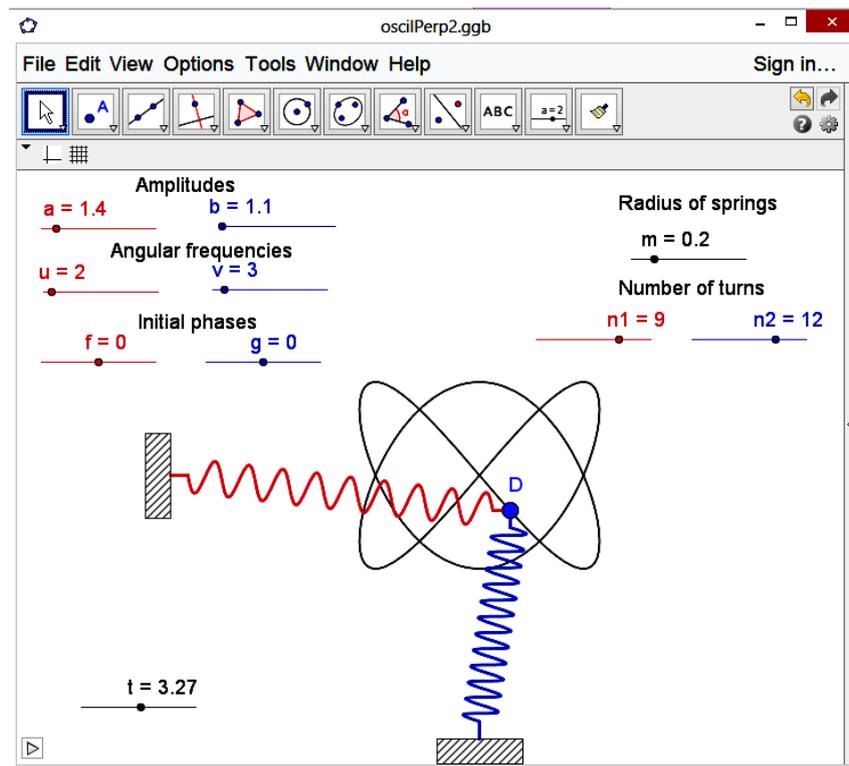

Fig. 6 – Generator of Lissajoux figures created with GeoGebra.
The colored versions can be accessed at http://www.infim.ro/rrp/.

In according with the relations (7) and (10), in the input bar we will introduce the commands:

- Curve[a1+(s – a1)cos(θ1) –m sin(p1 s + q1)sin(θ1), sin(θ1)(s–a1) + + m sin(p1 s + q1) cos(θ1), s, a1, a1 + r1];
- Curve[m sin(p2 s + q2) cos(θ2) – (s – b1) sin(θ2), b1 + m sin(p2 s + q2) sin(θ2) + (s – b1) cos(θ2), s, b1, b1 + r2].

The considered independent variables are associated with sliders that will allow changing their values, even from the graphic panel of the application (Fig. 7). To view the movement obtained by composing the two oscillations, in the *Properties* window of the numeric variable *t*, we will start the animation for the time parameter and we will set conveniently the parameters of the animation. For example, we choose for the animation speed the value of 0.8 and for the increment step the value 0.01. Also, we set the animation to be ascending.

2.4. SPRINGS CONNECTED IN PARALLEL

Another possible use of GeoGebra is to create interactive worksheets that present different situations in a problematized manner. As an example, we created two different simulations for the motion of two springs connected in parallel and students were asked to determine which the correct version is. For the first simulation we assume that the resulting motion is obtained by composing two oscillations of the same direction, each characteristic for one of the two springs. Since the elasticity constants of the two springs were chosen with close values, the superposition of the two oscillations would generate a phenomenon called "beats", simulated by our animation (Fig. 5). The independent variables used were the amplitude *a*, the initial phase φ, the mass *m* of the attached block, the elasticity constants of the two springs, $k1$ and $k2$ and the variables $n1$ and $n2$ representing the number of turns of the two springs.

GeoGebra offers the possibility to use two graphic panels: in the first we achieved the simulation of the motion of the block which is subjected to the two parallel elastic forces, and in the second we plotted the temporal dependencies of the displacement produced by the two elastic forces when acting independently and when the oscillations are composed (Fig. 5).

Using the input bar we defined the independent variables mentioned above and we displayed on the first panel the associated sliders. Then we defined the functions describing temporal variations of displacements for the three cases considered: $f(x) = a \sin(\omega 1\, x + \varphi), \quad g(x) = a \sin(\omega 2\, x + \varphi), \quad h(x) = f(x) + g(x)$ and we plotted them in the second panel.
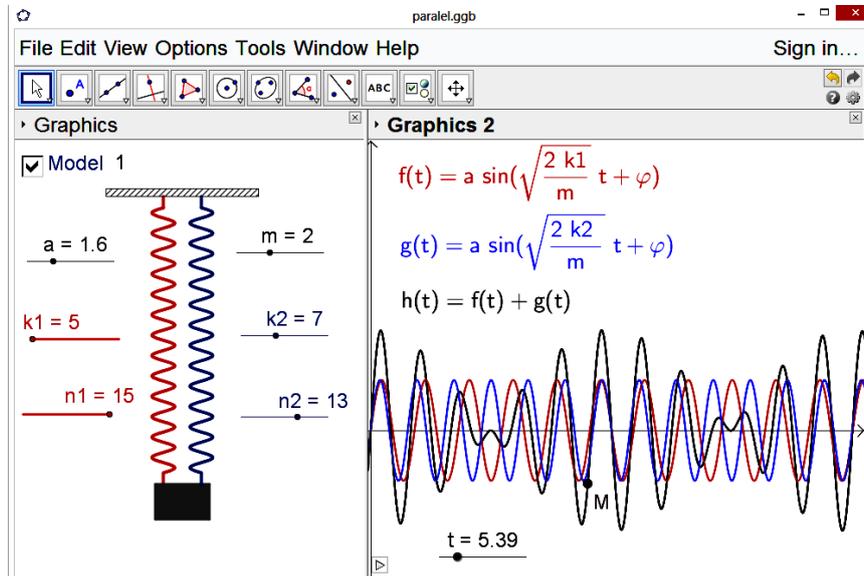
Fig. 7 – Springs connected in parallel. Model 1. The colored versions can be accessed at http://www.infim.ro/rrp/.

In the first panel we represented the two springs, with the fix extremities in points A and C and with the mobile ends in the points B, respectively D. To define the position and graphical representations of the springs, we introduce the following commands:

- ✓ $t = 0$, $0 \le t \le 200\,\pi$ (time parameter, with step increment 0.01)
- ✓ $yA = a1 + a2 + 2$; $yB = a\sin(\omega1\,t + \varphi) + a\sin(\omega2\,t + \varphi)$
- ✓ $A = (-0.5, yA)$; $C = (0.5, yA)$; $B = (-0.5, yB)$; $D = (0.5, yB)$; $r = AB$;
- ✓ $p1 = 2n1\,\pi\,/\,r$; $p2 = 2n2\,\pi\,/\,r$; $q1 = -p1\,yA$; $q2 = -p2\,yA$; $m = 0.5$;
- ✓ Curve[$m\sin(p1\,s + q1) - 0.5$, s, s, yB, yA];
- ✓ Curve[$-m\sin(p2\,s + q2) + 0.5$, s, s, yB, yA].

The main periods of the two component motions are $2\pi/\omega1$, respectively $2\pi/\omega2$. Since in the present case we have $\omega1 = s1/100$ and $\omega2 = s2/100$, where $s1$ and $s2$ are integers, it follows that $T = 200\pi$ is a common period of the two oscillations, so it is also a period for the oscillation resulted from the composition. For this reason, for the continuity of the movement in the simulation, when we start up the animation of temporal variable t, the range of values for t has been set to the interval $[0, 200\pi]$. If the two oscillations which are composed have equal amplitudes, then the elongation of the superposed movement, $h(t) = f(t) + g(t)$, can be rewritten as

$$h(t) = 2a\cos\left(\frac{\omega1-\omega2}{2}t + \frac{\varphi1-\varphi2}{2}\right)\cos\left(\frac{\omega1+\omega2}{2}t + \frac{\varphi1+\varphi2}{2}\right). \qquad (11)$$

If the angular frequencies $\omega 1$ and $\omega 2$ have close values, there is the phenomenon called *beats*, with the principal period equal to $\dfrac{2\pi}{\omega 1 - \omega 2}$. The graph of function

$$h1(t) = 2a \cos\left(\frac{\omega 1 - \omega 2}{2}t + \frac{\varphi 1 - \varphi 2}{2}\right) \tag{12}$$

wrap around the graph of the function h given by the relation (11). The function $h1$ given by the relation (12) describes the variation of the amplitude of the oscillation over the time.
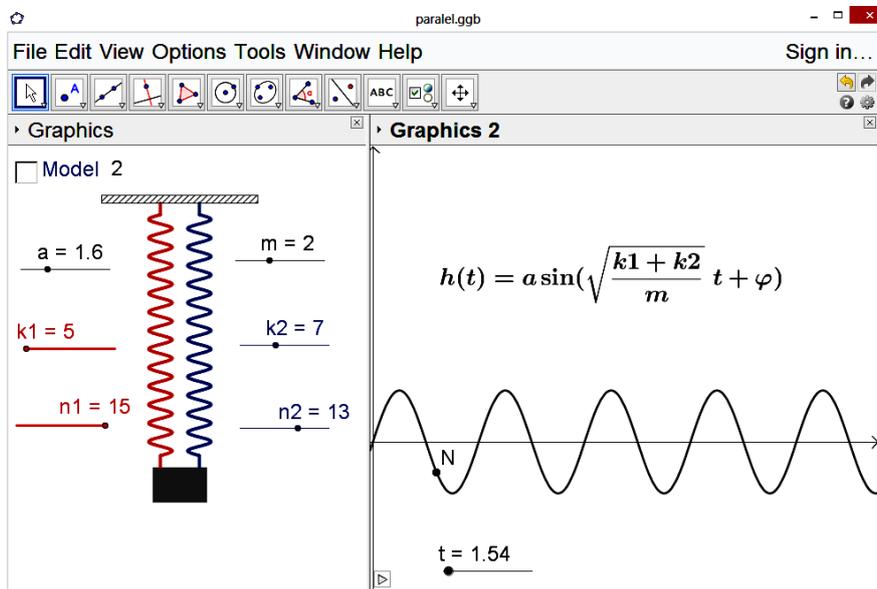

Fig. 8 – Springs connected in parallel. Model 2. The colored versions can be accessed at http://www.infim.ro/rrp/.

The second model that we asked students to analyze considers that the resultant force acting on the block is $F = -k1\,x - k2\,x = -(k1 + k2)\,x$, and then resulting movement is the same as in the case of a pendulum with a single spring, with elastic constant $k1 + k2$, so that we have a simple harmonic oscillatory motion (Fig. 8). The simulation of the movement was performed as in the previous model, but the command yB = a sin($\omega 1\ t$ + φ) + a sin($\omega 2\ t$ + φ) was replaced by yB = = a sin($\omega\ t$ + φ), where the angular frequency ω is defined by command ω = = sqrt(($k1+k2$)/m).

Both versions were included in the same worksheet, being displayed succesively by checking / unchecking the checkbox button in the first panel of the

worksheet (Fig. 7 and Fig. 8). The correct version will be chosen by the students after analyzing the two variants and discussing them in small working groups. The presented problem-solving situation, through the inclusion of two alternative simulations, obliges the student to discuss, to argue, and finally to understand correctly the movement of the considered physical system. Creating problematized learning situations helps the students to develop critical thinking, reasoning capacity and investigation.

3. CONCLUSIONS

The GeoGebra educational software is a valuable teaching resource, which can be used to create interactive, dynamic models, useful in the study of physical phenomena. The versatility of the software is high, and the models can be created in a variety of ways, even by students, under the guidance of a teacher. Introduction to the learning process of activities of modeling of real phenomena increases students' creativity, facilitates the formation of connections between different areas of knowledge, developing simultaneously competencies in Science, Mathematics and Information Technology.

Interdisciplinarity, seen as an increase of the permeability of the borders between different school disciplines, provides a favourable context for creating motivating learning situations, more closely to those the students will encounter later in their professional activity.

The proposed activities will take into account the principles of constructivist method in learning. Students can build models themselves, working in teams and using the mathematical knowledge acquired in the ninth grade. The work tasks are assigned to groups of students, beginning with the simplest, then increasing gradually the degree of difficulty. First, it is proposed the construction of a spring model, using known properties of the sine function. In the first example, 2.1, the oscillatory movement of one of the extremities of the spring was accomplished by starting the animation in the oscillating style, using the *Properties* dialog window. In the second example, 2.2, harmonic oscillatory motion was generated by the projection on the *x*-axis of a point that moves uniformly on a circle. The two simulations may be included in the same worksheet, in two separate graphic panels, in order to be compared easily.

In Section 2.3 we present a GeoGebra construction of a Lissajous figures generator, using only its parametric equations. The angular frequencies of the two oscillations that overlay can be modified from the graphic panel of the application, by using the associated sliders. On the generated curve was built a point whose animation simulates its cyclical movement. Students who have more advanced mathematical skills can complete this model with the two springs that oscillate along of two perpendicular directions. To represent these springs we can use the

transformation of coordinates of a point in plane by a rotation with center and angle given.

In section 2.4 we propose two different models for the oscillatory motion of a pendulum with two springs with distinct elasticity constants, connected in parallel. The first model is based on the assumption that the movement of the block is the result of the superposition of the two oscillatory movements obtained if the two springs act independently, and so the phenomenon of *beats* occurs. The second model is based on the fact that the resultant force is itself an elastic force, and the system is equivalent to a simple pendulum with a single spring with the elasticity constant equal to $k1+k2$. Therefore, the movement obtained is a simple harmonic oscillation. Students are asked to indicate which of the two models corresponds to reality, bringing physical arguments. It is very important that students understand that models are just surrogates of real systems, they approximate the actual processes and always have limitations. The experiments and the study of the models are complementary activities that reinforce each other.

Models, simulations and virtual experiments created using the mathematical educational software GeoGebra provides an important intuitive support in the study of oscillatory motion and also initiates students in the use of instruments and methods specific for knowledge and scientific research. Ways to use GeoGebra in order to deepen knowledge of Physics are various: students can create their own models of the studied systems, or use the worksheets created by the teacher, with concrete tasks, loaded on *GeoGebra Tube* and available online. The objectives are the development of critical thinking and the ability to justify with scientific arguments, as well as the development of mathematical skills applied in different contexts, with the integration of the technologies that we are now at fingertips. The ability to use these technologies becomes one of the key components in the pedagogical training of teachers of Science.

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