Dynamic Damper Control Extension for Two-wheeled Applications

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***Abstract*— This paper presents the development of a dynamic control system that expends the functionality of the shock absorber of a two-wheeled, human propulsion vehicle, which adapts to road conditions, both in urban and off-road environments. The road surface and tilt dependent dynamic damper control system reduces vibrations and enhances stability, resulting in a smoother and safer ride, with increases efficiency and versatility.**

***Keywords*— vehiche dinamics, shock absorber, dinamic damping, bicicle control, bicicle dinamics, bicycle frame, anti-squat, dynamically stabilized vehicle, personal mobility vehicle**

I. INTRODUCTION

This article aims to improve the suspension efficiency of mountain bikes, combining the power delivered by turning the pedal to the ground as effectively as possible, as well as optimizing ground tracking while rolling and absorbing large shocks. The article's documentation first details the elements of the suspension, as well as examines the kinematic roots of the problem. It details the possible options for improving efficiency, and then examines the solutions currently available on the market. Finally, it discusses the implementation, with the aspects of the selection of the components used, the description of the chosen units, and the structure and operation of the control program.

A. Elements of the suspension

The spring and air spring are undamped energy reservoirs that absorb/store/resolve the vertical forces acting on the suspension. It is important that, in order to keep the correct ground tracking and dynamic ride height in the right range, when dimensioning, it is worth choosing the spring stiffness so that the suspension has 25-30% seat in a static state when loaded with the cyclist and his equipment.

The two-chamber oil-filled damper, which is used to limit oscillation on the one hand, and to increase winding efficiency by partially or completely closing it on the other. In most cases, it has two (compression and rebound) or four (fast/slow compression and rebound) adjustment valves. In this work, slow compression is controlled.

The materials used in bicycle frame production each come with specific advantages and disadvantages. Steel offers high flexibility, driving comfort, ease of repair, and a low price. However, it also has significant drawbacks, including high weight, poor corrosion resistance, and difficulties when used with full-suspension frames. Aluminum alloy is favored for its low weight, low price, machinability, malleability, and corrosion resistance. Despite these benefits, it compromises on driving comfort, is difficult to repair, and has stiffness issues.

Magnesium alloy is advantageous due to its low weight and ability to absorb vibrations well. On the downside, it has poor corrosion resistance, a low lifetime, and a high price. Titanium alloy stands out for its resistance, comfort, durability, stiffness, and the fact that it does not require surface treatment. However, it is expensive, difficult to manufacture, challenging to weld, and heavier compared to aluminum.

Carbon fiber composite excels with its very low weight, stiffness, capability of forming complicated shapes during production, repairability, and vibration absorption. Nevertheless, it comes with a high price, difficulty in processing and welding, and a higher weight compared to aluminum.

In addition to these common materials, bamboo and cardboard have also been explored for bicycle frames. Bamboo offers sustainability, shock absorption, and a unique aesthetic, but it can be inconsistent in quality and requires careful treatment to prevent decay. Cardboard, while innovative and eco-friendly, is less durable and poses challenges in terms of weather resistance and longevity.

The swing arms are used to connect the rigid frame of the bicycle and the wheel, namely by allowing the wheel to move in its vertical degree of freedom. They can be found in several designs, there are solutions with one pivot point, multiple pivot points and even sliding shafts. The project deals with a bicycle with a five-pivot four-link "horst link" swing arm system [1], see Fig. 1. In terms of rolling efficiency, its most important kinematic feature is anti-squat [2]. Table 1. summarizes the advantages, disadvantages and manufacturers of different types of rocker arms [3].

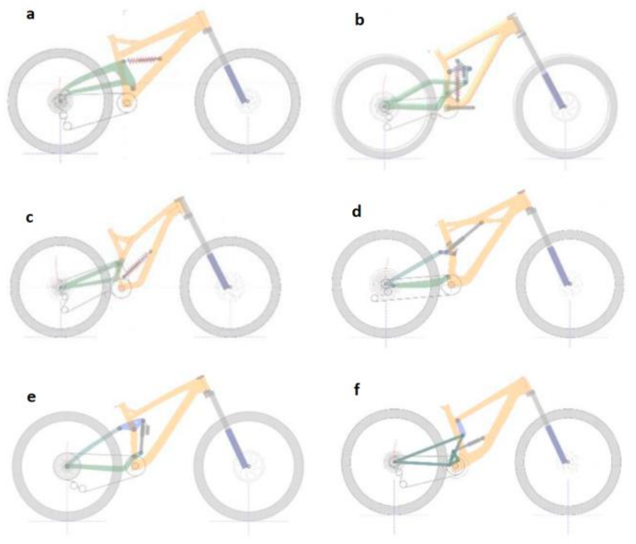

Figure 1: Single pivot (a); Single pivot with additional leverage (b); Single pivot with highly placed pin (c); Four pivot system – Horst Link (d); Four pivot system – Split Pivot (e); Four pivot system – VPP (f)

Suspension System	Advantages	Disadvantages	Company
One pivot	very simple, minimum service requirements	bad pedalling response moving is affecting by braking	Dewilwork, Morewood, Santa Cruz, Canondale

One pivot with levering	better regulation of the applied force on the damper	moving is affecting by braking, moving of rear tringle when pedalling	Merida, Kona, Trek, Transition, Scott
One-pivot High Pivot	eliminated impact of braking to suspension	long length of chain, higher weight, used just with downhill bikes	Commencal, Scott
Four-pivot Horst Link	simple system, almost no pedalling squat	suspension is sensitive to small terrain unevenness, affected by braking	Canyon, Radon, Specialized, Norco
Four-pivot Split pivot	the best drivability, a small drop of the rear triangle when pedalling, removes brake squat	higher weight, patent litigation	Pivot, Morewood, Trek
Four-pivot Twin link	balanced movement, suspension flexibility, almost no suspension moving when pedalling	higher weight, higher maintenance requirements	Santa Cruz, Ibis, Giant

Table 1: Comparison of suspension systems

II. THEORETICAL BACKGROUND

A. *Factors affecting winding efficiency*

The power delivered by the cyclist when pedaling is not a steady circular motion, but a stomping motion. In this way, instead of generating pure torque, some of the power is converted into heat by the compression of the suspension by the damping. The effectiveness is further worsened by the fact that, in the absence of a snap pedal, in the second half of the pedal stroke, some resistance must also be performed with the foot in order not to lose sole-pedal contact.

Anti-squat is a ratio that determines whether the force transmitted to the rear sprocket by the chain during pedaling compresses or stretches the suspension. To calculate it, you must first project a straight line between the intersection of the chain line/swing arm line and the ground contact point of the rear wheel, then take the vertical distance of this line from the ground in the axle of the front wheel, and then divide it by the vertical distance of the center of mass to the ground. Since this value varies from the chain line, the suspension seat and the center of mass, it is impossible to tune in such a way as to compensate for the vertical displacement generated when pedaling.

Since pedaling efficiency has a physiological limit, and the use of anti-squat cannot be optimal due to the variables, a significant increase in efficiency can be achieved by closing the valves of the shock absorber. Since the average cyclist turns the crank at 60-90 rpm, this falls into the low stem speed range. Limitation of this movement can be achieved either by completely closing the damping or by using a highly digressive ($\alpha<1$) damping curve, see Fig. 2. In order to absorb larger shocks expected during free fall or downhill, in these cases we need a linear ($\alpha=1$) or slightly progressive ($\alpha>1$) characteristic. Where α is the damping force – velocity relation for various values of exponent of velocity. The solution is the real-time control of the damping characteristic according to the conditions [5-10].

B. *Commercially available solutions*

Currently, the two largest brands of suspension struts and forks offer active bicycle suspension solutions. Both manufacturers launched their products at the end of 2019, which were initially only available as a solution built into the bike by the manufacturer. The starting price of these bicycles is between 5100 and 7700 euros, which compared to products with traditional non-controlled suspension but with the same equipment, the premium for active control means a difference of roughly 2000 euros. At the end of 2022, RockShox made its product available as an aftermarket option, which includes an active spring member, an active telescope and a pedal rotation sensor, with a suggested retail price of 3,130 euros.

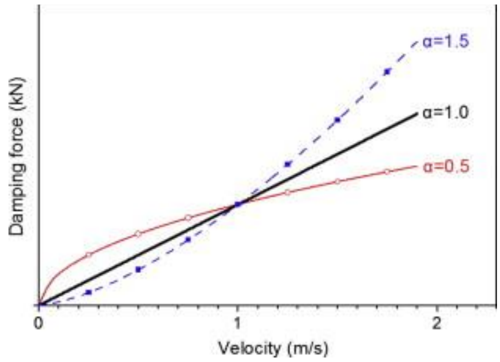

Figure 2: Flowchart of the alarm system [4]

The units are connected to each other via wireless communication. Due to the closed system, detailed information about its exact operation cannot be found. Based on the available information, the system coordinates both spring members and operates with the valves open in the normal state. When rolling on smooth terrain (service roads, asphalt roads), it closes the system completely for maximum efficiency, and provides partial closure on uneven terrain. When going downhill and free-falling, it fully opens the damping valves.

Fox's solution is based on the acceleration measurement of the central unit and the front/rear unsprung elements, which are connected by wire. Exact information is not available here either, but Live Valve works with closed rear and open front valves by default. The opening of the rear member is controlled by the central unit based on the shocks detected by the front wheel, and the system opens completely in free fall. The first telescope is closed only when the central unit detects from the rhythmic movement that the cyclist is riding with strong pedaling movements, standing up from the saddle.

III. REALIZATION OF A UNIQUE IMPLEMENTATION

A. *Mechatronical design*

For the implementation, a uniquely designed bicycle frame calculated with a static center of mass was designed, shown in Figure 3. The Anti-squat graph displayed as a function of the relevant wheel path is shown in Figure 4.

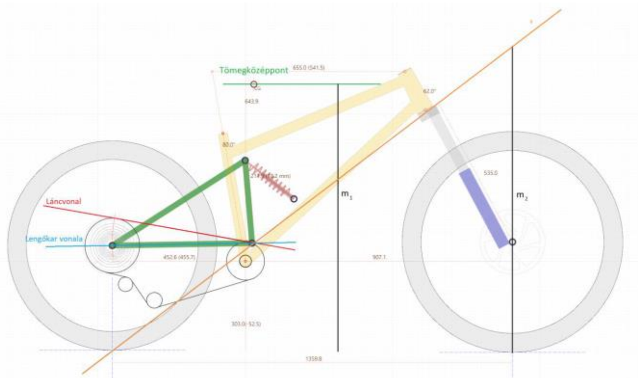

Figure 3: Bicycle frame to calculate Anti-squat

To implement the prototype, the central control unit is an Arm Cortex-M4F microcontroller-based development board (Arduino Nano 33 BLE), which has the possibility of implementing a bluetooth wireless connection and a matched antenna, as well as an integrated 9-axis IMU (Inertial measurement Unit) sensor (LSM9DS1). The digital acceleration sensor, gyroscope and magnetic field sensor IC manufactured by ST Microelectronics (LSM9DS1:) was matched to this. The latter has four measurement ranges, the smallest of which (±2g) is sufficient for current use.

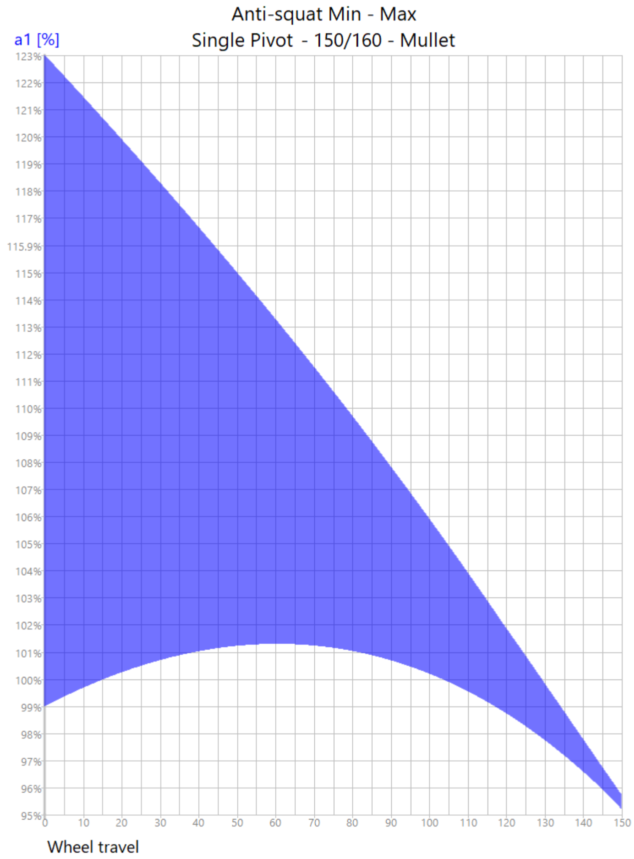

Figure 4: Anti-squat graph calculated with static center of mass

A 28BYJ-48 geared stepper motor was selected as an intervention during the mechanical construction of the prototype, the advantages of which are the small size and weight well suited to the application, mechanical self-support, energy efficiency, low supply voltage, availability and low initial cost. The connection to the microcontroller is provided by a power driver IC type ULN2003. Other additional components include a microswitch for recording end positions, current limiting resistors, pull-up resistors and connectors.

B. *Electronics design*

A development board shield printed circuit was designed for the prototype, which includes the necessary wiring, the USB power input, the stepper motor controller and limit switches. For the PCB design, the goal was to create an elongated shape for easier placement on the bicycle frame, see Figure 5. Similar hardware close, microcontroller based firmware solutions can be seen in [11-16]. The microcontroller-based solutions presented here can also be applied well in technical frontier areas [17-22].

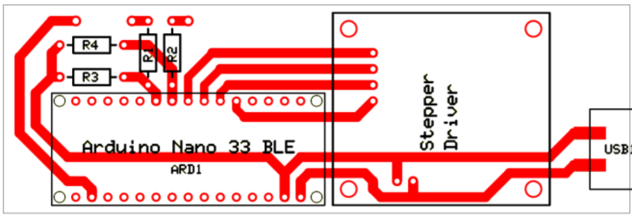

Figure 5: PCB design

C. *Mechanical attachment*

The attachment of the 28BYDJ-48 stepper motor to the spring strut (DT Swiss R 414) was solved by inserting a 3D printed joint made of ABS plastic. This intermediate piece can be attached to the recess separating the positive and negative air chambers of the spring strut with the help of a two-membered ring, and its shape that rests on the positive chamber helps the stable fixation.

The flattened shaft of the stepper motor and the hexagonal shaft of the strut were also connected with a 3D printed element made of ABS plastic (see Fig. 6.), since the low torque does not require the use of a more resistant material.

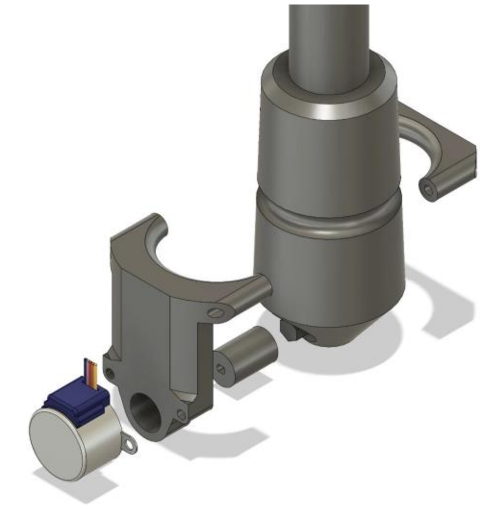

Figure 6: Intervenor isometric exploded view

D. *Software implementation*

In the program, after calling the IMU and stepper motor libraries, first initialize the stepper motor named m1 "AccelStepper m1(4, 5, 3, 4, 2);", where the first variable is the number of controlled PINs, the 2- 4 variables are the addressing of the PINs. In the next step, the software sets the inputs of the two limit switches as inputs. Finally, it sets the maximum allowable stepping speed, current speed and acceleration of the stepper motor. The values used were determined empirically. The main program first enables the IMU and the stepper motor m1, then creates the variables used: zerog - reference vertical, zerom1 - reference motor position, m1trg - stepper motor target position, min, max - minimum and maximum end positions.

The next step is the calibration of the end positions, which the program performs by writing the return value of the "calibrate" subroutine into the variable. After that, it calculates the middle position of the stepper motor by the quotient of the two end positions. It then picks up the current vertical position by writing the return value of the "m1target" subroutine to the "zero" variable.

After it have finished setting the basic conditions, the program enters a loop where it determines the desired motor position and then sends the motor there with the m1go subroutine, follow on Fig. 7. Hysteresis is programmed into the m1go subroutine, which keeps the control electronics of the stepper motor asleep by turning off the drive stage in case of small changes.

Communication between all elements of the system must be reliable and secure. It is proposed to regularly checking the system to ensure all elements function correctly, also setting up automatic notifications and alerts for errors, intrusion attempts, or other suspicious activities [23-26].

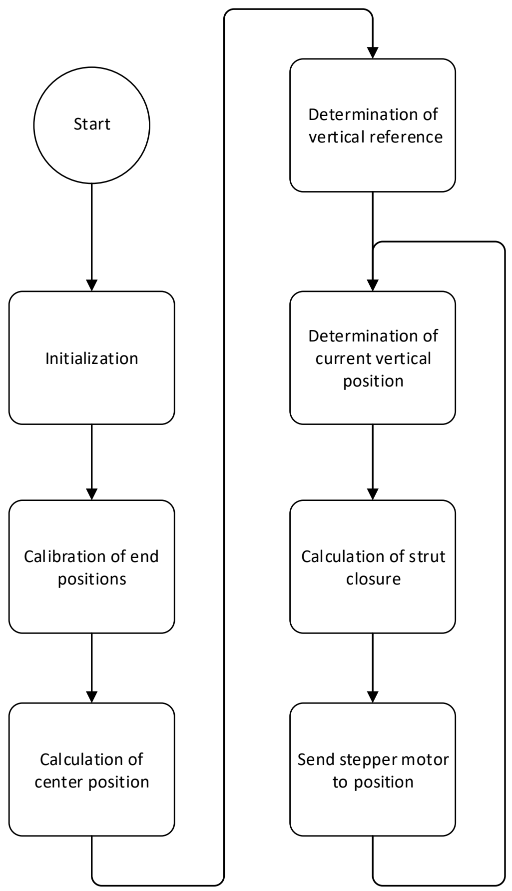

Figure 8: Flow chart describing the operation

CONCLUSION

The integration of dynamic damper control with human propulsion in a two-wheeled vehicle significantly enhances stability, reduces vibrations, and improves rider comfort. The development of a 3D model and functional prototype, along with a custom microcontroller program, validated the theoretical benefits and preliminary expectations. This innovative approach represents a substantial advancement in personal transportation, offering more efficient, versatile, and comfortable travel solutions for urban commuting and recreational use.

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