Management and Production Engineering Review
Volume 10 • Number 3 • September 2019 • pp. 124–135
DOI: 10.24425/mper.2019.130505

TESTING VIRTUAL PROTOTYPE OF A NEW PRODUCT IN TWO SIMULATION ENVIRONMENTS

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Received: 12 July 2019
Accepted: 20 August 2019

Abstract
This paper is a case study conducted to present an approach to the process of designing new products using virtual prototyping. During the first stage of research a digital geometric model of the vehicle was created. Secondly it underwent a series of tests utilising the multibody system method in order to determine the forces and displacements in selected construction nodes of the vehicle during its movement on an uneven surface. In consequence the most dangerous case of loads was identified. The obtained results were used to conduct detailed strength testing of the bicycle frame and changes its geometry. For the purposes of this case study two FEA software environments (Inventor and SolidWorks) were used. It has been confirmed that using method allows to implement the process of creating a new product more effectively as well as to assess the influence of the conditions of its usage more efficiently. It was stated that using of different software environments increases the complexity of the technical process of production preparation but at the same time increases the certainty of prototype testing. The presented example of simulation calculations made for the bicycle can be considered as a useful method for calculating other prototypes with high complexity of construction due to its systematized character of chosen conditions and testing procedure. It allows to verify the correctness of construction, functionality and perform many analyses, which can contribute to the elimination of possible errors as early as at the construction stage.

Keywords
CAD, FEA, dynamic simulation, virtual prototyping.

Introduction

The production process is a set of preparatory processes (design of products, production technologies, research and development, organising), basic processes (creation of products and services as a result of technological processes), supplementary processes (transport, storage, quality control, maintenance and energetic processes) as well as production control processes (information-decision process) [1]. Changes occurring in world markets, related to the increasing variety of merchandise, many variants of manufactured goods, but also to limited production resources and legal regulations forcing manufacturers to find new solutions. In the area of sustainable production, more and more attention is devoted to the influence of the preproduction and production stages on the shape of the production process [2]. The building of the prototype is a crucial stage of the process of creating a new product and is a certain verification of the design stage, happening before the implementation work [3–5]. Currently, the most often used practice while constructing new products were experimental research conducted on experimental prototypes (real). The use of real prototypes, despite high reliability of test results, generates high construction costs, does not help in limiting harmful emissions and makes it possible to assess only one version of the product. It needs to be said that the designed products must meet many detailed construction assessment criteria. Fulfilling all of these, often contradictory, requirements is very difficult. Before a satisfactory result is obtained a few or even a few dozen design iterations are required. The traditional design flow delays the time of introducing the product to market, especially in the case of complex mechanism structures. It also needs to be noted that the products created using traditional methods often vary from optimal solutions. There is a lack of precise determination of the size of deformations and loads on individual elements, which often leads to overdimensioning, which results in an increase in mass and size of the product.

One of the new, alternative approaches to designing is considered to be the process using software methods called virtual prototyping. It is based on creating a numeric model of a machine, device or technological process for example and then creating multi-variant simulations of the object's behaviours under various conditions, with the aim to achieve the most optimal solution in relation to the desired function of the object. Using such a design method allows to efficiently complete the majority of time-consuming and usually expensive stages which are parts of the process of creating a new product [4, 6–11]. Figure 1 shows a simplified schematic of creating a design agreed using an experimental prototype and a virtual one with a chart representing the ease of introducing changes in the design and the costs this entails. The approach to the implementation process of new products using virtual prototyping moves many significant tasks closer to the beginning of the process, to areas which are characterised with a greater ease of introducing changes in the design [4, 12]. Additionally, it enables the analysis of multiple solutions without the need to build numerous physical prototypes and research stations. It can be used both in relation to the entire construction, assemblies, or individual parts [13–15].

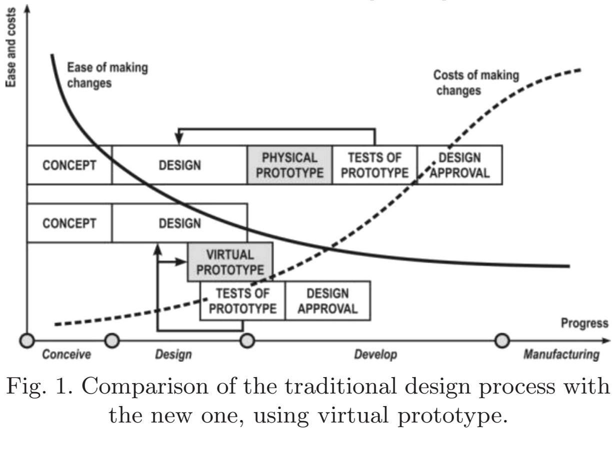

Fig. 1. Comparison of the traditional design process with the new one, using virtual prototype.

In the area of prototype testing there is often the need to conduct a kinematic and dynamic analysis of multibody systems whose parts are in motion in relation to the environment and each other. One of the commonly used methods is the so called Multibody Simulation Method (MBS), which is a generally used term to describe modelling, analysis and synthesis methods for real bodies, treated as multibody systems. The MBS theory is widely discussed and described by many researchers, e.g. [16–20]. Due to the complicated mathematical mechanism used to solve the multibody systems, numerical methods are widely used. A computer emulation of the designed objects enables to conduct a wide spectrum of their simulations, including the multivariance which is sought by designers. The use of this type of prototyping significantly reduces the number of conducted tests on real models and shortens the time before implementation into production.

There is currently a visible interest of designers in software which allows to conduct kinetic and dynamic simulations, often collectively referred to as Mechanical System Simulation (MSS). These systems are fitted with modules which enable strength calculations for stress statics, or natural frequency calculations. Another similarly common solution is the possibility of inputting the calculation results from MSS systems as input data for FEA software, which determine the stresses, deformations etc. The designed model can be modified and, through consecutive simulations, achieve an optimal solution [21, 22].

Taking into account that the design activities are completed in stages and that in many cases each of these stages is performed using different software, the problems of purchasing separate licences for individual software enabling its commercial use, as well as specialist training in operating the software arise. An alternative solution seems to be using a CAD system with integrated, additional modules. In response to demand for such software groups leading CAD/CAE software has been equipped with calculation environments integrating geometric modelling, FEA analysis and simulation modules e.g. CATIA, Inventor, NX, SolidWorks.

The methodology used in the paper included a literature analysis of the issues of design of structures, digital modelling and virtual prototyping. On the basis of the analysis, the areas insufficiently described in terms of virtual prototyping of bikes with cushioning, powered by human muscles, were identified. Secondly, a systematized approach to the design of such structures was proposed, taking into account the operational loads with the use of computer aid. The following stages of work were implemented: creation of a kinematic scheme of a vehicle, construction of a geometric CAD model, definition of test conditions and analysis with the use of MBS, identification of structural loads and carrying out a strength analysis of a selected element together with proposals for its modification.

Due to its wide recognition Autodesk Inventor Professional 2019 (INV) and SolidWorks 2018 (SLD) software were used in this work. It is an intermediate level software. Its popularity stems mainly from moderate purchase and usage costs combined with a wide range of functionalities. The use of such intermediate level software enables the user to design virtual models of advanced mechanical structures [6, 12, 23].

This paper focuses mainly on the strength analysis of the frame because of the responsible functions it performs. Bicycle frame constructions undergo a wide range of loads caused by their usage. Over the years many attempts were made to determine these loads using a variety of methods. One of the first published works on the measurements of loads affecting bicycles could be considered the publication [24] by Hoes et al. Peterson and Londry can be considered as pioneers of the implementation of the finite elements method in structural analysis. In their work [25] they designed a new bicycle frame and compared it with two existing models. Currently, the finite elements method is widely used. There are many publications available which describe usage of this tool in simulations in order to assess the strain of steel bicycle frames [26–28], as well as frames made of aluminum [29–31], composites [32–34]. There are also articles which compare constructions of frames made of various materials e.g. [35, 36].

While some articles shed light on the behaviour of specific elements or the entire frame designs, only a few present complete solutions for the design process.

The introduction of virtual prototyping enables the analysis of multiple solutions without the need to build numerous physical prototypes and research stations. It can be used both in relation to the entire construction, assemblies, or individual parts [23, 36, 37].

Current research studies analyse mainly classic, *Diamant* type frames [26, 29, 30, 32, 34, 35]. Few articles discuss other frame shapes [37, 38] and comparative analyses [34, 35]. Also few studies refer to mountain bike frames with suspension. Although the study [38] presents a numerical analysis of a mountain bike frame with suspension, there remains the necessity to define external loads. The study [28] presents the results of the analyses of a frame with suspension system, focusing only on the vibration analysis. There is a noticeable lack of studies describing the modelling of external loads of frames relating to real-life road conditions. The study [29] makes an attempt to do this, however, the presented analyses refer to a frame with no suspension.

In summary current research studies on the analysed issue demonstrate a noticeable lack of a comprehensive description of the issue of virtual prototyping of bicycle frames in the aspect of designing the entire construction of a bicycle with suspension. In addition, the available literature on virtual prototyping presents few papers containing a systematic description of the approach to designing more complex devices with the use of virtual prototyping. Most of the authors focus on the use of single software environments in the design process. Moreover, there is a shortage of work describing the behaviour of a complex construction under simulated working conditions.

The aim of this work is to present an approach to the design process using a virtual prototype of a bicycle and to determine the consequences of simulations on the process of designing a new product in various programs.

This paper introduces a systematic approach to construction design from perspective of strength, presenting test results for two different software environments with the ability to determine loads under simulated operating conditions. This approach allows to verify strength of the designed construction with greater reliability, along with the ability to effectively optimize geometry and minimize the probability of error.

The designed virtual prototype underwent initial testing in the INV dynamic simulation environment which enabled to determine displacements and stresses at selected nodes of the vehicle in conditions of movement on a rough surface. The work presents the results of numeric tests of selected points of the vehicle using varying stiffness of springs in the front suspension and movement speed. The obtained results of maximum values, returns and directions of forces were used to analyze the strength of the frame structure of the designed bicycle. Two different FEA environments offered by INV and SLD software were used to compare the test results. The numerical calculations carried out allowed to identify the most heavily loaded areas of the tested construction. The usage of a homogeneous digital model allowed efficient implementation of changes enabling the achievement of a proper safety coefficient.

Although the paper discusses the approach to virtual prototyping based on a single bicycle structure case, this method can be easily extended to other mechanism constructions.

Construction of the geometric model of the vehicle

The geometric model of the individual assemblies of the vehicle was created using the INV software. The individual parts of the vehicle were connected with each other using appropriate nodes within the subgroup environment. The inspiration behind the creation of a three-dimensional virtual model of the vehicle was the construction of the Hanzz Fritzz 160 HPA bicycle manufactured by the company Cube [39]. This model was selected due to its highly complex build, for which the classic methods of multibody element dynamics are characterised with a high degree of complexity and a time-consuming process of finding solutions. The bicycle is fit to ride various surfaces and is a part of the full-suspension mountain bike family. At the front, the bike uses a classic, telescopic suspension system with a regulated spring stiffness, with no damping elements. The rear suspension is fitted with a special trailing arm, fastened to the frame, with a single cylindrical coil spring and a hydraulic damper. The wheel diameter is 27″ and the wheelbase is approx. 1200 mm.

During the construction of the model a crucial stage was the defining of the materials for individual components. A module of the INV software was used, called *Eco Materials Adviser*. This module was designed in cooperation with Granta Design Ltd. This tool enables the designers to optimise their material selection based on the data on the materials' impact on the environment and production costs, helping the manufacturers to make the best possible decisions and selecting the best solutions which would fulfil the environmental requirements [40]. The *iProperties* command dialogue window enables to carry out calculations of the basic physical properties such as: mass, surface, volume, center of mass and main moments. The weight of the vehicle model, determined using the *iProperties* command, was 14.45 kg. In order to replicate the real conditions of the bicycle in motion as best as possible, a model of a rider was added to the three-dimensional bicycle model, corresponding to the average size of an adult man weighing 85 kg.

Multibody systems were created in an introductory working process, in which the entire design consists of many components within a single assembly file. The advantage of such solution is the fact that bodies can share edges, which makes fitting the curves, fitting and joining easier. Figure 2 shows a schematic view and view of the designed geometric model of the vehicle. The dimensions of the bicycle including the location of the center of mass are presented in Fig. 3.

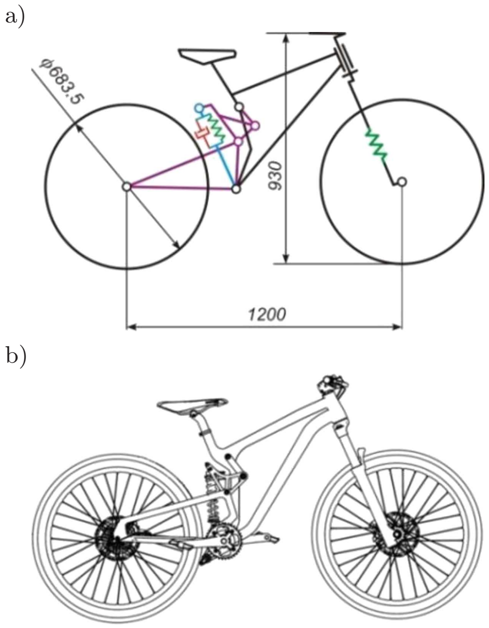

Fig. 2. View of the schematic (a) and the geometric model of the vehicle (b).

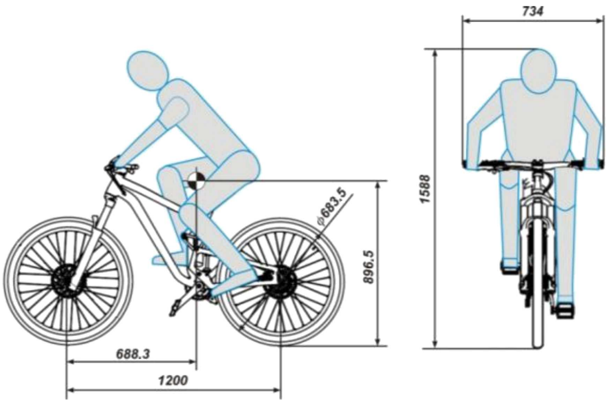

Fig. 3. View the dimensions and locations of center of mass.

The elements responsible for the movement of the mechanisms were inserted into the main assembly individually, as inserted assemblies form at this level static (fused) groups.

This initially prepared geometric model of the vehicle served as a basis to design a virtual model in the dynamic simulation environment, which is one of the modules of the INV software.

Virtual prototype testing in a dynamic simulation environment

In the dynamic simulation environment of the discussed software, after creating the geometric model, it is possible to conduct a kinematic and dynamic analysis of multibody systems. The software has a large library of moving connections. In the dynamic simulation environment it is also possible to define the load of each element with values of torque and forces as well as forced movement on each node using speed, displacement or acceleration. Thanks to the available tools of the software, the user has the possibility to observe the values of forces and moments created during movement and verify the behaviour of the designed mechanism. The prepared model was characterised by a significant degree of complexity, which was why it was necessary to define the movement nodes manually, despite the existing functionality of automatic conversion of nodes within an assembly to movement nodes available in the dynamic simulation.

Description and test conditions

The virtual model of the road was defined as the base element (static element) in relation to which the vehicle moves. Roll nodes were introduced between the road surface and the wheels of the vehicle. Damping elements in the vehicle were defined using spring – suspension force connections. Elements of the suspension participate in the load transfer. They must be taken into account in the model, if it is to reflect precisely the loads on the frame [4, 6, 21, 22].

Figure 4 shows a collective diagram (test plan) presenting the test conditions and the observed values obtained during tests.

The behaviour of the vehicle was tested with the following, changing parameters (Fig. 4):

- R_{wst} – rear wheel spring stiffness: 32 N/mm, 64 N/mm, 128 N/mm;
- R_{sd} – rear suspension damping: 0.5 Ns/mm, 1 Ns/mm, 10 Ns/mm;
- F_{wst} – front wheel spring stiffness: 11 N/mm, 22 N/mm, 44 N/mm;
- S – vehicle speed: 5 km/h, 8 km/h, 9.5 km/h, 10 km/h.

The simulation was conducted with the vehicle model moving on road profile, whose parameters are presented in Fig. 5.

In order to obtain measurement data and trajectory observations for the movement of selected elements, measurement points were defined using the software's *Track* tool. In this work, the measurement points were located on the axis of the front wheel hub and on the handlebars. The loads on the steering bearing were also registered. The choice of these nodes was to a large extent determined by determining of maximum loads and displacements occurring in the area of the front suspension as it interacts with the rider and the surface. After conducting the simulation, time courses od displacements and resultants of load forces of the model were obtained. Based on this data it is possible to locate time periods, during which the analysed construction and its elements undergo the most negative states of load or deformation. The generation of individual reports, creation of charts and their observation and analysis is possible with the software's *Output Grapher.*

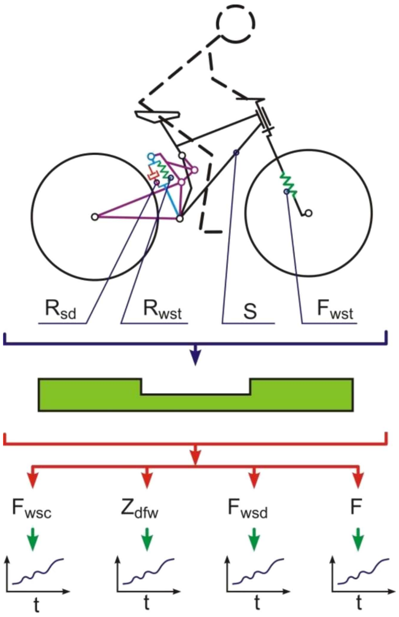

Fig. 4. Collective diagram showing test conditions and observed values obtained during testing.

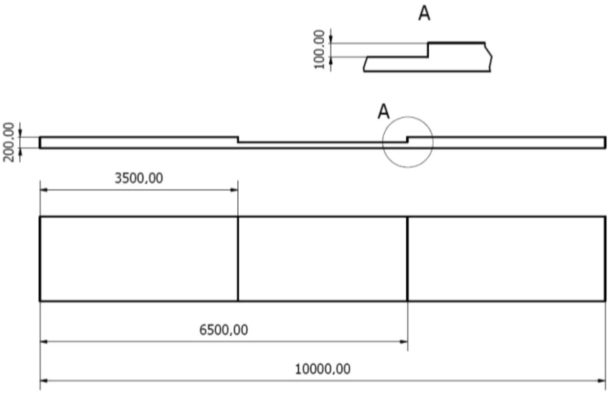

Fig. 5. Road profile – a representation of riding off and on a 100 mm curb.

The following final values for the simulation were selected (Fig. 4):

- F_{wsc} – front wheel spring compression [mm];
- Z_{dfw} – displacement of the measurement point on the front wheel hub [mm];
- F_{wsd} – displacement of the measurement point on the handlebars [mm];
- F – forces on the steering bearing [N].

Virtual prototype test results in a dynamic simulation environment

Dynamic simulations were conducted for each combination of parameters presented in Fig. 4. As a result of these tests time courses of displacements, speed and acceleration as well as forces and moments at joints were obtained. This section presents the selected, most characteristic results of the dynamic simulation for a vehicle moving on a road profile. The profile represents a very common situation during normal riding – riding across a street (riding off a curb and then onto another curb). Figures 6–9 show example results of the dynamic simulation for this road profile and front wheel spring stiffness 11 N/mm.

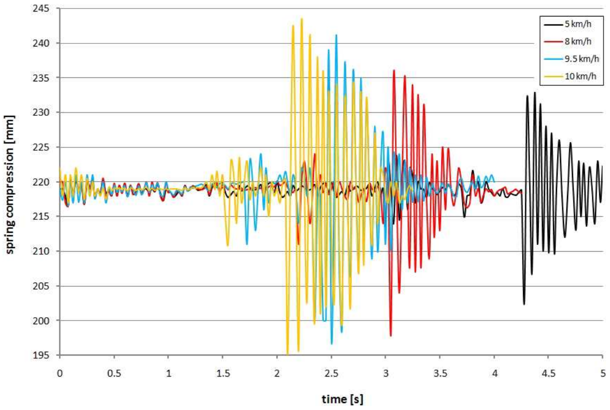

Fig. 6. Observed front wheel spring compression (F_{wsc}) over time for four different velocities of the vehicle.

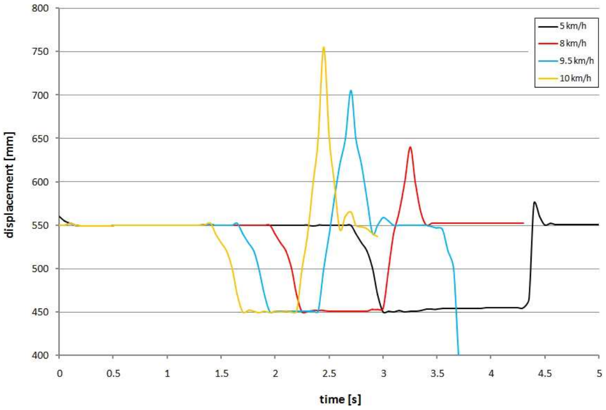

Fig. 7. Observed displacement of the measurement point on the front wheel hub (Z_{dfw}) over time for 4 speeds.

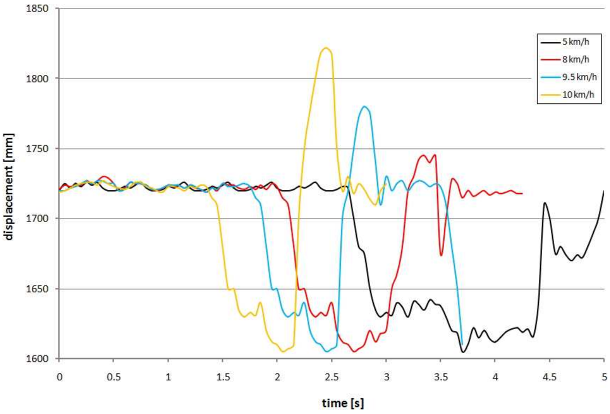

Fig. 8. Observed displacement of the measurement point on the handlebars (F_{wsd}) over time for 4 speeds.

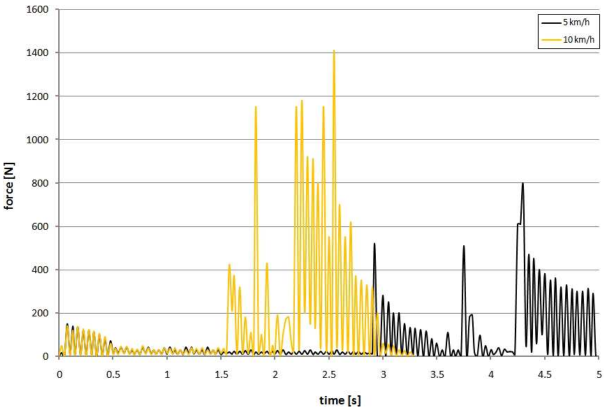

Fig. 9. Observed forces (F) on the steering bearing over time for 2 different speeds.

The presented time courses are only a fragment of the obtained results. Their aim is to present the relation of displacement and force in selected construction nodes from the vehicle's speed. Based on the presented graphs it can be observed that both the displacement as well as load increase significantly with the increase in speed. In the case of riding over a curb, the compression of the front wheel spring (F_{wsc}) increases from 13.6 mm for a speed of 5 km/h to 24.1 mm for a speed of 10 km/h. The force in the steering bearing is also dependent on the vehicle's speed and it increases from 765 N for a speed of 5 km/h to 1402 N for a speed of 10 km/h. Significantly lower values of displacement and load were observed while riding off a curb in comparison to riding onto a curb. It needs to be stressed that the obtained time courses allow to acquisition data on the behaviour of practically every construction node at any selected point of its movement, which is very hard to obtain when using a physical prototype. To summarise, the approach using a virtual prototype allows for a more detailed analysis of the designed product's behaviour without the need to place a multitude of measuring sensors on the tested object.

Analysis of dynamic simulation test results

Based on all of the obtained simulation results, it was stated that the displacement of the handlebars and the forces on the steering bearing and the rider's arms are most influenced by the stiffness of the front wheel spring and the vehicle's speed. The extreme values of the obtained results are significant in relation to the durability of the construction and ride comfort. Due to this, further analysis was limited to the maximum force and displacement values.

Figure 10 show a collation of maximum force (F) values in the steering bearing depending on selected travel speeds and the front suspension spring stiffness of 11 N/mm, 22 N/mm and 44 N/mm. Figure 11 show a collation of displacement of the measurement point on the on the handlebars (F_{wsd}) for 4 speeds and the front suspension spring stiffness of 11 N/mm, 22 N/mm and 44 N/mm.

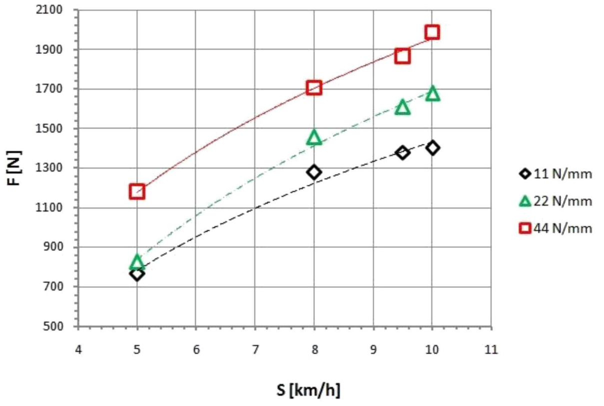

Fig. 10. Impact of the front wheel spring stiffness and speed on maximum force in the steering bearing (F).

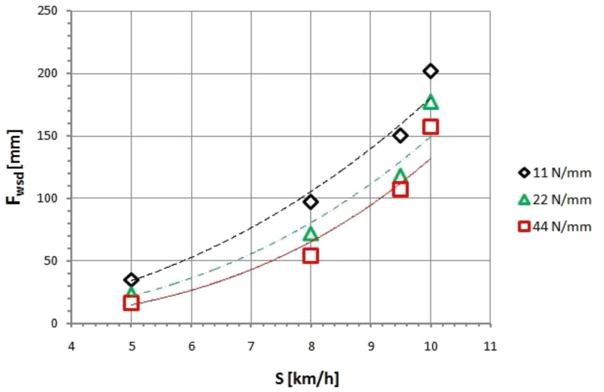

Fig. 11. Impact of the front wheel spring stiffness and speed on displacement of the point on the handlebars (F_{wsd}).

Based on the conducted simulations in relation to the values of the parameters influencing the behaviour of the front wheel suspension it can be stated that:

- an increase of speed by 5 km/h (from 5 km/h to 10 km/h) causes an increase of the force in the steering bearing average by 700 N and an increase of the maximum vibration amplitude of the handlebars average by 125 mm,
- an increase of the front wheel spring stiffness by 33 N/mm (from 11 N/mm to 44 N/mm) causes a decrease of the maximum vibration amplitude of the handlebars average by 50 mm but increases the force in the steering bearing average by 450 N.

It can be stated that the maximum vibration amplitude on the handlebars was strongly influenced by the stiffness of the front wheel spring and the speed of the vehicle. Higher speeds meant larger force on the handlebars. The force value in the steering bearing increased with the vehicle's speed and the stiffness of the front wheel spring.

During simulation tests the influence of the damping of the shock absorber and the stiffness of the rear suspension spring on the compression value of the front wheel spring and the displacement and force in the handlebars was observed. In the case of the analysed road profiles, lower displacements in the handlebar occur when using lower values of damping of the rear shock absorber. An increase of the rear shock absorber damping caused an increase of the compression amplitude of the front wheel spring, regardless of the tension of the rear spring. It was also observed that with the increase of the damping value of the rear suspension the force value in the steering bearing increased.

In general – a higher speed of the vehicle causes an increase of the maximum vibration amplitude in the handlebars and of the loads on suspension elements as well as forces on the handlebars.

The stability of the model's movement was influenced by the vibrating vertical components, which changed depending on the selected stiffness, damping and speed. The vibration amplitude was limited by an increase of the stiffness of the suspension springs, but this influenced negatively the frequency of vibrations, which increased due to the road unevenness.

Strength analysis of the bicycle element

Based on the INV simulation of the entire bicycle structure behaviour under various conditions, the most dangerous case of load was identified. In the case of riding onto a curb the force (F) in the headset increased to the value of 1986 N at a speed of 10 km/h and front suspension stiffness 44 N/mm. A significantly lower value of displacement and load were observed at the moment of riding off a curb in comparison to the moment of riding onto another curb. The basic aim of this analysis was the determination of the strength in the individual elements of the bicycle's frame and the assessment of the durability of used profiles. The frame was extracted from the entire bicycle construction, and external influences were replaced with appropriately formulated loads and constraints.

The FEA numerical analysis was conducted using two environments offered by INV and SLD. The same research parameters were consistently applied to the discretisation of the computational model and boundary conditions. Due to the complex geometric shape of the analysed frame, a high quality mesh based on parabolic tetrahedral elements was used for its discretisation. The final selection of the discretisation parameters was preceded by an analysis of the influence of the finite elements mesh thickness on the calculated values of von Mises stress. Table 1 presents the information on the chosen parameters of the generated mesh. Figure 12 presents the view and the chosen discrete form of the bicycle frame in INV. Figure 13 presents the view and the chosen discrete form of the bicycle frame in SLD.

Table 1
Mesh parameters.

Type mesh	Parabolic tetrahedral
Average Element Size	5,027 mm
Minimum Element Size	1,005 mm
Grading Factor	2
Maximum Turn Angle	60 deg
Upper Jacobian Ratio Bound	16 Points
Quality	High

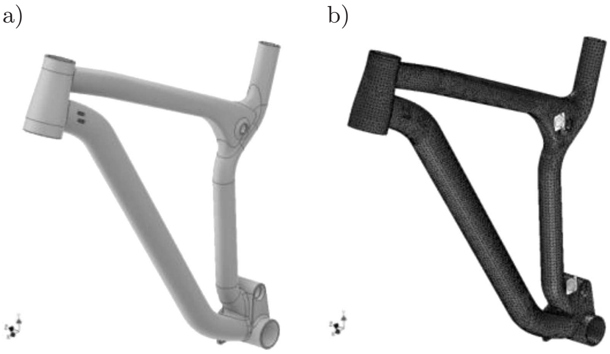

Fig. 12. Model of the analysed frame in INV (a) and view with element mesh overlay (b).

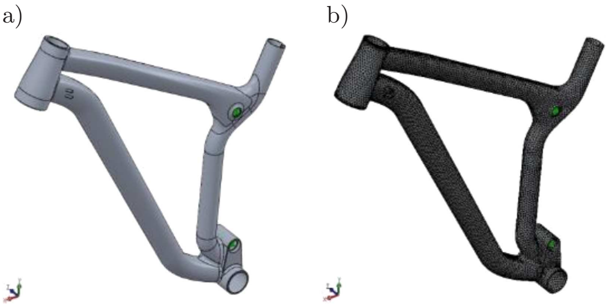

Fig. 13. Model of the analysed frame in SLD (a) and view with element mesh overlay (b).

The following strength properties of the material were determined (aluminum 6061 T6): linear elastic isotropic material, Poisson's ratio – 0.33, Young's module – 68.9 GPa, Kirchoff's module – 25.9 GPa, tensile strength – 310 MPa, yield limit – 275 MPa.

The external load affect on the vehicle's frame were generated inside the dynamic simulation environment. Their maximum values were exported, alongside directions, into the strength analysis environment. Based on the conducted dynamic simulation two locations of force application were determined: lower headset mount (locating bearing) and the upper headset mount (expansion type bearing). The appropriate anchoring of the model in two places with the rear suspension was also introduced. Both anchoring locations use a clevis fastener.

The conducted numeric analysis allowed to identify the locations with a high level of material stress, which could lead to the deformation of the frame. The analysis took into account two values, which are calculated by the INV and SLD software: strain according to the von Mises hypothesis and safety coefficient.

After analysing the obtained results it could be stated that the highest reduced stress could be found in the lower part of the so called seat tube. The maximum reduced stress reached the value of 263.8 MPa in INV and the value of 222.1 MPa in SLD. The safety coefficient for this spot in the frame was $k = 1.04$ (INV) and $k = 1.24$ (SLD). Another dangerous spot was the middle section of the seat tube below the upper anchor of the swingarm, where strains of approximately 185.4 MPa (INV) were noted and the safety coefficient was $k = 1.48$ (INV). Similar results in the qualitative sense were obtained using SLD software where stress of approximately 166.2 MPa were noted and the safety coefficient was $k = 1.65$. Both these values of reduced stress come dangerously close to the yield limit and can lead to deformations of the construction or even to the tearing of the material. The conducted analysis pointed to the necessity of construction changes in the identified nodes.

The numeric analysis showed that the main construction issue of this frame were the low values of the safety coefficient for the seat tube. There were spots on the seat tube, which were characterised by reaching the highest reduced stress. One suggested solution was to increase the thickness of the seat tube's walls. Due to construction and technological reasons it seemed beneficial to make the walls thicker by decreasing the internal diameter along the entire seat tube. The assumption was made that the minimum safety coefficient (k) should reach the value of at least 2 in both environments. Iterative numeric calculations were conducted, increasing the wall thickness (g) each time by 0.5 mm. Table 2 shows the results of numerical calculations of the maximum reduced stress determined according to the von Mises hypothesis ($\sigma_{\max}$), minimum safety coefficient and percentage differences of results obtained in INV and SLD environments.

Table 2
Results of numerical calculations and percentage differences of values.

No	g	$\sigma_{\max}$		$\Delta\sigma$	k		Δk
		INV	SLD		INV	SLD	
	[mm]	[MPa]		[%]	[MPa]		[%]
1	1.5	263.8	222.0	15.8	1.04	1.24	19.2
2	2.0	184.2	180.1	2.2	1.49	1.53	2.7
3	2.5	143.6	139.1	3.1	1.91	1.99	4.2
4	3.0	135.5	127.4	6.0	2.03	2.16	6.4

Calculations of the percentage difference in the results for two types of software environment and calculation methods have been conducted according to Eqs (1) and (2), and these values are given in Table 1

$$\Delta\sigma = \left| \frac{\sigma_{\max}^{\mathrm{INV}} - \sigma_{\max}^{\mathrm{SLD}}}{\sigma_{\max}^{\mathrm{INV}}} \right| \cdot 100\% \,, \qquad (1)$$

$$\Delta k = \left| \frac{k_{\min}^{\mathrm{INV}} - k_{\min}^{\mathrm{SLD}}}{k_{\min}^{\mathrm{INV}}} \right| \cdot 100\% \,, \qquad (2)$$

where $\sigma_{\max}^{\mathrm{INV}}$ – the maximum reduced stress determined in INV environment, $\sigma_{\max}^{\mathrm{SLD}}$ – the maximum reduced stress determined in SLD environment, $k_{\min}^{\mathrm{INV}}$ – the minimum safety coefficient determined in INV environment, $k_{\min}^{\mathrm{SLD}}$ – the minimum safety coefficient determined in SLD environment.

On the basis of Table 2, we can observe differences in quantitative terms in the results of simulation using INV and SLD software. These differences, however, are not large and reach 15.8% for maximum stress and 19.2% for minimum safety coefficient. It was observed that, in all analyzed cases, SLD software generated lower stress values in relation to INV software.

Based on the obtained dependency it was established that the optimum wall thickness for the seat tube should be 3.0 mm. This would allow to achieve the minimum safety coefficient of the analysed construction of $k = 2.03$ for INV environment and $k = 2.16$ for SLD environment. Figure 14 presents the distribution of reduced stress after the change of dimensions of the bicycle frame.

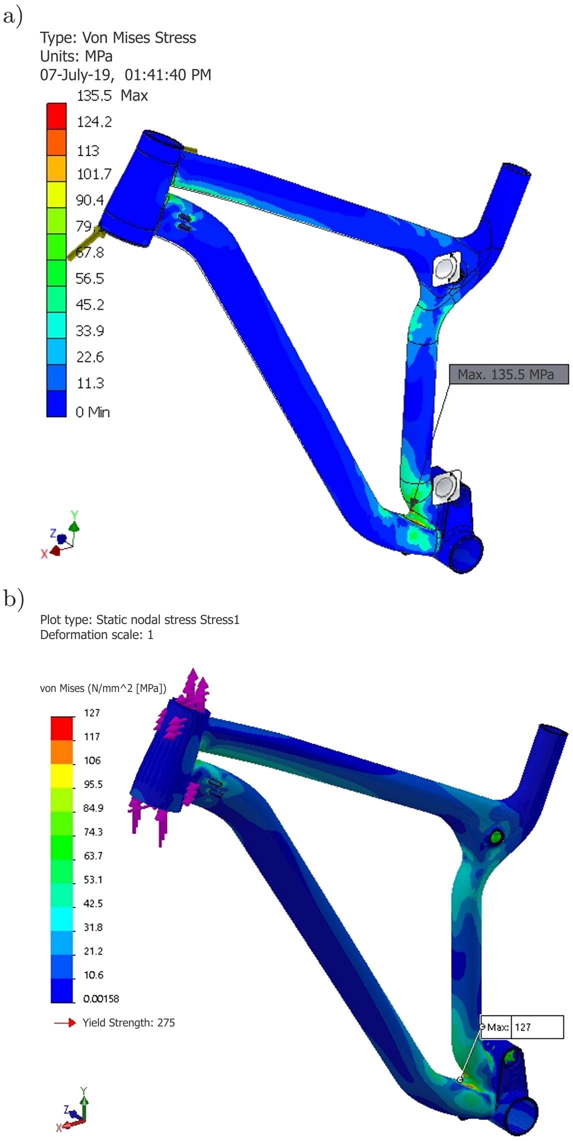

Fig. 14. Obtained results of the strength analysis after change of wall thickness: (a) von Mises stress distribution map in INV, (b) von Mises stress distribution map in SLD.

Conclusions

Virtual prototyping enables to verify design solutions in relation to various requirements and technical assumptions. This work presents an example of the approach to the method of design, including the testing of device prototypes. This method makes it possible to introduce the product into the market quicker and is more commonly used. It enables the verification of the construction, functionality and conducting of many analyses, which can contribute to the elimination of potential errors as early as in the construction stage.

The integration of all tools used in the virtual prototyping design process into one software creates the possibility for fast and cheap adjusting of the designed product to the conditions, in which it will be used and for the verification of the influence of changes of these conditions on the designed product. It is widely claimed that 80% of a product's overall environmental impact has been 'built in' by the end of the conceptual design phase [40]. At this point, the designer has typically selected materials and manufacturing processes, and defined the product lifecycle: these constrain not just the final economic cost but also fix many of the environmental costs. The INV software, thanks to the included tools such as the *Eco Materials Adviser* enables an effective and correct selection of materials for any construction in relation to their effect on the natural environment and future disposal. A similar module is offered by the SLD software. The *Sustainability* tool allows users to measure the environmental impacts of designs, including the effects of materials, assembly and disposal.

The built-in analytical tools allows to analyse the model through stress tests and verify the model's behaviour in motion, which created a wide range of possibilities for assessment of the created prototype.

The dynamic simulation module of the INV software gives the opportunity to, among other things, determine the loads, track measurement points, prepare animated visualisations and generate reports in the form of graphs. It should be noted that the *Design Accelerator* and MBS environments contained in the INV software are highly advanced and therefore it was decided to use them in the initial stages of this work. The *Motion* environment implemented in SLD also offers many potential opportunities, but focuses mainly on the kinematic analysis of the construction.

A dynamic simulation based on the usage of MBS is a useful tool in virtual prototyping. A very important issue during the creation of the virtual model is the defining of appropriate joints between the individual kinematic nodes of the device in order to ensure the proper number of degrees of freedom. This requires a precise verification of all standard joints obtained as a result of automatic conversion of assembly joints, and if there is need, defining the joints directly in the dynamic simulation environment.

The simulation presented in the paper enabled to determine the turns, directions and values of forces acting on the frame model at any moment of the vehicle's movement. This approach allows to identify the maximum loads and changes the dimensions of the bike frame in terms of the appropriate strength of its individual components.

Comparing the strength analysis capabilities of INV and SLD software, the SLD environment offers much more types of available types of strength analysis. SLD offers users wide selection of strength analysis tools to reflect real-world conditions at their models. Example tools include high-cycle fatigue, and features to assess endurance under nonlinear static, thermal and buckling conditions. Such analyses are only available in the INV using an additional environment, e.g. *Nastran In-CAD*.

The strength analysis of the bike frame, using two environments: INV and SLD, gave convergent results in terms of quality and quantity. In both cases, hazardous areas were identified in the same construction sectors. The maximum percentage difference in the results of the reduced stress values was about 16%. In the case of estimating the safety coefficient of the structure, the difference was approximately 19%. It was observed that in all analyzed cases SLD software generated lower stress values in relation to INV software.

The paper presents that using only one software environment for designing mechanisms, despite many advantages associated with the use of a uniform digital model, is exposed to the risk of making a mistake that may affect security. It is recommended that the obtained results of numerical simulations should be additionally verified using various methods. This increases the complexity of the production technical preparation process, but, at the same time, increases the certainty of creating the correct, safe product.

Moreover, it can be said that by offering more specialized, mechanical toolsets, INV and SLD fill in the gap between design, engineering and manufacturing, especially in the field of virtual prototyping.

In general, before making the right decision on the choice of software to support production preparation work, it is necessary to adopt appropriate criteria adapted to the needs of the enterprise. The most important criteria include the possibility of the transposing the existing projects into a new system, the costs of new software and the possibility of cooperation with partners, i.e. compatibility with their software.

This work is an element of a much wider analysis of the issue of vehicle movement, in conditions other than those presented here. The created model can be used in further studies on vehicle behaviour e.g. in conditions taking into account acceleration.

Researches have been carried out in the framework of work WZ/WIZ/3/2019 and financed from the funds for science.

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