DEVELOPMENT OF THE PREMOTO3 MOTORCYCLE

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A group of students from Warsaw University of Technology, Faculty of Automotive and Construction Machinery Engineering, was taking part in an international engineering competition MotoStudent 2018 as the WUT SiMRacing Team. The main purpose during the competition was to design and develop a prototype of a PreMoto3 racing motorcycle. The competition was organized by Moto Engineering Foundation and TechnoPark MotorLand, supported by the International Motorcycling Federation (FIM). The main idea of this contest can be expressed by the following sentence "The next generation of engineers will have a challenging competition for testing their skills."

Development, mechanical engineering, MotoStudent competition, PreMoto3 motorcycle

I. INTRODUCTION

The designed motorcycle (Fig. 1) is based on 4-stroke single cylinder engine from KTM RC250 road motorcycle, 250 cm^3 displacement, max. power 30.87 HP / 9000 rpm and max. torque 24 N·m / 7250 rpm. With 95 kg weight, 1250 mm wheelbase, 23.3° caster angle and 85 mm trail, both adjustable, is compact, lightweight racing motorcycle which perfectly fits the idea of the PreMoto3 class. An inverted front suspension with compression/rebound regulation and rear suspension with Pro-Link linkage system provides adequate maneuverability. Aerodynamic package optimized using Computational Fluid Dynamics (CFD), made of Carbon Fiber Reinforced Polymers (CFRP) is lightweight solution with as low aerodynamic drag as possible. With technological innovation in the form of monocoque CFRP subframe in Out-of-Autoclave (OoA) prepreg technology is an unique solution within PreMoto3 class motorcycles. Equipped with self-developed acquisition data system based on minicomputer Raspberry Pi 3 configurated with linear suspension potentiometers, wheel speed sensors, accelerometers and GPS system gives the opportunity for continuous development, both for students involved in the competition and for improving rider skills.



Fig. 1. Visualization of the PreMoto3 motorcycle design

II. CHASSIS GEOMETRY AND MOTORCYCLE DYNAMICS

Geometric dimensions and parameters such as the center of gravity, weight, ergonomics have been based on a model built using BikeSim software and ergonomic analyses performed in CAD software. Using realistic multibody physics model based on analytical calculations implemented in BikeSim software there have been carried out simulations of the dynamic behavior of vehicle in response of driver inputs taking into account 3D ground geometry or aerodynamic forces acting on the motorcycle. Built model has 29 degrees of freedom. The main requirements for motorcycle behavior was the compromise between maneuverability, stability and ability to brake and accelerate. For defined parameters such as total weight of motorcycle and rider, stiffness and damping characteristics of front and rear suspension, lever ratio of the ProLink system, after iterative process using simulation events included in the software and events adapted against competitions in the MotoStudent Final Event, parameters such as weight distribution, wheelbase, caster angle, trail, swingarm length and its inclination angle or required damping coefficients of the steering system were estimated.

In order to ensure proper handling and stability of the motorcycle, certain dependencies which should be met have been identified:
– slip angles of the rear wheel should be greater than slip angles of the front wheel to ensure better cornering,
– during cornering the rider must block the handlebars, which otherwise tend to rotate further,
– in the whole range of speed in rectilinear motion and during cornering such phenomena as wobble, weave and chatter should be in stable range.

While driving a motorcycle a couple of oscillation modes may occur, such as the wobble, wave and chatter modes associated with vibrations [2]. They occur at different frequencies - driving speeds. They can be visualized coupling BikeSim and Matlab software for linearizing the vehicle model (applying frequency domain analyses for root locus plot). Fig. 3 presents a root-locus plot during straight-line driving for speeds of 10 - 180 km/h with a step of 10 km/h, while in Fig. 4 when driving in an arc with an overload of 0 - 1.1 G and a step of 0.1 G. For values on the real axis less than 0 modes are in the desirable stable range. Values on the imaginary axis correspond to circular frequency.

Forces acting on wheels were estimated using various dynamic scenarios for earlier estimated parameters. For the coordinate system with the x-axis facing the front of the motorcycle and the z-axis pointing up the following forces were determined:

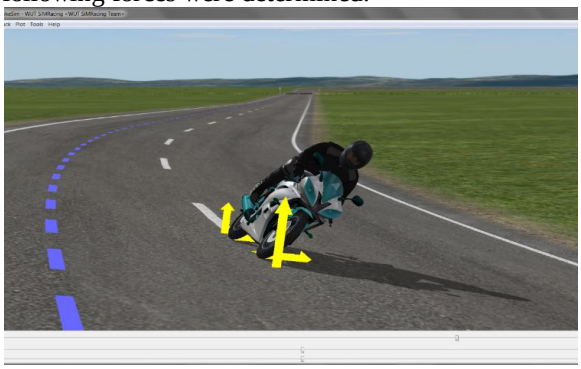


Fig. 2. Example of BikeSim simulation

Table I. Forces acting on wheels

R_{x1} [N]	R_{x2} [N]	R_{y1} [N]	R_{y2} [N]	R_{z1} [N]	R_{z2} [N]	
-1726	0	0	0	2216	0	Extreme braking
0	1745	0	0	0	1934	Wheelie
-82	326	754	1016	749	929	Maximum lean angle

– longitudinal reaction acting on the front wheel (R_{x1}) and the rear wheel (R_{x2}),

– lateral reaction acting on the front wheel (R_{y1}) and the rear wheel (R_{y2}),

– vertical reaction acting on the front wheel (R_{z1}) and the rear wheel (R_{z2}).

Using simulations performed in BikeSim software maximum forces (considering dynamic loads) acting in three cases were determined (Table I).

Thrust force in the chain and shaft transmission (with chain force in chain transmission) can cause compression or extension of the rear suspension. Introducing squat ratio parameter which can be defined as the ratio between the moment generated by load transfer and moment generated by sum of the thrust and chain force, for assumed wheelbase and height of the center of gravity rear suspension characteristic during thrust phase depends on radii of the drive and rear sprocket, length of the straight line section of the chain, momentary position of the swingarm and vertical distance between the drive sprocket axle and the swingarm pivot.

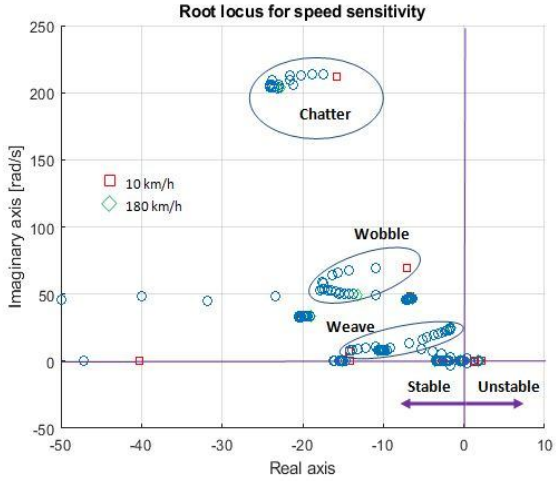


Fig. 3. Root-locus for speed sensitivity

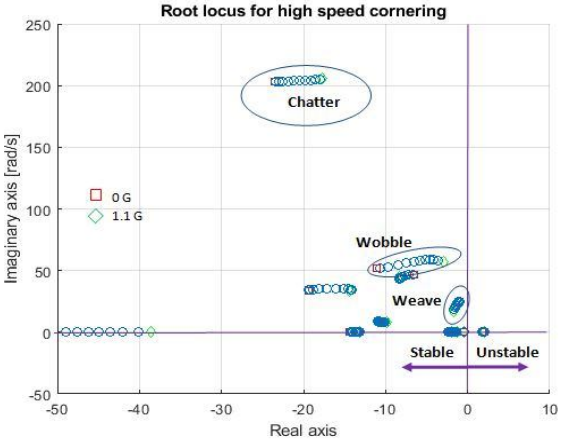


Fig. 4. Root-locus for high speed cornering

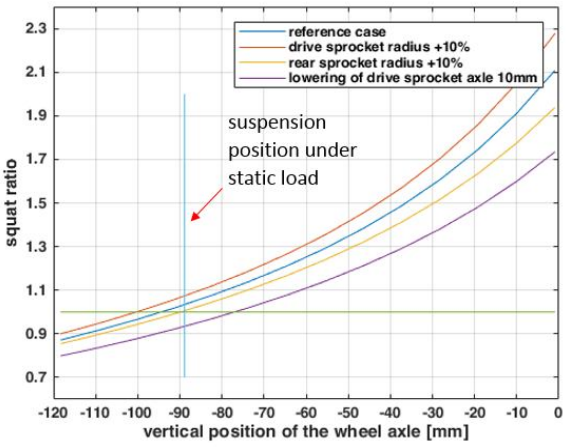


Fig. 5. Squat ratio versus vertical position of the rear wheel axle

Using Matlab software for the assumed final ratio vertical distance between drive sprocket and swingarm axle has been appointed. Thrust and chain force slightly extend suspension (squat ratio < 1) in its position under weight of the rider and motorcycle. As it is shown in the Fig. 5 increasing by 10% radius of

the rear sprocket has an positive effect, because it strengthens the effect of suspension extending. Increasing by 10% radius of the drive sprocket has an opposite effect. Lowering of the drive sprocket axle by 10 mm has strong negative effect on the rear suspension behavior. However, for all cases curves has similar increasing deviation.

III. DEVELOPMENT

A. Fuel Supply System and Induction System

The fuel supply system uses the Yamaha YZ250F throttle with the Electronic Fuel Injection (EFI) and with an increased throat diameter in relation to the throttle dedicated to the KTM RC250 engine. The air cleaner box has been 3D printed in Selective Laser Sintering (SLS) method from Polyamide PA 2200 material (density: 930 kg/m^3).

The location above the cylinder head requires the use of a material with high melting point (176°C for Polyamide PA 2200), limits the length of air supply ducts and allows the

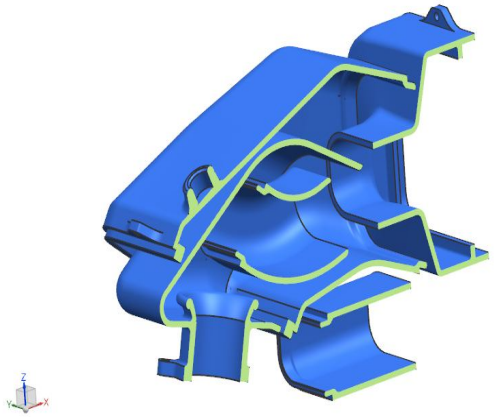


Fig. 6. STL model for SLS 3D printing of intake system

centralization of the mass. The air cleaner box, with 5 liters of capacity, contains an air filter and air pressure sensor. The air inlet, located under the bottom triple clamp in the high pressure zone, promotes optimal engine filling. The modular design allowed to reduce manufacturing cost and allowed to print all the elements in the working area 195x220x300 mm (Fig. 6).

The thin-walled fuel tank with capacity of 8 liters, welded from aluminum alloy 5754, has been moved from the area above cylinder head (a typical solution for road motorcycles) towards the rear of the motorcycle to centralize the mass and reduce the moments of inertia. The use of an external fuel pump allowed to lower the fuel tank and position it in the subframe area. The location near the center of gravity of the entire structure allows to compensate the impact of changing the volume of fuel during the race (Fig. 8). In accordance with [7], the tank has been filled with flame retardant foam, which counteracts the rapid change of the center of mass due to the

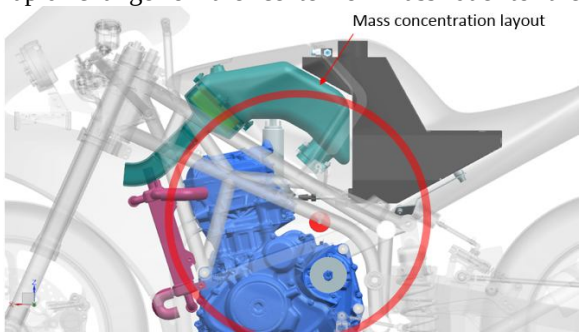


Fig. 7. Induction and fuel system layout

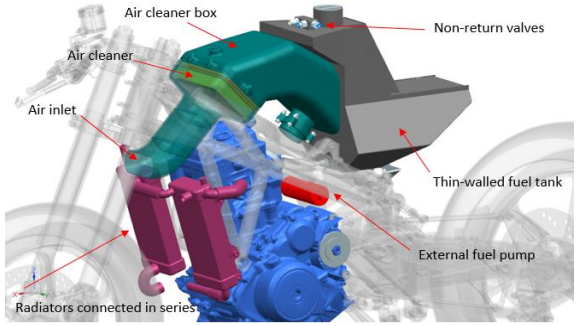


Fig. 8. Induction and fuel system

movements of the fuel inside the tank. In addition, two non-return valves with opening pressure of 0.2 bar were used, which protects against spillage of fuel in the event of a motorcycle rollover (Fig. 8). The first of these allows the escape of fuel vapors through the catch tank and counteracts the emergence of danger overpressure. The second one allows filling the volume of fuel with air and counteracting danger under pressure.

B. Frame and swingarm design

The main goal in the design of the chassis (Fig. 12) was the development of a compact structure based on the KTM RC250 engine, which allows the mass centralization and obtaining as low moments of inertia as possible increasing the motorcycle's ability to quickly change direction. Main features of chassis design:

1) Engine tilted by 3 degrees rearward relative to position in road motorcycle KTM RC250.
2) Adjustable caster angle and front suspension offset using replaceable inserts.
3) Inverted shape swingarm with axial loose clearance mechanism.
4) ProLink linkage system.

The chassis design is a steel trellis frame made of chromium molybdenum steel 4130 tubes and structural steel as attachments points. The engine, attached in three points in open structure is used as a

rigid rod closing the frame structure enhancing torsional and lateral stiffness of the whole construction [5]. Using the Finite Element Method (FEM) model (built of second-order shell, solid and beam elements) was developed a solution based on two rows main tubes providing high torsional stiffness which increases performance in fast chicane maneuvers.

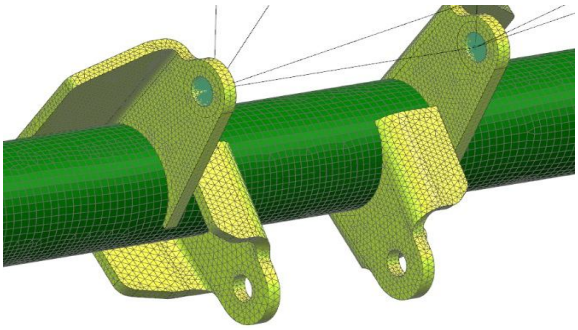


Fig. 9. First design of bottom engine attachments

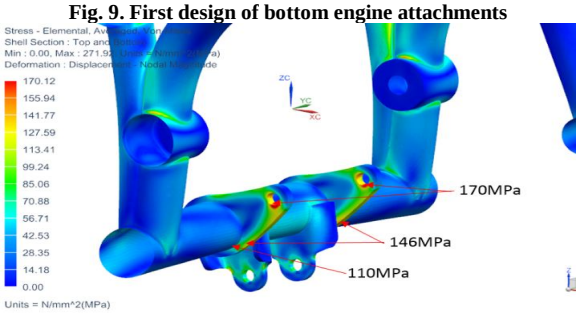


Fig. 10. Von Mises stresses on redesigned bottom engine attachments

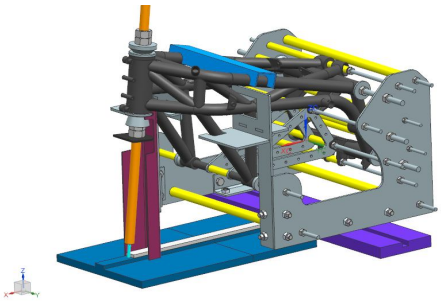


Fig. 11. Frame welding jig

Strength analysis were performed for four load cases for previously assigned loads. With total weight of 8 kg developed solution provides torsional stiffness at the level of 4100 N·m/deg (measurement with the engine mounted). The use of FEM simulations at the initial stage allowed to locate dangerous areas. Based on the calculations, the area of the lower engine attachments was redesigned (Fig. 9), which allowed to reduce the von Mises stresses from 280 MPa to 170 MPa in the vicinity of the mounting hole (Fig. 10).

For torsional and lateral stiffness tests [6] results for a simplified beam and complex shell FEM model were compared (

Table II). Calculations were performed taking into account the presence of the engine.

Differences between models can be observed for torsional stiffness test case with engine presence. This discrepancy is a result of simplified CAD model of top and bottom engine attachments in beam model. Properly attached engine has strong influence on the frame torsional stiffness and natural frequency.

Elements were welded together using Tungsten Inert Gas (TIG) method (Fig. 13). Used ER-70s welding wires for tubes thickness below 3 mm avoid the need for heat treatment after welding [4]. Dimensional stability was achieved by developing the construction of the welding jig shown in the Fig. 11. By determining the relevant construction points with the help of precision drawn bars and fitted sleeves, the influence of thermal stresses on the deformation of the frame in the welding process was reduced. In the economy aspect, the total manufacturing cost of the frame has been lowered by developing a design that does not require expensive machining in steel.

Replaceable inserts (blue elements in Fig. 14) allows adjusting of caster angle in the range of +/- 0.7 deg. Machining of the insert for a non-zero position requires using a 5-axis CNC machine or special holders for conventional 3-axis milling machines. Eccentric holes in the

Table II. Comparison of beam and shell model

	Engine presence	Beam model	Shell model
Torsional stiffness [N·m/deg]	with	3228	4098
	without	1247	1309
Lateral stiffness [N/mm]	with	2174	2222
	without	1639	1685

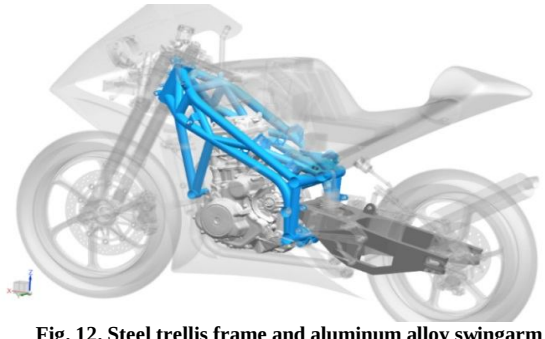


Fig. 12. Steel trellis frame and aluminum alloy swingarm



Fig. 13. TIG welded frame of developed PreMoto3 motorcycle

elliptic inserts (red elements in Fig. 14) allows the suspension offset to be adjusted in the range of 0 - 2.76 mm, which allows to change key parameters from the driving characteristics point of view. Machined triple clamps of high-strength aluminum alloy 7075 were optimized using ANSYS Topology Optimization in terms of mass and stiffness.

The inverted shape swingarm in comparison with typical solutions provides to shift toward the front a center of gravity to concentrate mass and as the result to decrease moments of inertia of the whole structure. It was designed as a TIG welded construction of aluminum alloy 6082 T6 sheet metal components and rectangular profiles (Fig. 17).

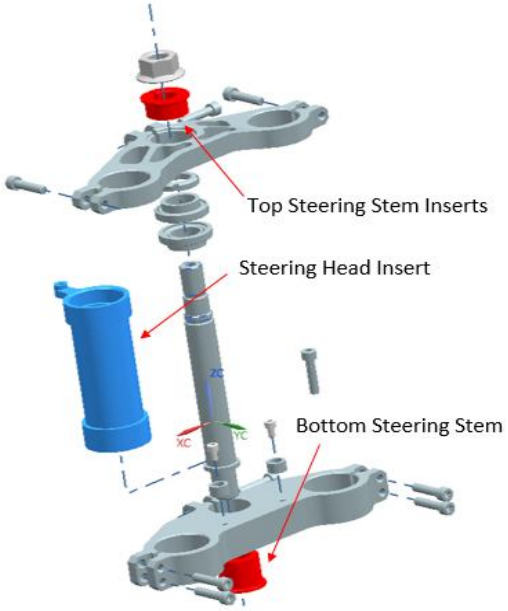


Fig. 14. Triple clamp assembly with caster angle and trail regulation

The use of metal sheets and standard extruded aluminum alloy profiles allowed to reduce expensive machining operations to minimum. The use of 4043 welding wires allowed (after heat treatment) partial restoration of strength and durability properties in the Heat Affected Zone (HAZ). After optimization carried out during design process an overall mass of swingarm is 4.2 kg with lateral stiffness 1030 N/mm (Fig. 18). Though it's unsymmetrical shape there is difference in torsional stiffness in clockwise and counterclockwise direction (Fig. 15). Furthermore, the torque does not act along the axis of symmetry in the height of the rear wheel spindle. The developed swingarm stiffness parameters for torque acting along the motorcycle axis of symmetry, that were estimated using shell FEM model, are included in Table **III**.

According to Fig. 16 axial loose between swingarm spacers and swingarm attachment points in the steel trellis frame (2) can be removed with use of an adjusting bolt (3). The adjusting bolt (3) can be tighten to the specified torque turning the pivot bolt (4). Lock nut (1) prevents loosening of the adjusting bolt (3). Using the adjusting bolt instead of distance bushings simplifies the assembly process and eliminates any looseness in frame-swingarm assembly.

The ProLink rear suspension system (Fig. 19) was developed using the kinematic model created in MSC Adams software, which allowed to determine characteristics of the lever mechanism (e.g. spring deformation versus vertical wheel displacement, spring deformation velocity versus vertical wheel displacement) and to determine forces acting on suspension components, which were later used in FEM analysis.

Table III. Comparison of arm deflection in torsional stiffness test

Deflection of the left arm [mm]	Deflection of the right arm [mm]	Torsional stiffness [N·m/deg]
1.68	1.06	681 / 856

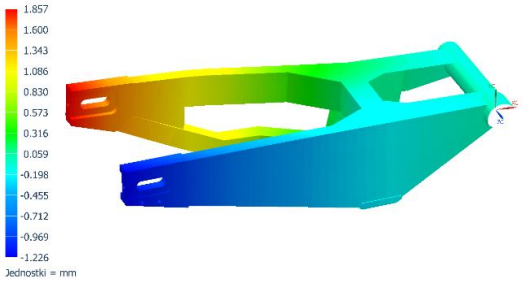


Fig. 15. Vertical deformation in torsional stiffness test [mm]

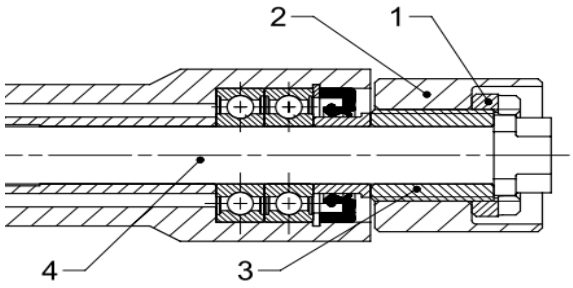


Fig. 16. Right swingarm attachment point with adjusting bolt design

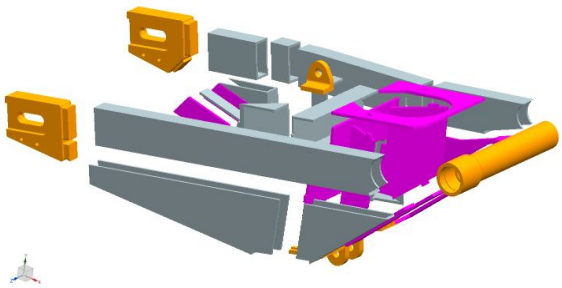


Fig. 17. Swingarm components – extruded aluminum (grey), sheet metal (violet), machined aluminum (orange)

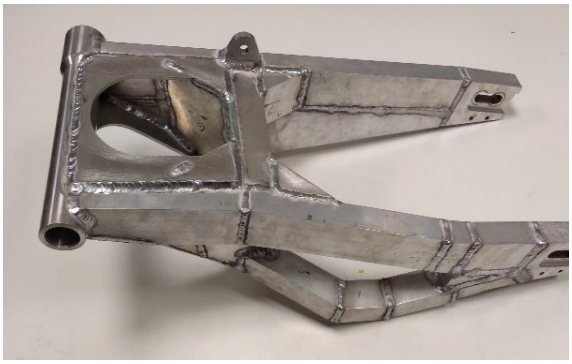


Fig. 18. Swingarm after TIG welding and heat treatment process

For developed linkage system the ratio between the vertical velocity of the wheel and the deformation velocity of the spring varies from 2.2 in fully rebound position to 2 for fully compressed position (Fig. 20). For low frequency excitations related with high spring deformations the ability of the system to damp vibrations increases. A typical range of speed ratio values varies from 2.0 to 4.0 [1]. The lower speed difference, the smaller shock absorber can be used, which results in weight reduction. In addition, the compact design of the ProLink mechanism allows the placement of the lever system mass closer to the center of gravity.

Strength calculations of ProLink system was based on forces evaluated using kinematic model built in Adams software. The full compatibility of the reaction forces with the kinematic model was achieved by modeling the entire lever mechanism assembly including the simplified definition of the shock absorber and shock arm attachment

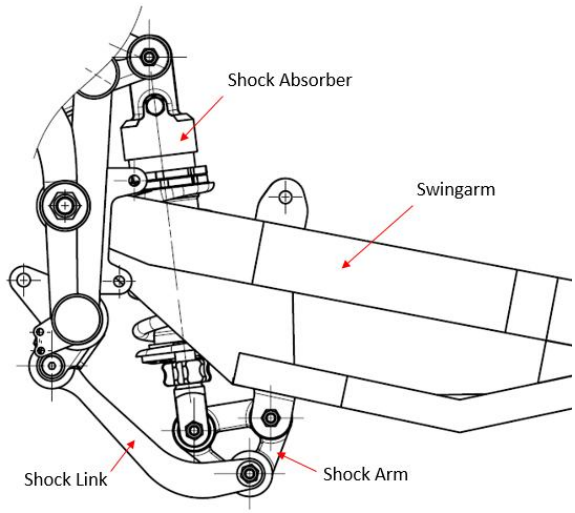


Fig. 19. Geometry of ProLink rear suspension system

in the swingarm. According to Fig. 21 forces acting on the lever mechanism and the swingarm were modeled as a load with bearing distribution (A). As a constraints cylindrical joints in shock's mounting (B) and fixed constraint on surfaces in shaft (C) were used. All bearings were simulated as sleeves (4) connected with housings by cylindrical face gluing, and shaft (5) combined with sleeve (4) by cylindrical face contact. Shafts (5) are connected with the shock link (2) and shock absorber (3) by surface gluing.

Using nonlinear structural analysis full compliance with the kinematic model was achieved. After iterative process of design changes maximum stresses in the shock arm have been reduced to the level of approximately 100 MPa for 2017A aluminum alloy (Fig. 22).

For elements with predetermined geometry, like wheel spindles or the swingarm pivot axle, replacing steel with titanium alloy Ti-6Al-4V allowed to weight reduction of approximately 43%.

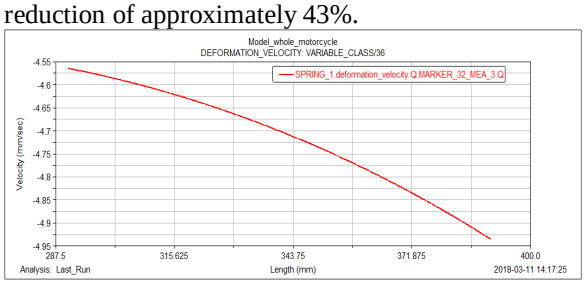


Fig. 20. Spring deformation velocity versus vertical wheel displacement for constant vertical wheel velocity v_w = 10 m/s

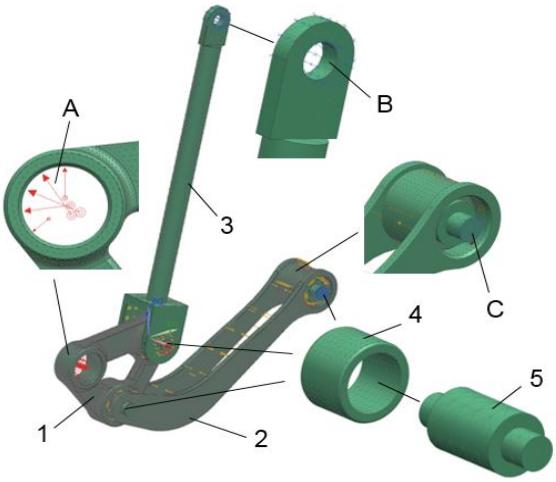


Fig. 21. FEM model of the lever system assembly

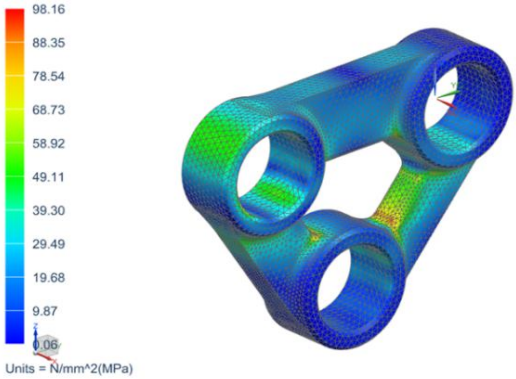


Fig. 22. Mises stresses on the shock arm in the worst load case

C. CFRP monocoque subframe

The use of a monocoque subframe made of epoxy-carbon composite allowed to reduce the weight by about 1.5 kg in relation to the weight of the

aluminum subframe along with rear seat fairing. The integration of several elements within one module reduces the labor-intensity of service work enabling the removal of the whole module by unscrewing four screws. Moving the electronic modules from under the seat into the area of engine and instrument panel allowed to move the center of gravity towards the front reducing the length and weight of the wires. The introduced division of the subframe module into three separate elements allowed to simplify the molds and models.

D. Aerodynamics and fairings

For PreMoto3 class motorcycles, due to low engine power, aerodynamic drag F_D is crucial and can be defined as the relationship [3]:

$$F_D = 0.5 \cdot \rho \cdot C_D \cdot A \cdot v^2 \quad (1)$$

where ρ – density of the air, C_D – drag coefficient, A – frontal area, v – forward velocity of the motorcycle.

Vertical component reduces the load on the front wheel and in some cases on the rear wheel. For evaluation of lift force in (1) parameter C_D should be replaced by parameter C_L which represents the lift coefficient.

Using Computational Fluid Dynamics, design of fairing and inclination angle of front screen was optimized performing 2D and 3D calculations. Simulations were performed using k-ω SST turbulence model taking into account pressure drop on radiators modeled as porous media domain. Inlet of intake system was placed in high pressure area in the axis of motorcycle symmetry (Fig. 23). After iterative process of small changes in fairing shape (Fig. 24), values of drag area ($C_D A = 0.24$ m^2) and lift area ($C_L A = 0.03$ m^2) corresponds to values reached by Grand Prix motorcycles in 2-stroke 125 cm^3 displacement class.

Using a carbon fiber instead of a glass fiber allowed to reduce the weight of the aerodynamic package by 38 % for laminate of approximately equal stiffness. The stiffness and strength of carbon fiber allowed to use only four layers of fabric with aramid fiber reinforcement in the proximity of fairing fastenings. Only two-piece front fairing with four attachment points (quick release system with split pins) facilitates servicing possibilities.

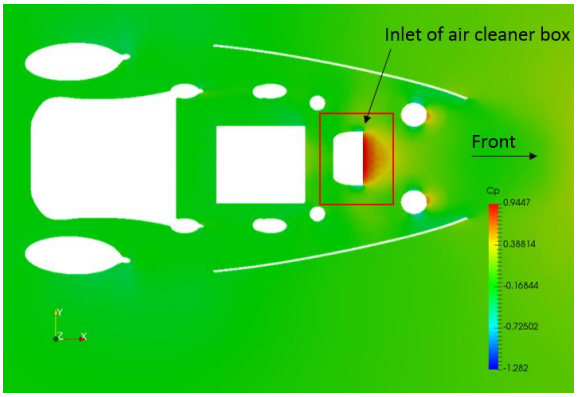


Fig. 23. Pressure distribution C_p on the height of air inlet to the air cleaner box

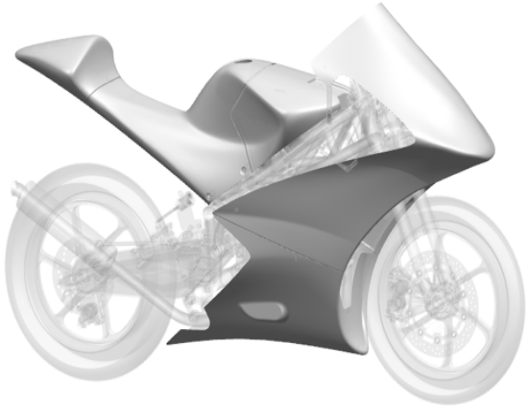


Fig. 24. Aerodynamic package

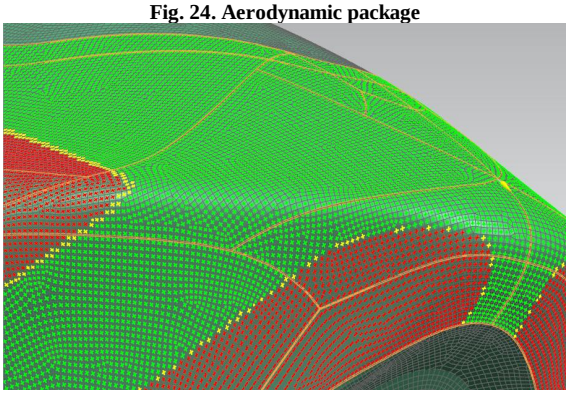


Fig. 25. Fabric draping possibilities, yellow indicates warp & weft fibers close to lock angle, red indicates that maximum allowed shear between warp & weft has been exceeded

Furthermore, front fairing can be manufactured using the one element mold. Due to using CAD software, it is possible to facilitate the manufacturing process by predicting fabric workability and preparing two-dimensional templates. Using Siemens NX 11 Laminate Modeler and Draping Methodology allowed to predict shear between warp & weft fibers, which improved and shorten manufacturing process (Fig. 25). Draping algorithm for woven fabrics allows fibers rotate to each other assuming that the fibers are inextensible. Due to possibility of creating flat patterns the waste of material and probability of error were strongly reduced. Wet lay-up with vacuum bagging reduces the overall manufacturing and material cost.

E. Data acquisition system

The system of measurement and data acquisition is based on Engine Control Unit (ECU) and Raspberry PI 3 minicomputer. The simplified scheme of electronic control system is shown in the Fig. 26. All of analog sensors (except the linear suspension potentiometers) are connected with ECU, which is responsible for proper engine operation. Some of the data collected by ECU is transferred via UART transmission protocol to the additional computer PI 3. The ECU controls operation of the engine and determines ignition timing and the amount of fuel that

should be injected into engine. The system has additional sensors like GPS, accelerometer with gyroscope and linear suspension potentiometers. Communication between analog linear suspension potentiometers and data acquisition system forced the addition of an analog-digital

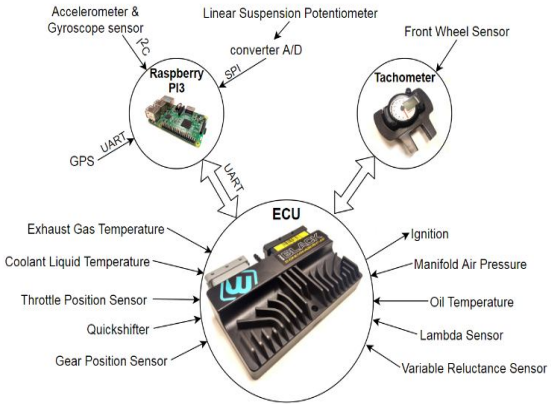


Fig. 26. Simplified scheme of electronic control and data acquisition system

converter. All the data can be read using a computer by USB communication. The tachometer has an external front wheel speed sensor and is connected with the ECU.

CONCLUSION

Developed motorcycle based on the road motorcycle engine is a cheaper alternative in comparison with constructions equipped with prototype engines or high efficiency engines from motocross motorcycles. Road motorcycle engine also allows to extend maintenance intervals and lower maintenance costs. Developed PreMoto3 motorcycle equipped with engine with smooth power delivery mounted in a full prototype chassis is a product which should met all requirements of young riders at the beginning of their careers.

MotoStudent competition is an interdisciplinary competition and a first step for young engineers, which gives the opportunity to participant in a commercial project going through all the phases associated with the launch of the product on the market.

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