Methodology for Effective Design of Motorcycle Structures

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***Abstract*—One of the important tasks that goes before the main stage of motorcycle design is the choice of the motorcycle type. This paper discusses the main types of motorcycles, their characteristics, design features, and geometric parameters that need to be taken into account at the very first stage of product development – the technical proposal. This paper also discusses the forces acting on various parts and components of the motorcycle, and various load cases (when braking/accelerating sharply or turning). Determining the external forces that act on the motorcycle is very important for setting input parameters for calculating topological optimization and generative design. Topological optimization and generative design are the most important technologies for effective design of various motorcycle structures. They are embedded in separate calculation modules of modern CAE programs. Without knowledge of the load conditions and forces that act on various elements of the motorcycle, it is impossible to make an accurate calculation to optimize the mass of the structure or to conduct a generative design for parts and components of the motorcycle. Therefore, the method of effective design consists not only in the application of topological optimization and generative design, but also mainly in the knowledge of design features, geometric parameters, external forces, and load conditions of various types of motorcycles.**

***Index Terms*— stress analysis, strength analysis, input parameters, static forces, dynamic forces, topology optimization, load cases**

I. Introduction

Motorcycles as well as cars are divided into different categories (types): cruise, tourist, sports and others.

When choosing a specific type for designing a motorcycle, you need to take into account its features such as: wheelbase length, trail, weight distribution on the front and rear axles, handling, stability. Handling and stability are closely related to the geometry of the motorcycle. For example, increasing the castor leads to an increase in the trail, which increases the stability of the motorcycle but at the same time reduces the handling of the motorcycle on the road [9]. We'll look at this in more detail in the following sections of the paper.

After determining the type selection, designers consider what loads are experienced by various elements of the motorcycle structure and in what load modes the motorcycle will operate. As the loading modes considered critical variations of loads on the elements of a motorcycle. For example, the critical load for the front steering column occurs at the moment of hard braking of the motorcycle when the rear wheel begins to detach from the road [10, 11].

Knowing the forces acting on the motorcycle elements and load conditions helps you accurately set input parameters for generative design and topological optimization. For example, topological optimization suggests building a model based on an existing model based on several criteria (weight reduction, increased strength) [12, 13]. For generative design, you don't need to have a source model. It is enough to specify the main structural elements and fasteners, and apply loads to them depending on the loading case. After that, generative design will offer many solutions to the problem based on various manufacturing methods. This option is more resource-intensive in contrast to topological optimization. Using this approach can significantly reduce the time required for design development and reduce the weight of the finished product (motorcycle).

Without knowledge of the forces applied to the elements of the motorcycle, we cannot accurately check or create a new motorcycle design. Motorcycle structural elements such as the frame and rear fork using topological optimization or generative design can be too light and cannot withstand external loads or become too heavy. Products such as the frame and rear must be designed so that when an external load is applied, the stresses are the same everywhere. Only in this case are products with a minimum weight obtained.

II. Motorcycle Geometry

Let's start by looking at the standard motorcycle geometry shown in Fig1. It is important to note that the motorcycle itself consists of two structural groups, connected by a steering column [1, 2]. The first group includes the front fork, front wheel, steering wheel, headlights and other parts that move when the steering wheel is turned. The second group includes the frame, electric motor, rear wheel, battery pack and all components that do not move with the control system. The second group also includes the driver.

The axis of the steering column is inclined at an angle αn relative to the road. The distance c between the points A of intersection with the road axis of the steering column and B - the contact of the front wheel with the

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road is called the offset of the front fork. The average values of the protrusion of the front fork of motorcycles with 80-100mm trail and the angle of inclination of the steering column αn = 60-62 °. The running weight of a motorcycle G with driver and luggage is centered at the center of gravity C and distributed between the front and rear wheels into components G1 and G2

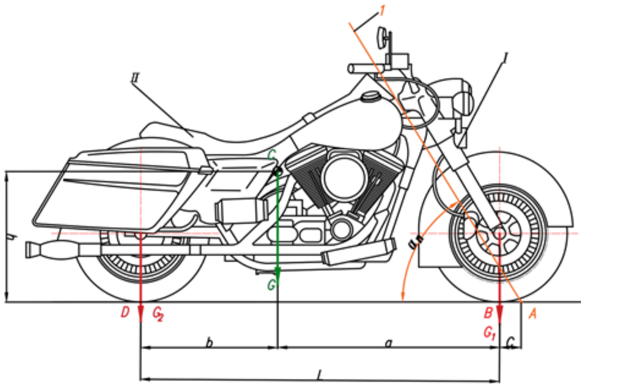

Figure 1. Main parameters of the motorcycle:

I, II - design groups of the motorcycle; α_n is the angle of inclination of the steering column axis; **c** - trail; L-motorcycle base; G is the running weight of the motorcycle; h, b - coordinates of the center of gravity; 1- steering column axis

The trail c is a very important parameter in a motorcycle, it is responsible for the stability of the motorcycle on the road. The stability factor R of a motorcycle is calculated using the formula:

R_n=c/(L+c)*100% , where L is the center distance of the motorcycle wheels, if the value of c takes a negative value, then the motorcycle is not stable while driving [4].

For clarity, consider the geometric parameters of various motorcycle models

The geometric characteristics of the steering column. The values of the angle of the steering column - castor β_1 will vary depending on the intended use of the motorcycle. For example, on motorcycles for speedway it is 19 °, for sport bikes 21-24 °, for touring motorcycles 27-34 °.

The trail value controls with the angle of the steering column. For a feeling of good motorcycle handling when zooming in. Trail parameters also vary depending on the type of motorcycle and its wheelbase, ranging from 75-90mm on sport bikes, 90-100mm on sport bikes and up to 120mm on heavy hikers.

The size of the wheelbase is considered depending on the motorcycle. Length 1200 mm for small scooters, 1300 mm for light motorcycles (125 cc), 1350 mm for medium bikes (250 cc) and 1600 mm for large touring motorcycles.

R_P-motorcycle steering ratio R_P= c/(L+c)*(N_f/N_r), where N_f is the load on the front wheel, and N_r is the load on the rear wheel.

III. Motorcycle Types

Let's consider in more detail each type of motorcycle, its geometric parameters and features. We will compare sport bikes, choppers, cruisers and touring motorcycles in detail. We will also look at the main differences between scooters and motorcycles. The main types of motorcycles are shown in Fig. 2.

Figure 2. Motorcycle types.

Fig. 2 shows 4 types of motorcycles (sport bikes, choppers, cruisers, touring motorcycles) and a scooter. In the upper left corner – Honda VTR1000F; in the upper right corner –Suzuki GSX-R 750; in the middle left – Harley Davidson 1200 Sportster; in the middle right – Kawasaki VN800; in the lower left corner – Honda XL600V Transalp; in the lower right corner – Aprilla Gulliver 50.

The most important parameters for the problem under study are shown in Table I for sport bikes.

TABLE I. Sport Bikes

Honda VTR1000F (Fig. 2-a)					
L, mm	β_1, deg	c, mm	Weight distribution %	R_n	R_P
1430	25	97	49.2/50.8	6.35	6.14
Suzuki GSX-R 750 (Fig. 2-b)					
L, mm	β_1, deg	c, mm	Weight distribution %	R_n	R_P
1395	24	96	50.4/49.6	6.44	6.54

Sport bikes have good handling and gain high speed due to forced (high-speed) engines. Landing on a sports bike is tilted forward, for better streamlining, the driver lies with his chest on the tank during the race. Wheels are light-alloy wheels with relatively wide rubber for better grip. A plastic body kit is installed on motorcycles to improve aerodynamic properties. The wheelbase varies from 1390 to 1430 mm. The angle of inclination of the front fork relative to the vertical is 23-25. Weight distribution in modern sports bikes tends to be 50/50 front and rear respectively.

Table II shows data for choppers.

TABLE II. CHOPPERS

Harley Davidson 1200 Sportster (Fig. 2-c)					
L, mm	β_1, deg	c, mm	Weight distribution %	R_n	R_P
1485	29,6	116,8	45/55	7.29	5.96

Choppers are heavy bikes that provide a low, feet-first ride. This type of motorcycle does not have side fairings. Equipped with low-speed engines. Poor handling (RP = 5.96).

Let's compare the parameters of the considered types of motorcycles with the cruiser parameters, which are shown in Table III.

TABLE III. CRUISERS

Kawasaki VN800 (Fig. 2-d)					
L, mm	β_1, deg	c, mm	Weight distribution %	R_n	R_P
1625	34	149	43/57	8.4	6.34

This type of motorcycle is similar to the driver's landing with choppers. Cruisers have a longer wheelbase compared to choppers and a greater angle of inclination (β_1=34°) of the front fork relative to the vertical. Due to the greater angle of the fork, the trail increases and, as a result, stability on the road increases. Motorcycles of this type have the best stability on the road (R_n=8.4). However, at the same time, cruisers lose in handling to sports motorcycles.

Table IV shows data for touring motorcycles.

TABLE IV. TOURING MOTORCYCLES

Honda XL600V Transalp (Fig. 2-e)					
L, mm	β_1, deg	c, mm	Weight distribution %	R_n	R_P
1505	28	108	47.4/52.6	6.7	6.03

Tourist motorcycles are designed for long-distance trips. They have a more comfortable and high landing compared to choppers and cruisers. This type has the most capacious fuel tanks, provides for the installation of additional trunks (small Luggage compartments), which increases the curb weight of the motorcycle. Motorcycles have a long wheelbase: from 1500mm to 1600mm. Lower handling compared to sports motorcycles (R_P= 6.03).

At the end of the review, we will consider the scooter parameters, which are shown in Table V.

TABLE V. SCOOTERS

Aprilla Gulliver 50 (Fig. 2-f)					
L, mm	β_1, deg	c, mm	Weight distribution %	R_n	R_P
1255	25,5	55	42/58	4.2	3.04

Due to the fact that the engine, CVT (Continuously Variable Transmission), and tank of scooters are located next to the rear wheel, most of the weight is applied to the rear axle. In some scooters, the weight distribution can reach 30/70 in favor of the rear axle. This weight distribution can cause the front wheel to roll over or frequently lift when accelerating sharply. Scooters have poor stability (Rn=4.2) and terrible handling (RP=3.04), which is clearly evident at high speeds. Scooters, unlike motorcycles, have a smaller wheelbase (1200-1255 mm) and smaller wheels of 10-13 inches, which greatly reduces cross-country performance.

IV. CENTER OF MASS POSITION

The position of the center of the motorcycle's mass is important in determining the loads that act on different parts of the motorcycle. In Fig. 3 we can see how the center of gravity shifts when the driver sits on the motorcycle. When the rider sits on the motorcycle, the center of mass shifts to the rear axle on all types of motorcycles.

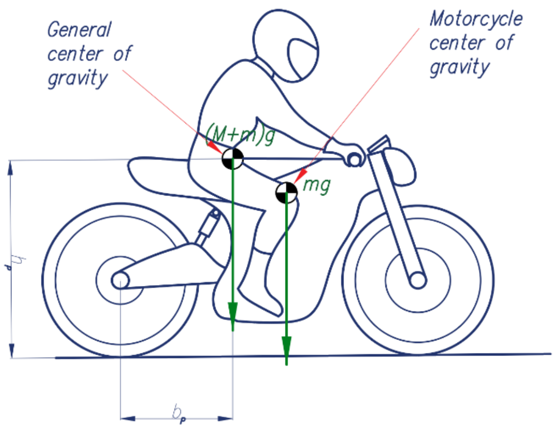

Figure 3. The position of the center of gravity of a motorcycle with and without a driver.

The height of the center of gravity of the motorcycle alone has values ranging from 0.4 to 0.55 m, but the presence of the driver raises it to values ranging from 0.5 to 0.7 m.

The h/L ratio without a driver and with a fully extended suspension ranges from 0.3m to 0.4m; lowest values for cruising motorcycles and scooters, highest for enduro motorcycles.

V. ACTION OF STATIC AND DYNAMIC FORCES

Consider the static and dynamic forces acting on a motorcycle [5-8]

The action of static forces. The C_1 center of gravity of structural group I is located at a distance from the steering column axis.

Because of this, when the motorcycle deviates from the vertical plane by an angle β_1, a moment is created that turns the fork in the direction of the inclination: $M_1=G_1 r\sin\beta_1$ (if the driver does not turn the steering wheel), G_1 is the gravity force of structural group I. At points B and D (see Fig. 4), horizontal reactions occur due to the deviation of the general center of gravity.

The overall horizontal response is:

$Y=Y_1+Y_2 = P_1 tg\beta_1$, where Y_1 is the horizontal reaction of the front wheel, Y_2 is the horizontal reaction of the rear wheel. Then:

$Y_1=G\frac{b}{L}\,tg\beta_1$; $Y_2=G\frac{L-b}{b}\,tg\beta_1$

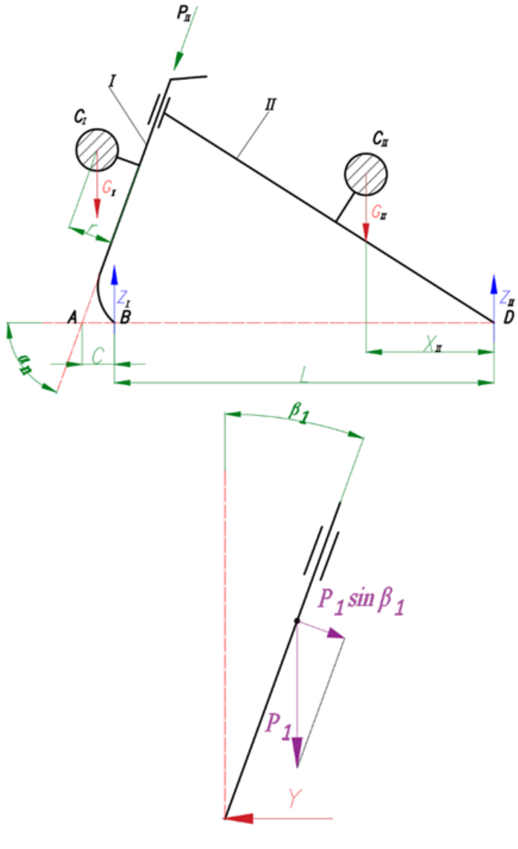

Figure 4. Static diagram of motorcycle

The torque applied to the front fork is defined as:

$M_{Y1}=\mathbf{Y_1}c\sin\alpha_1\cos\beta_1 = G\frac{b}{L}\,\mathbf{c}\sin\alpha_n\sin\beta_1$;

The steering column rises when the front fork is turned, therefore the gravity force of structural group II, concentrated in the center of gravity of C_{II}, prevents the rotation of the control group I nodes. This force is directed along the axis of the steering column and is determined from the conditions of equality of moments relative to point D:

$P_{II}(L+c)\sin\alpha_n=G_{II}x_{II}$; $P_{II}=G_{II}\frac{x_{II}}{(L+c)\sin\alpha}$

Actions of dynamic forces. In addition to static forces, a moving motorcycle is also affected by dynamic forces, which include:

- gyroscopic effect of rotating masses
- centrifugal forces
- reactive forces of rolling tires
- inertial forces of distributed masses

The gyroscopic effect of rotating masses. To determine the gyroscopic moment, the formula is used:

$M_r=\mathbf{J\omega_1\omega_2}\sin\boldsymbol{\alpha_B}$, where J is the moment of inertia of the gyroscope; $\boldsymbol{\omega_1}$- angular speed of gyroscope rotation; $\boldsymbol{\omega_2}$- angular velocity of gyroscope axis rotation; $\boldsymbol{\alpha_B}$ is the angle between the direction of the angular velocity vectors. When $\boldsymbol{\alpha_B=90°}$, $\mathbf{M_r= J\omega_1\omega_2}$;

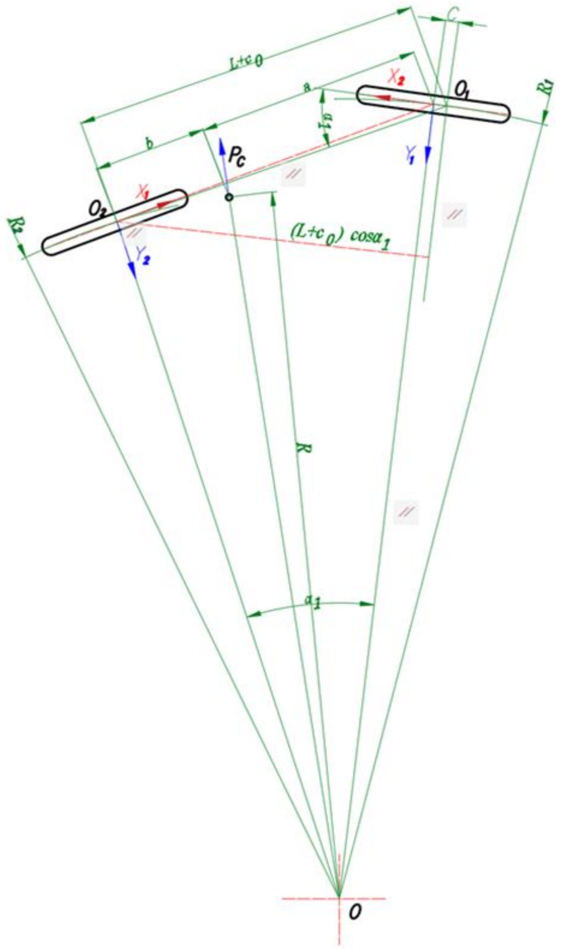

Figure 5. Diagram of the forces that act on the motorcycle when driving along a curve.

Centrifugal forces. When the motorcycle moves on the road at a constant speed in a straight line, the following forces act on the motorcycle: the gravity force of the motorcycle with the driver G, (applied at the center of gravity); vertical reactions Z_1 and Z_2, applied at the points of contact of the wheels with the road and balancing the force of gravity; traction force $P_K = X_2$, directed towards the movement; front wheel rolling resistance X_1 against the motion (see Fig. 6). When the motorcycle moves along a curve (that is, when entering a turn), a centrifugal force Pc also appears, applied at the center of gravity and lateral reactions Y_1 and Y_2, balancing the action of the centrifugal force.

The instantaneous center of curvature O is at the point of intersection of the perpendiculars to the tangents drawn in the road plane to the wheels. Front wheel turning radius:

$R_1 = \frac{L+c}{sin\alpha} - c*tg\alpha_1$, where α_1 is the angle of rotation of the front wheel relative to the rear. Fig. 5 shows that the wheels roll along a trajectory with different radii, since $R_2 = R_1 cos\alpha_1$ the wheels roll at different speeds. Centrifugal force when turning:

$\mathbf{P_c} = \frac{G}{g} \bullet \frac{v^2}{R}$

We can assume that the force P acts parallel to the axis OO_2, since the size of the segment b is much less than the value of the radius R.

When the motorcycle is moving under drag force: $X_1 = Z_1 f = Gf\frac{L-a}{L}$; $X_2 = P_k$;

Fig. 5 shows that the reactions X_1 and X_2 are in different directions. When the motorcycle brakes:

$X_1 = P_{m1}$; $X_2 = P_{m2}$;

The reaction Y_1 is determined from the equation of the equilibrium of moments about the axis passing through the point O_2 of the rear wheel touch [3]:

$Y_1((L+c_0)cos\alpha_1 - c) - X_1(L+c_0)sin\alpha_1 - P_c b = 0$

$Y_1 = (P_c b + X_1 L sin\alpha_1)/L cos\alpha_1$

We find the reaction Y_2 by projecting the acting forces line OO_2. Let us make the equations:

$Y_2 + Y_1 cos\alpha_1 - X_1 sin\alpha_1 - P_c = 0$;

$Y_2 = P_c + X_1 sin\alpha_1 - Y_1 cos\alpha_1 = P_c + X_1 sin\alpha_1 - P_c\frac{b}{L}$

$- X_1 sin\alpha_1$; $Y_2 = P_c(1 - \frac{b}{L}) = P_c\frac{a}{L}$.

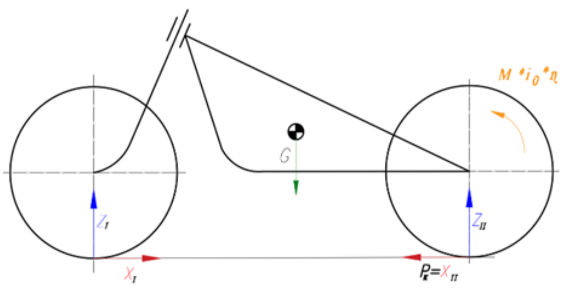

Figure 6. Diagram of the forces that act on a motorcycle when driving on a horizontal road at a constant speed in the forward direction

In addition to the action of reactions at the points of support of the motorcycle, the centrifugal force tends to overturn it relative to these supports in the direction opposite to the turn. To keep the motorcycle stable, it must be tilted towards the corner.

According to the equilibrium condition of the motorcycle, the sum of the moments of forces relative to the O_1O_2 axis is zero: $P_c h_d = G h_d tg\beta_1$; but since $P_c = \frac{Gv^2}{gR}$ then $\frac{v^2}{R} = gtg\,\beta_1$, i. e. the resultant forces G and P_c are in the plane of the motorcycle.

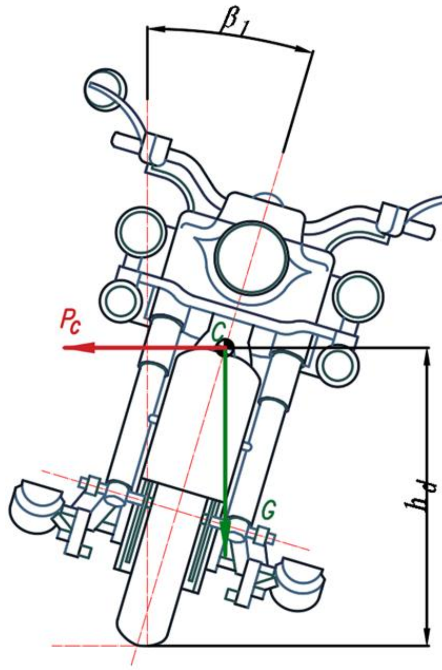

Figure 7. Diagram of the forces acting on the motorcycle when driving along a curve

When the motorcycle moves along a curve in the center of gravity C_1, a centrifugal force P_{c1} arises, which is a component of the total centrifugal force P_c (see Fig.7). This component tends to rotate structural group I to its original position and can be determined by the formula:

$P_{c1} == \frac{G1}{g} \bullet \frac{v^2}{R}$.

Moment with which the force P_{c1} acts on group I in a plane perpendicular to the steering column axis: $M_{Pc1} = P_{c1} r cos\alpha_1 cos\beta_1$

The influence of centrifugal force on group I is opposite to the influence of static forces.

VI. Conclusion

Thus, the research conducted in this article allows us to draw several important conclusions:

- At the very first stage of development (technical proposal), it is important to choose the type of motorcycle.

- Comparative analysis of different types of motorcycles shows that sports motorcycles that have the best speed characteristics are designed with an emphasis on handling. More modern models are made with a 50/50 weight distribution for better braking properties. Cruisers, choppers, and touring motorcycles have their center of mass shifted much closer to the rear axle than sport bikes, which makes their braking performance worse. But cruisers and choppers have better stability on the road because of the larger castor. It is important to understand that each type of motorcycle is designed for certain operating conditions and you always have to choose between stability and handling. Sports motorcycles are designed for the track, for these conditions, landing is important (influence on streamlining) and handling, but for the sake of increased handling, they sacrifice stability, which is compensated by the driver's experience and control skills. Cruisers and choppers are designed for slow trips over medium distances, so they do not care about increased handling at high speeds, which is why handling is neglected in favor of stability. Tourist motorcycles are designed for comfortable long-distance travel, so they can't be designed with an uncomfortable sports fit (despite the fact that the sports fit is better in terms of aerodynamic qualities).

- The considered static and dynamic forces will help to accurately set input parameters for generative design and topological optimization

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

O. O. Baryshnikova formulated the research direction, problem statement, and edited the article.

D. V. Strugovshchikov analyzed the design features, loading factors, formed a calculation model, and wrote an article.

All authors had approved the final version.

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