UNIVERSITÀ DI TRENTO

Master degree in Mechatronics Engineering

Mechatronic Systems Simulation - Modeling

Drag Reduction Mechanism

Projectwork - System Design

Group 17

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1 Requirements

1.1 Requirements description

High aerodynamic efficiency
A DRS system is designed with the specific objective of improving the aerodynamic performances of the car, adapting them to the circuit section, whether a higher adherence or a lower drag effect is needed. However, the mechanism itself can affect the aerodynamics of the vehicle, both by increasing the resistance section to the air flow and generating turbulence on the rear wing. It's fundamental to limit these effects as much as possible to not compromise the overall performance of the car.

High precision
Every part of an F1 racing car must be designed with the best precision (that) a team can offer. In the word "precision", our team wants to include all the possible improvements that can be implemented in the DRS mechanism: avoid the overshoot in the motion, do not transmit any type of vibration to the rear wing. By guaranteeing these characteristics, it is possible to obtain a system that makes a movement with high accuracy and repeatability.

Quick motion
In Formula 1 races, usually the winner has a gap of about a few hundredths of a second with the other drivers. These data allow us to understand how small details can be very influential on the behavior of the cars during the race. Among these, one of the most important factors concerning the DRS is the quick motion during his opening. On track there are some zones where the drag reduction system can be activated: it is therefore very important that this mechanism can operate as soon as possible at the start of these, considering the high speeds reached by cars. This aspect not only concerns about the flap opening, but also about all the actuation system that must be designed so that it can respect the quick times required.

Low power consumption
Power within the car is generated mainly by the engine (some energy can be recovered in the braking process and stored in internal batteries), therefore any system installed drains energy directly from it. For example, a hydraulic actuated DRS usually exploits the hydraulic system, powered by the engine, installed in the car to pilot the gearbox. Hence it is important to reduce as

much as possible the power consumption of the DRS in order to mitigate the drop of the power provided to the rear axle.

Compliance with rules

The numerous Formula 1 regulations, both technical and sporting, are made and enforced by the FIA (Fédération Internationale de l'Automobile). The technical ones mainly concern the chassis, the engine and the tyres. The DRS has to respect these regulations too: its dimensions and maximum displacement must be projected according to the specifications issued by the FIA, published in the "Formula 1 Technical Regulations" document [1]. Furthermore, according to these rules, the design must be such that failure of the system will result in the uppermost closed section returning to the normal high incidence position. Finally this mechanism can be activated only in specific zones of the track and it can be deactivated by the race director in dangerous conditions.

Easy to assemble

Besides the requirements regarding performances and reliability of the system, we also considered its simplicity of assembling and maintenance. The aim is to reduce the complexity of installation, the encumbrance of the mechanism with respect to the overall car structure and make maintenance simpler and quicker.

Durability

Despite the continuous control of the cars, every component must be designed to last as long as possible. The DRS mechanism, unlike other parts, is not replaced at the end of each race. Furthermore, this part of the car cannot be changed during the race, during the pit stop. During the 2013 Bahrain GP, Fernando Alonso's Ferrari had a problem at the DRS and the driver had to retire as the mechanism was unable to close the movable flap. One of the main factors that reduces the durability of components is wear, due to friction, but also the vibrations reduce the life of the mechanism.

Structurally safe

When racing, Formula 1 cars reach outstanding speeds, over 350 km/h. This results in high drag and down forces acting on the rear wing. The DRS pilots the rear wing flap, thus it must sustain high stress due to the aerodynamic forces acting on it. It's important to evaluate the mechanical stresses in the worst case scenario and design the DRS in terms of rigidity to avoid structural faults. A breakdown of the mechanism may result in an unpredictable and uncontrollable behavior of the flap, compromising the race safety. An example is a full open configuration, enforced by the aerodynamic forces, in a curve of the circuit, drastically reducing the adherence of the car and compromising the turn maneuver controllability. This is strictly related to the regulations established by FIA (section 1.1).

Lightweight
Another important requirement is the lightweight of the entire mechanism, so that it does not have a large impact on the weight of the car. This aspect is significant because also the weight is regulated by the FIA and it has to remain bound within certain limits. Furthermore, the weight is very influential in the case in which the DRS is installed on the rear wing: a great weight would lead it to flex. This factor results in loss of aerodynamic efficiency and also, since the wings' flexibility is regulated by the FIA, a great weight could lead to non-compliance with the rules.

1.2 Requirements rate

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Table 1: Customer requirements based on relative importance.

2 Model comparison

The starting point for the choice of a drug reduction system is the analysis of the existing solutions, in order to examine their advantages and disadvantages and realize a system which is an evolution of the previous concepts. The main existing solutions are push - up type, pod - rocker type and pod - pull type.

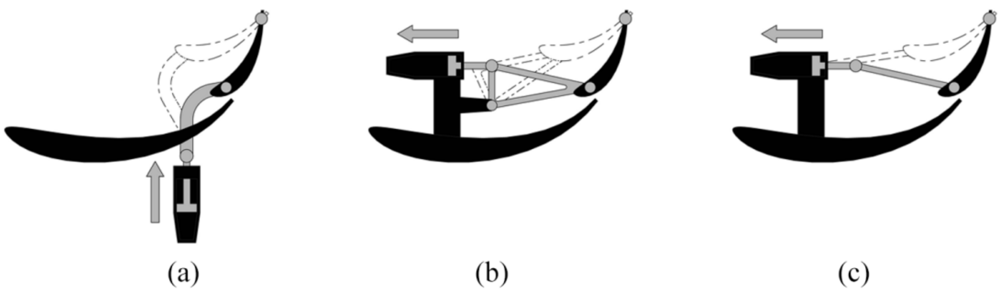

Figure 1: Existing DRS solutions: (a) push-up type, (b) pod-rocker type and (c) pod-pull type. Closed configuration is shown in filled greyscale view, whereas open configuration is contoured by a dashed line [2].

The first is simple and economic because it requires only a link between actuator and flap, with at most two bearings placed at the link extremities. Another advantage of this mechanism is the easy access to hydraulic lines for maintenance. However, it creates aerodynamic disturbance on the underside of the wing surface. It also requires a great effort to the actuator because of the disadvantageous mechanism lever ratios.

The second mechanism has the advantage of requiring a lower effort to the actuator thanks to the rocker that increases the leverage of the piston. It also allows to eliminate any aerodynamic disturbance under the mainplane, since the hydraulic lines pass through the endplate. The disadvantages are the higher cost of the system and the difficult maintenance of the hydraulics.

The third solution presents the same advantages of the pod - rocker mechanism but it is simpler because the rocker is replaced with a single link. However it introduces friction and time delays in both opening and closing phases.

Finally, among the existing solutions, the best mechanism is the pod - pull that is used by the majority of the Formula 1 cars, although it requires a great effort to the actuator.

3 Engineering specifications

Front section
The teams that project the cars don't spread technical specifications because of the competition between them. Due to this reason, in order to define the weight and the volume of a DRS used in Formula 1, we decided to create a model of them using a 3D modeling software. Starting from the known dimensions of the rear wing (of which we have found a 3D model), we have created an approximated model of the DRS, based on the proportions that exist between the wing and them, observed by some images of the existing solutions.

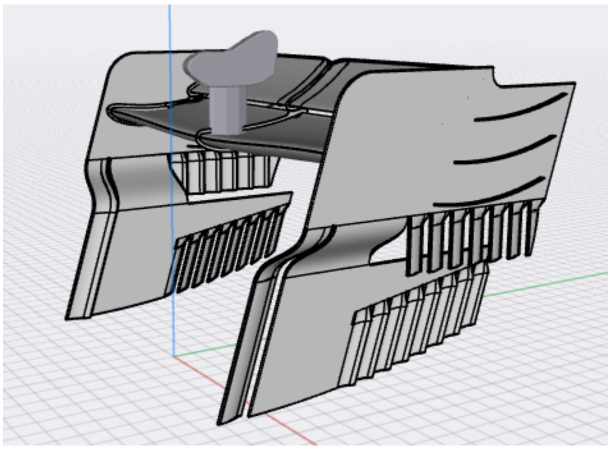

Figure 2: The model we have create to obtain the approximated dimensions of the DRS.

The software allows us to obtain the dimensions of the DRS front section.

Maximum overshoot
The overshoot is the difference between the highest position reached by the movable wing and the position that, when the mechanism is activated, it should reach, equal to the max displacement. The distance between the two flaps must lie between 10mm and 15mm at their closest position. When the DRS mechanism opens the two wings the maximum distance must be equal to 50mm. Assuming the wing is not fully closed, the maximum overshoot is 5mm.

Vibrations
In order not to introduce vibrations on the rear wing it is important that the DRS mechanism does not oscillate under the effect of the drag force and the forces of inertia. It is possible to quantify the resistance to vibrations by modeling the entire mechanical system as a first order low pass filter and reporting as engineering specifications the filter cut-off frequency and the slope of the line in the bode (attenuation) diagram. Therefore, using a lumped parameter model consisting of a mass and a spring, it is possible to calculate the two required specifications and modify them according to the type of stiffness required and the maximum displacement allowed.

Opening time
One of the most important engineering specifications required of the mechanism is the opening time. This is given by the time that elapses between the closed position, identified with $0°$, and the open one at $70°$. For this performance index our group has approached the analysis in two ways. From the analysis of the DRS mechanism illustrated in the article of Dimastrogiovanni [2], the opening time is equal to $0.01s$. Otherwise, analyzing videos of the last F1 race, the opening time of Ferrari's DRS is $0.05s$. This type of result was achieved by scanning the video frame by frame. For this reason, two targets have been set: disgusted and delighted one.

Power
The DRS power, determined by its actuation system, affects two main aspects of its performance: system's opening time (in order to obtain a quick motion, the required power is higher) and consumption, so it's subject to a delicate trade off between the two. Neglecting dissipations depending on the mechanism design, the minimum necessary power is defined as the product of the instantaneous velocity and the instantaneous applied force. From figures *11b, 12* in the article of Dimastrogiovanni [2], we estimated that the maximum necessary power to drive the DRS is approximately $1600W$, identified for an opening angle of $20°$.

Maximum displacement

According to the FIA regulations, The flap will be able to pivot around a point near the trailing edge (20 millimeters of it), away and upward from the main plane up to a maximum distance of 50mm into a more horizontal position, and open up the slot gap.This specifications are represented in the following figure:

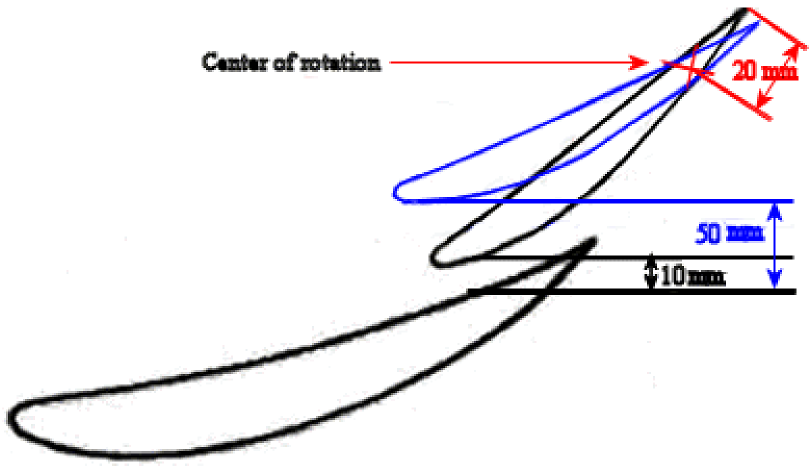

Figure 3: The maximum displacement defined by the FIA regulations.

Number of bodies

This specification strongly depends on the mechanism design. It's hard to specify a specific target, but analyzing existing designs a low value is suggested.

Weight and volume

We used the same model created to compute the DRS front section to estimate the volume of our DRS and in a second moment, considering the material of which it is made, we have derived its approximate weight.

Number of joints
To quantify the effect of friction, the number of joints has been included in the specifications of the QFD. In the case of the DRS mechanism, there are mainly revolute joints, which introduce a frictional moment, proportional to applied force, the radius and the frictional coefficient with the following equation:

$$M = F \cdot R \cdot (\frac{\mu}{\sqrt{1+\mu^2}})$$

Each revolute joint exerts this moment M, so the total frictional moment is proportional to the number of revolute joints.

Maximum sustainable moment
The max sustainable moment can also be defined as the max moment the mechanism must apply to the flap during operation. The main terms affecting this parameter are the combination of drag and downforce acting on the flap due to aerodynamic interactions and the inertial force of the system during motion. It's hard to define the terms analytically due to the evolving aerodynamics during the flap opening, hence we used simulation results as target value (fig. 11b, article [2]): $13Nm@20°$.

Stiffness
To guarantee structural safety, it is important that the mechanism is rigid. A parameter capable of representing this characteristic is stiffness. As a first approximation it is possible to model the DRS mechanism using the lumped parameters. The whole mechanism is subjected to a drag force and to the forces of inertia due to the acceleration of the machine. Assuming a maximum displacement in the highest part of the mechanism equal to dz, it is possible to obtain the stiffness by making the ratio between the resultant of the forces and the displacement in the same direction:

$$K = \frac{F}{dz}$$

3.1 Matching between requirements and specifications

High aerodynamic efficiency

- **Front section** We defined the front section as the parameter defining the aerodynamics of the system, given by the relation between drag force and drag coefficient:

$$F_D = \frac{1}{2} A C_D v^2 \tag{1}$$

  with ρ air density, A reference area, C_D drag coefficient, v relative velocity between fluid and object. We don't take into account the drag coefficient, determined by the mechanism geometry and design, because it's beyond our expertise field and we are not able to compute it.

- **Number of bodies** In general an higher number of bodies lead to a greater volume of the mechanism, thus an higher drag effect is generated, but it strongly depends on the design and shape of each body.

- **Volume** Assuming the available space in the z direction (with respect to the convention where the z axis aligned with the car driving direction) is more or less constant given the rear wing design, a greater volume means a higher frontal section, thus a higher air friction.

High precision

- **Max overshoot** We defined the overshoot generated by the system as a key parameter identifying the precision of the mechanism.

- **Vibrations** We defined the vibrations generated by the system as a key parameter identifying the precision of the mechanism.

- **Number of bodies** Due to the nature of measurements, the dimension of a mechanical body will never perfectly match the designed ones. So an higher number of bodies lead to an accumulated error in the design parameters, decreasing the precision (however the effect should be negligible).

- **Number of joints** For the same reason cited for the number of bodies, more joints leads to greater parameters uncertainty. Furthermore, the friction also enhance the stick-slip effect of the mechanism.

- **Maximum sustainable displacement** Generally, for the actuator, precision and maximum sustainable force are correlated by a trade off.

- **Stiffness** A greater stiffness decreases low frequency vibrations and the stick-slip effect, leading to an higher precision.

Quick motion

- **Opening time** We can directly correlate the quickness of the motion to the opening time.
- **Power** Given a certain force the mechanism must apply to the flap, a greater power applied increase the motion speed.
- **Number of bodies** A high number of bodies increase the system's inertia, lowering it's speed.
- **Number of joints** Being friction a dissipative phenomenon, it lowers the speed of the system.
- **Max sustainable moment** Fixing the available power, an higher needed moment lowers the motion speed.
- **Weight** An increased inertia leads to a less responsive mechanism.

Low power consumption

- **Opening time** Given a certain force the mechanism must apply to move the flap, a lower opening time is traduced in an higher power requested from the actuator.
- **Power** The power consumption is defined as the requested power from the actuator to move the flap.
- **Number of bodies** For the same reason above, an increased inertia leads to an higher energy consumption to move the mechanism.
- **Number of joints** Higher dissipations lead to a greater power consumption.
- **Maximum sustainable moment** Fixing the requested motion speed, an higher needed moment leads to a greater power consumption.
- **Weight** An increased inertia leads to an higher energy consumption to move the mechanism.

Compliant with rules

- **Maximum displacement** The max displacement is defined by regulations.

Easy to assemble/maintain

- **Number of bodies** A high amount of parts increase the complexity of the mechanism and so the assembling steps. If there are more components, more parts may fail, thus more maintenance is required.
- **Volume** It is the parameter defining the mechanism encumbrance, and so how hard is to install the DRS on the car.
- **Number of joints** An increased friction effect increase the need of maintenance.

Durability

- **Number of joints** An increased friction effect increase the usury of the system.
- **Stiffness** Generally a stiffer mechanism better withstand solicitations and stress, making it more durable.

Safe

- **Maximum sustainable moment** A mechanism that better withstand external forces is structurally safer.
- **Stiffness** Generally a stiffer mechanism better withstand solicitations, making it structurally safer.

Light weight

- **Front section** Assuming the available space in the z direction (with respect to the convention where the z axis aligned with the car driving direction) is more or less constant given the rear wing design, a higher frontal section means a greater volume, thus a higher weight.
- **Number of bodies** In general an higher number of bodies lead to a greater weight of the mechanism, but it strongly depends on the design and shape of each body.

- **Volume** Volume is directly correlated to the system weight given a fixed average density.
- **Maximum sustainable moment** Given a certain material used to build the mechanism, a lighter system usually can withstand lower external forces.
- **Weight**

QFD *(EXPERIMENTAL) HP-LDMS*	Front section	Max overshoot	FRS: cut-off	FRS: attenuation	Time constant	Opening time	Power	Max displacement	# of bodies	Volume	# of joints	Max sustainable moment	Weight	Stiffness
Improvement direction														
Units	cm^2	mm	Hz	db/dec	s	s	W	mm	-	cm^3	-	Nm	kg	N/m
Requirements / Funcional: High aerodynamic efficiency	⦿								◎	⦿				
High precision		⦿	⦿	⦿					◦		◦	◦		◎
Quick motion					⦿	⦿	◎		◦		◦	◎	◦	
Low power consumption						◎	⦿		◦		◦	⦿	◎	
Compliant with rules								⦿						
Easy to assemble/maintain									⦿	⦿	⦿			
Durability											⦿		◦	◎
Safe												⦿		⦿
Light weight	◎								◎	◎		◦	⦿	◦

Correlation legend	
Hard correlat.	⦿
Medium correlat.	◎
Poor correlat.	•
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Figure 4: Relations between requirements and specifications of the project.

3.2 Trade off between specifications

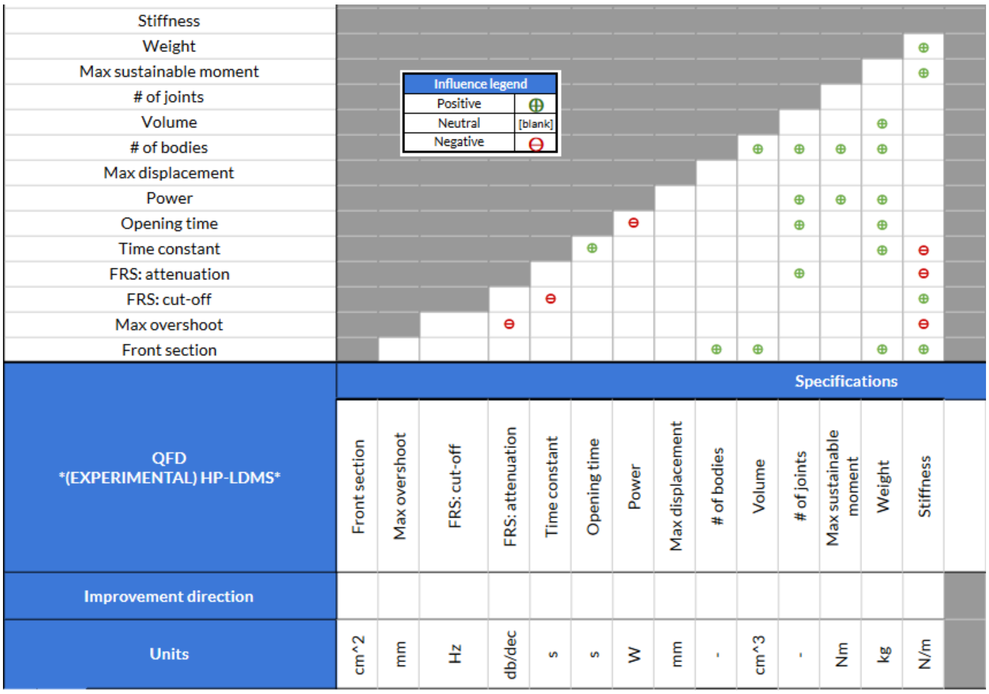

Figure 5: Relations between specifications of the project

3.3 Target

	Front section (cm^2)	Max overshoot (mm)	Opening time (s)	Max displacement (mm)	Volume (cm^3)	Number of joints	Weight (kg)	Stiffness (N/m)
Target (delighted)	60	0	0.01	50	500	2	1.2	
Target (disgusted)	70	5	0.05	50	700	3	2	3e6

Table 2: Defined target which must be satisfied by specifications.

References

[1] FIA. *Formula 1 Tecnichal regulations*. URL: https://www.fia.com/sites/default/files/formula_1_-_technical_regulations_-_2022_-_iss_11_-_2022-04-29.pdf.

[2] Mauro Dimastrogiovanni, Giulio Reina, and Andrea Burzoni. "An improved active drag reduction system for formula race cars". In: *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* 234.5 (2020), pp. 1460–1471.