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An analysis of rope tension forces while towing a sailplane

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Abstract

This article presents a model of a rope, which is an example of a rope used when a glider takes off by means of towing with the use of an aerial winch, winding the rope attached to the glider. The finite element method used in MESH software was used for the model. This method allows us to take into account not only bending flexibility but also longitudinal flexibility. Such an approach to the subject of simulation allows for obtaining results relatively quickly while maintaining an appropriate level of accuracy. This allows for further exploration of the phenomena occurring in the glider towing process. The construction of a fast algorithm enables its implementation in the glider towing process control systems. The aim of this article is to present numerical analyzes of commonly used tow ropes. This paper presents the results of the analysis of the synthetic rope commonly used in gliding, comparing the obtained results with the classic steel rope.

Keywords: glider, Winch, Launches, Rope, Aviation Safety.

1. Introduction

Gliders, as flying structures, are characterized by the lack of their own propulsion enabling the take-off itself, and when already in the air, they maintain themselves by taking advantage of favorable weather conditions by performing a gliding flight. When delving into the subject of gliding, it is impossible to meet the most popular way of taking off, which is taking off with an aerial winch. In this process, I use the effect of accelerating the glider (and, at the same time, allowing it to take off) by winding a rope attached to the fuselage. By giving it the appropriate speed, the generated aerodynamic force allows the sailplane to take off into the air and then, after releasing, to conduct a free flight (Pazio, Winczo, 1985, EASA 2020). When analyzing this process, particular attention should be paid to the accompanying phenomena (Abłamowicz, Nowakowski, 1980). Among other things, phenomena related to the towing ropes used. Therefore, for this purpose, in this study, the distribution of forces and moments on the glider was analyzed. Then, using MESH software, the course of the glider take-off process behind the winch was simulated (Gibson, 1985, Gibson, 2009). In the literature, several approaches to the subject may be found. Already in 1987, in an article entitled (U. König's, 1987) "Theorie des Windenstarts", the author comprehensively describes the winch take-off analysis. In many other studies, the authors presented their approach to the described issue, focusing their efforts on the set goals, different for individual studies, using some of the variables influencing the course of the start-up process depending on current needs. The main aim is to present a comparative analysis of those commonly used in towing gliders with the use of aerial winches. In this study, we will focus on the possibility of using analyzes by simulating the physical properties of commonly used steel and synthetic ropes. The next step was to carry out subsequent iterations of the project towards building a lightweight algorithm that uses the minimum amount of data but maintains a satisfactory level of obtained results.

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2. Description of the individual elements of sailplane towing.

The process of taking off gliders behind the winch as an air operation is systematized by a number of legal norms. However, they are loose provisions regulating the general outline of the entire process. Despite the existing regulations, there is room for one's "own" interpretation of carrying out the hauling process itself.

As long as the main safety procedures are followed the towing speed, control of the maximum line pull force, rope length, and the components of the tow set, the same approach to the course of the individual take-off phases may differ depending on the persons involved in the process (Browning, 2006).

Both the winch operator and the glider pilot have an influence on the towing process. These differences are due to the following:

- technical factors: the use of various equipment, such as winches, gliders, or various airport aprons;
- human factors: acquired habits, transfer of habits during training;
- weather conditions: weather conditions have a key influence on the take-off of gliders.

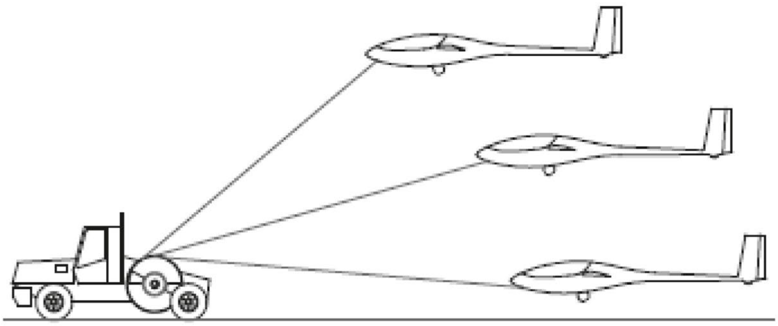

Figure 1. Winch – Rope – Glider set
Source: own materials.

The visualization of the process is presented in Figure1 above, which additionally presents the three key phases of the glider take-off behind the winch.

a. Glider winch

In practical applications for towing gliders with the winch method, dedicated devices that usually use internal combustion engines (electrically powered structures are becoming increasingly common) are employed to wind a rope or multiple ropes in multi-drum constructions. These are both stationary and self-propelled devices, facilitating airport organization. However, they constitute a stationary structure during proper operation, winding the rope with the sailplane attached to the drum. The drive transmission poses a major problem for the winch operator because the non-linear characteristics of the power and torque diagram of the motor

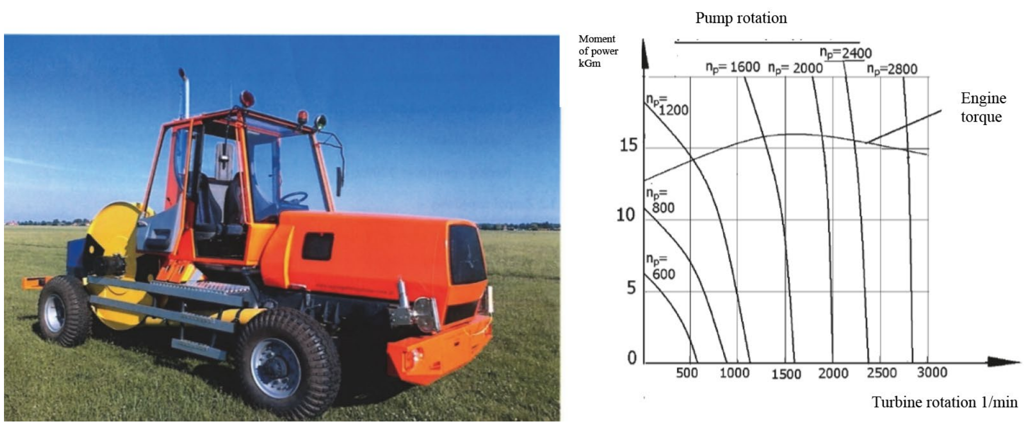

Figure 2. WS-02-JK glider winch and characteristics of the torque converter used
Source: (Leśniak, 1961).

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used are additionally overlapped with another non-linear characteristic related to the element used for transmitting power to the drums. See the figure below.

The presented winch is a series-produced winch of Polish design. It is commonly used in sailplane units and usually in the case of sailplane pilotage courses due to the low cost of a single tow, which is many times less than the tow behind the plane. These winches have the following basic parameters:

- power: 270 HP,
- weight: 700 kg,
- drive transmission to the drums: fluid coupling.

The above data was used for implementing the software during numerical analysis as base constants.

b. Rope

Another element involved in towing is the towing rope. The rope is responsible for transferring the power generated by the winch motor to the sailplane. This process is carried out by winding it up and "pulling" the glider, thus at a speed that allows the glider to take off.

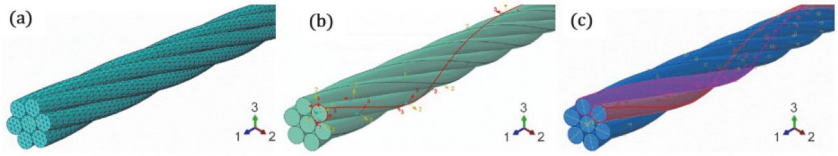

Figure 3. 3D1 models of the CFRP rope: (a) a mesh with 8-node tetrahedral elements, (b) a description of the material orientation (fiber axis) along the length of the helix, and (c) highlighting one of the 12 pairs

Source: (Bere, Neamtu, Udroiu, 2022).

Many types of ropes can be distinguished; however, in practice, for towing gliders, interlaced steel and synthetic ropes are usually used. Source: own materials

The complexity of analyzing the behavior of individual types of ropes is really considerable. Therefore, the method presented in the study (Bere, Neamtu, Udroiu, 2022) will be used for the analysis. The winch presented above allows for winding up to 3500 m of towing rope. In practice, additional equipment is used to ensure the functionality of the tow rope. A typical set of accessories is presented in the photo below:

In addition to the rope, the kit includes the following:

- Parachute: it is responsible for slowing down the descent of the set after the glider detaches and has a positive visual role, making it easier to find the end of the rope after falling to the ground;
- Mechanical fuse: protects the sailplane and the rope against excessive forces;
- Mounting shackles and chains: mechanical elements that enable the correct assembly of the rope.

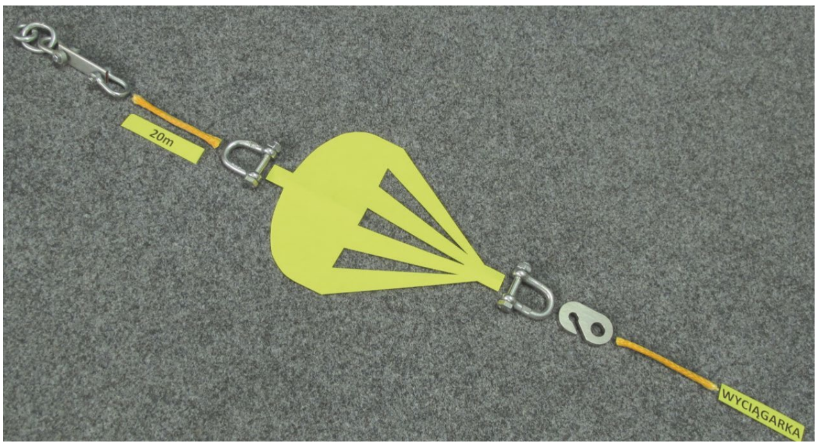

Figure 4. Diagram of the tow rope set

Source: own materials.

As part of the analyzes, the connection diagram and the impact of individual elements were simplified – including mainly the impact of the parachute, due to the negligible value on the final result.

The commonly used DYNALAUNCH synthetic rope with the following parameters was selected for the simulation:

- diameter 5 mm
- breaking load of 22 kN
- weight 1.18 kg / 100m
- 100% Dyneema
- UV resistant

c. Glider

From the functional point of view, the most important element of the system is the towed sailplane. In addition, the end result of the entire towing process is that it is placed at the appropriate height to continue free flight safely. According to the nomenclature, gliders do not have their own propulsion; therefore, they rely on external devices to take off from the ground. In the case under consideration, it is an aerial winch. For the purposes of the analyzes, a domestic production glider, PZL KR-03 Puchatek, was selected. The glider has two places in the cabin and is intended for basic training. Due to its popularity, it is often used in gliding schools. It is the only Polish metal glider produced in post-war Poland, characterized by the following parameters:

- Max perfection: 27;
- Bearing area: 19.44 m^2;
- Sash profile: FX S 02 / 1-158;
- Permissible speed: 200 km / h;
- Towing speed: 95 – 130 km / h;
- Span: 16.40 m;
- Weight: Own: 335 kg, Starting weight: 540 kg;
- Towing speed: 95 – 130 km / h.

Figure 5. PZL KR-03 Puchatek
Source: own materials.

This model was chosen due to its popularity of this model. Despite its relatively old age, it can be found at almost every glider training point, where it is often the base of machines on which flying adepts take their first steps in aviation.

The above parameters were taken into account when creating the model in the further part of the study in such a way that the obtained results reflect the physical parameters of the commonly used models of sailplane construction from the above photo.

3. Analytical analysis of the distribution of forces

In practice, during the take-off behind the winch, the towing rope is attached to the sailplane at the front of the structure – the front hook (mainly used in the case of towing behind the plane) and in the lower part of the fuselage – the lower hook (usually used during take-off behind the winch). At the same time, it is more practical to use the lower hitch due to the changes in the angle of the towing rope to the flight path of the sailplane. However, at the beginning, the general distribution of forces during the launch of the

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glider behind the plane will be addressed. Namely, to visualize the issue, a symbolically sketched glider with the indicated acting forces in Figure 6 will be used. This situation shows the forces acting at the in-run stage, i.e.:

$\vec{S}$– force coming from the towing rope – parallel to the ground surface,
$\overrightarrow{P_X}$ – aerodynamic drag force,
$\vec{T}$ – the force of friction against the ground,
$\vec{Q}$ – sailplane weight,
$\vec{N}$ – substrate reaction,
$\overrightarrow{P_Z}$ – lifting force.

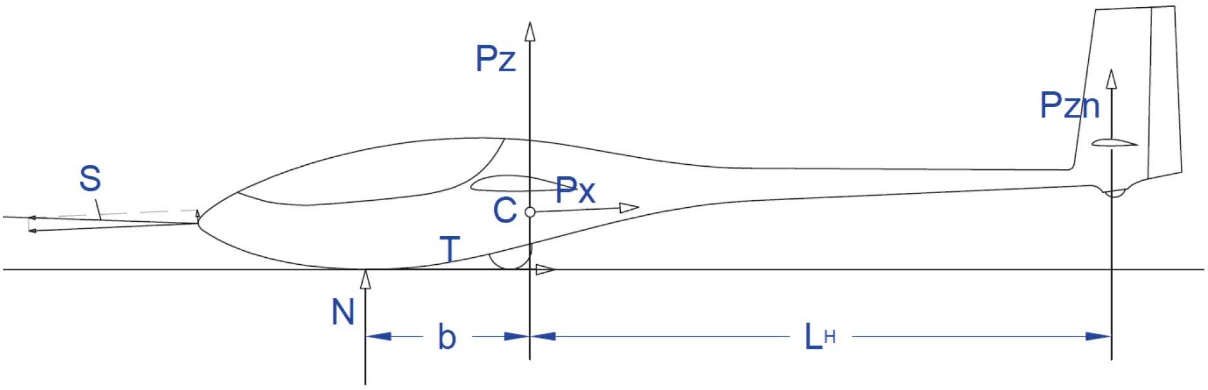

Figure 6. Distribution of the acting forces during take-offs
Source: own materials.

Due to the action of frictional forces and ground reactions, the torsional moments N · b and (T · h) are generated beyond the center of gravity of the sailplane. These moments, together with the moments generated from the rope tension force S and aerodynamic forces, are balanced by the moment of force generated at the tail of the height PH. We write down the equilibrium situations of forces and moments as:

$$\begin{cases} \vec{N} + \overrightarrow{P_z} + \overrightarrow{P_H} = \vec{Q} \\ \vec{S} = \overrightarrow{P_X} + \vec{T} \\ P_H I_H = \vec{N} b - \vec{T} h \end{cases} \tag{1}$$

where:
$\vec{T}$ – μN,
$\vec{N}$ – substrate reaction,
μ – chassis friction coefficient against the ground.

During the take-off to give an accelerated motion, the forces from the winch must exceed the other forces acting. The increase in speed causes an increase in the value of the aerodynamic forces of both the lift $\overrightarrow{PZ}$ and the aerodynamic drag force $\overrightarrow{PX}$, while the ground reaction forces $\vec{N}$ and friction $\vec{T}$ decrease. The key moment is leveling up and then exceeding the lift force over the weight of the sailplane because, at this point, the sailplane leaves the ground and the distribution of the acting forces changes to the form:

$$\begin{cases} \overrightarrow{P_z} + \overrightarrow{P_H} = \vec{Q} \\ \vec{S} = \overrightarrow{P_X} + \vec{T} \\ M = \overrightarrow{P_H} I_H \end{cases} \tag{2}$$

where:
M – moment introduced by forces whose line of action does not pass through the center of the mass of the sailplane at the moment it leaves the ground. This situation is presented visually in Figure 7.

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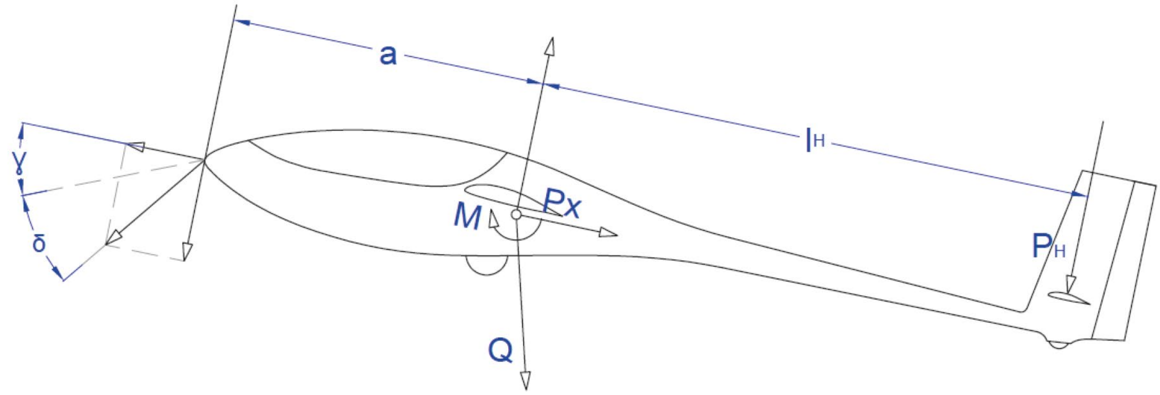

Figure 7. Distribution of forces during the take-off of the sailplane behind the winch, front catch
Source: own materials.

In this case, the distribution of the force resulting from pulling the rope S changes with the rope's height and degree of winding and the angle of the force components S1 and S2 that are formed. Only the component parallel to the ground surface contributes to the forward velocity v of the sailplane and is therefore desirable. On the other hand, the component S2 perpendicular to S1 has an unfavorable effect because it causes a suspension of the torsional moment directing the front of the sailplane towards the ground. This moment must be corrected by a suitable deflection of the elevator. An additional unfavorable effect is the need to reduce the rope's weight, forcing the necessity to generate a much greater lifting force than taking off behind the plane (Anderson, 2007). We obtain the equilibrium state by satisfying the following expression:

$$\begin{cases} \overrightarrow{P_z} = \vec{Q}cos\gamma + S_2 + \vec{P}_H \\ \overrightarrow{S_1} = \overrightarrow{P_X} + \vec{Q}sin\gamma \\ \overrightarrow{S_2}b = \overrightarrow{P_H}I_H \end{cases} \tag{2}$$

where:
$\overrightarrow{S_1}$ – horizontal force component $\vec{S}$,
$\overrightarrow{S_2}$ – vertical component of the force $\vec{S}$.

4. Description of the simulation

While modeling the occurring phenomena, the Abaqus environment was used. It is a dedicated MESH simulation environment enabling work in the graphic interface, which is a significant facilitation in relation to competitive solutions. For the analysis, the software in the educational version was used, offering satisfactory simulation possibilities, and enabling easy access to the appropriate results.

The sailplane model is presented as a point with assigned physical parameters corresponding to the construction parameters of KR 03 Puchatek to facilitate the interpretation of the results. The same was done with the winch, which was placed motionless on the base point. In order to give realistic results, appropriate physical parameters were simulated, consistent with real values. The analyses used the parameters of composite ropes. Its parameters were presented in the previous fragment of the text. The simulation results and the corresponding parameters of the steel rope are presented below with similar parameters. The results of the wire rope simulation were omitted in this study because they were the basis for assessing the correctness of the analyzes performed due to the availability of the results of this type of analysis. The following parameters were used for the rope, i.e., the main element under consideration:

- Young's Modulus: 1.2e11 [Pa]
- Shear Modulus: 1.36e9 [Pa]
- Density: 980 [kg / m ^ 3]
- Poisson's ratio: 0.33

The Abaqus software offers many types of analyzes. In our case, the finite element analysis was chosen, giving approximate results, but the results are satisfactory at this stage. The calculations were based on the rope length: 500m and the rope release

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angle: 60 degrees. The initial conditions adopted in this way make it possible to simulate the phenomena occurring during the take-off of the sailplane. The most interesting parameters are the rope deflection value, the so-called overhang. This effect reduces the towing efficiency as it ultimately changes the direction of the line tension vector on the sailplane. This effect can be reduced by increasing the rope tension force and the use of lighter ropes. However, in practice, it is only feasible to reduce the weight of the rope by using lighter ropes with similar strength parameters (Ferreira Luz, A.o Wink de Menezes, Silva, Cimini, Campos Amico, 2018). As a result of the simulations of the operating rope tension forces, the following simulation results were obtained:

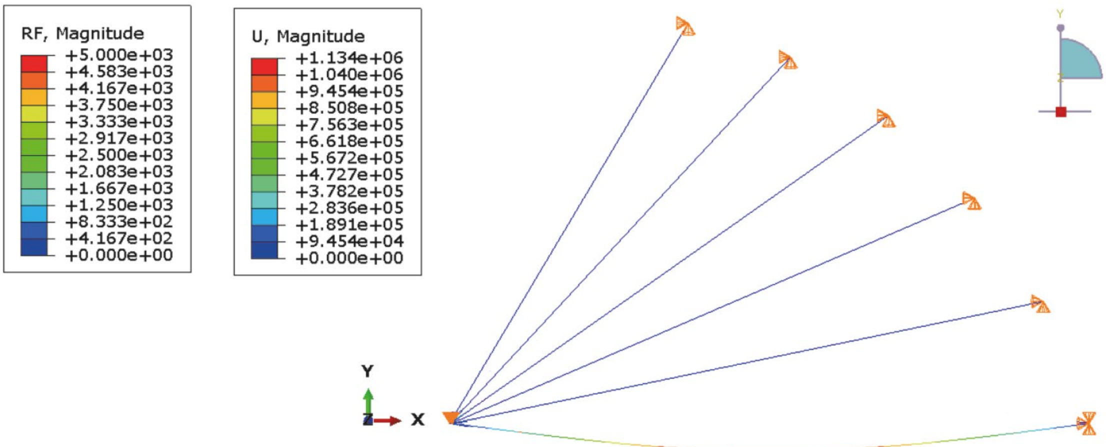

Figure 8. Results of the simulation of the stresses of the cable towing the angle of 0 deg
Source: own materials.

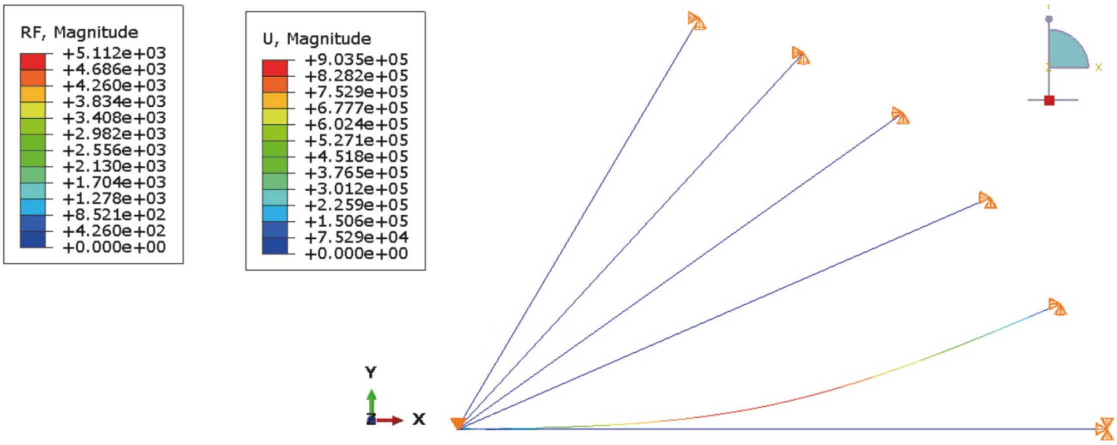

Figure 9. Results of the simulation of the stresses of the rope towing the angle of 12 degrees
Source: own materials.

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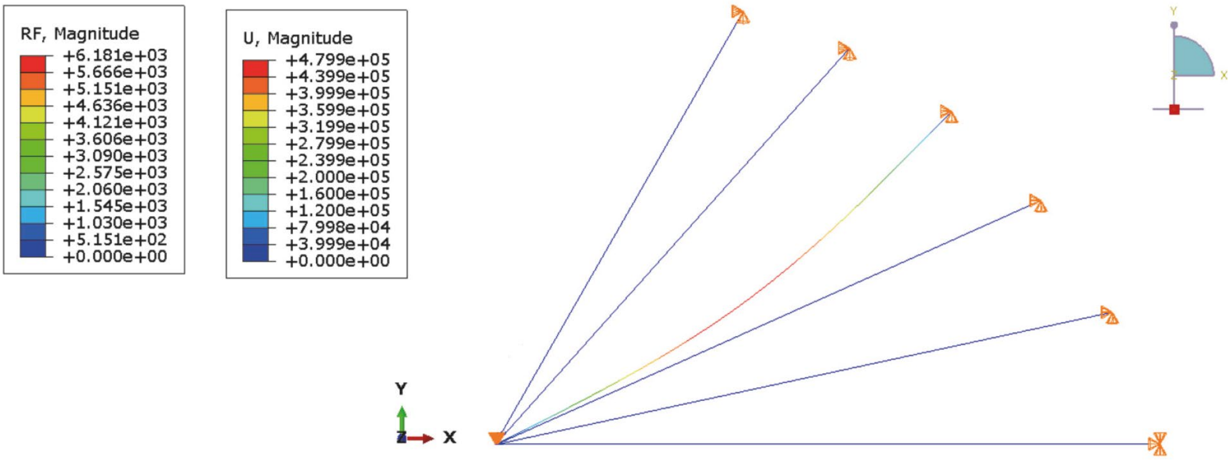

Figure 10. Results of the simulation of the stresses of the rope towing the angle of 48 degrees
Source: own materials.

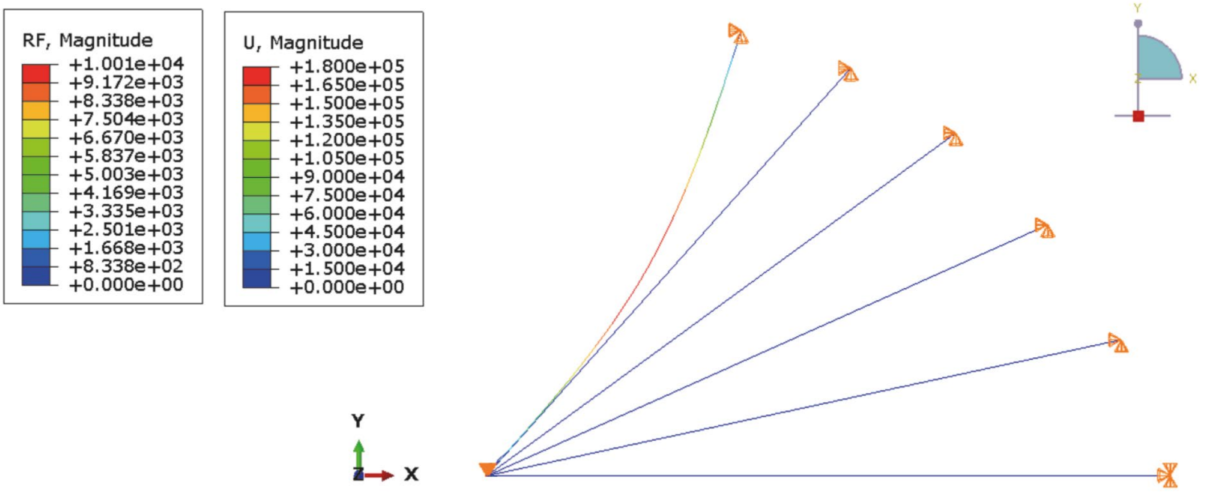

Figure 11. Results of the simulation of the stresses of the rope towing the angle of 60 degrees
Source: own materials.

The graphs presented above show the simulation results for individual stages of the glider towing process from the initial state, i.e., the start of towing until the release point – the moment of reaching the angle of the rope to the ground of 60 degrees was considered as the release point. For a better analysis of the obtained graphs, the distributions of individual elements have been marked with colors:

- RF: reaction force acting at the point where the rope is attached to the sailplane;
- U: linear displacement.

Based on the research results, the correlation between the magnitude of the reaction and the technical results of the driving forces and the extracts from the sampling test were depicted and assessed. Due to their influence, weather conditions, like the wind (which was found out to be a relevant value for the final result), also turned out to be significant. Additionally, the rope's shape and structure play an important role. However, because we successfully created an algorithm that can be implemented in the process of safe towing, the above variables, which overall have relatively little impact, will be omitted.

By making use of considerable facilities in creating subsequent iterations, it was possible in a relatively simple and quick way to reach successive iterations of the compiled project to such a number of parameters having a significant impact on the final results that ensure a satisfactory level of accuracy and complexity of the algorithm.

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5.Conclusions.

Conducting the simulation is an introduction to building an accurate model of a seemingly simple process, a sailplane with a winch. This analysis enables the penetration and visualization of the glider hauling process and the behavior of the simulated synthetic rope. The so-called rope overhang, which introduces an undesirable effect of "pulling" the glider towards the ground, reduces the generated lifting force. Additionally, if you try to measure the hauling parameters (the line tension vector and the glider's angles of attack), you should allow for the above-mentioned sag effect because the obtained results will be burdened with a systematic error obscuring the correct interpretation of the obtained results. The simulation model used is not ideal (the ground is not taken into account as a limiting element for the deflection of the rope in the case of small angles of deflection of the rope). However, being aware of these limitations, we obtain much information about the phenomenon under study. Another conclusion is the confirmation of the correctness of the selection of synthetic ropes at the expense of classic steel ropes due to the lower degree of occurrence of the rope deflection effect. In the case of using composite ropes, compared to steel ropes with comparable strength parameters, aside from weight (the considered composite rope 1.18 kg / 100m, while a steel rope with similar strength parameters is already 8 kg / 100m), greater flexibility and reduced stretchability may be gained. Translating this into the simulation results, we obtain a reduction of the sag effect by about 80% using composite ropes, making it a lot easier when you need to analyze the parameters of the glider tow. Additionally, by reducing the "sag" effect, the question of the possibility of resigning from taking this phenomenon into account in fast algorithms converting basic hall parameters in security systems becomes justified.

Declaration of interest
The author/authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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