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Introduction

A hybrid electric vehicle (HEV) is a type of hybrid vehicle and electric vehicle which combines a conventional internal combustion engine (ICE) propulsion system with an electric propulsion system. In recent years hybrid vehicles (HV) and HEV in particular are subject to special attention being studied and researched due to the rising cost of fossil fuel and to the always increasing strictness of the rules regarding air pollution. The presence of the electric powertrain is indeed intended to achieve either better fuel economy than a conventional vehicle, or better performance. Development of electronics and its decreasing cost even induced manufacturers to invest on HEV. Cars are not the only vehicles interested by this evolution, research and production is already involving trucks, buses, ships, bikes and also aircrafts.

Modern HEVs make use of efficiency-improving technologies such as regenerative braking, which converts the vehicle's kinetic energy into battery-replenishing electric energy, rather than wasting it as heat energy as conventional brakes do. Some varieties of HEVs use their internal combustion engine to generate electricity by spinning an electrical generator (this combination is known as a motor-generator), to either recharge their batteries or to directly power the electric drive motors. Many HEVs reduce idle emissions by shutting down the ICE at idle and restarting it when needed; this is known as a start-stop system. According to various research studies, vehicles are at a standstill for one-third of the time while in urban areas. Start-stop system operate by cutting the engine when the driver comes to a complete standstill. The engine is switched back on when the brake pedal is released. Such systems are a good route for automakers to reduce emissions and meet CO_2 reduction targets.

In order to design and to match as precise as possible electric motor to the internal combustion engine, a physical-mathematical model of the engine is required. This thesis work is therefore built around the creation and the implementation of a MATLAB simplified model of the ICE and its successive use inside a SIMULINK schematic with the aim of analyze the evolution of physical parameters during starting time.

HEV can be classified by drivetrain structure, by degree of hybridization and also by nature of the power source. These classifications can also be useful to understand the functioning and the components of the vehicles.

Types by drivetrain structure

Parallel hybrid

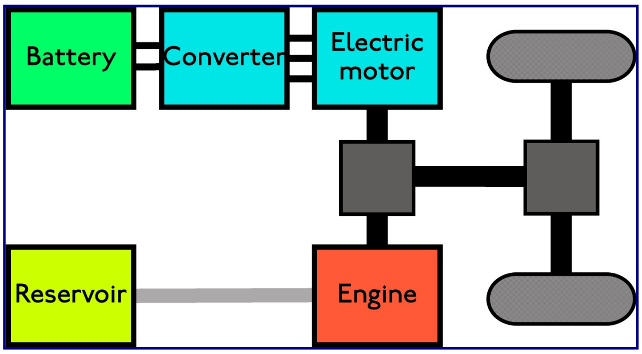

Figure 1 Structure of a parallel hybrid electric vehicle. The gray squares represent differential gears.

Parallel hybrid systems, which are most commonly produced at present, have both an internal combustion engine and an electric motor connected to a mechanical transmission. Most designs combine a large electrical generator and a motor into one unit, often located between the combustion engine and the transmission, replacing both the conventional starter motor and the alternator. To store power, a hybrid uses a large battery pack with a higher voltage than the normal automotive 12 volts. Accessories such as power steering and air conditioning are powered by electric motors instead of being attached to the combustion engine. This allows efficiency gains as the accessories can run at a constant speed, regardless of how fast the combustion engine is running.

Parallel hybrids can be categorized by the way the two sources of power are mechanically coupled. If they are joined at some axis truly in parallel, the speeds at this axis must be identical and the supplied torques add together. Most electric bicycles are in effect of this type. When only one of the two sources is being used, the other must either also rotate in an idling manner or be connected by a one-way clutch or freewheel. With cars it is more usual to join the two sources through a differential gear. Thus the torques supplied must be the same and the speeds add up, the exact ratio depending on the differential characteristics. When only one of the two sources is being used, the other must still supply a large part of the torque or be fitted with a reverse one-way clutch or automatic clamp.

Parallel hybrids can be further categorized depending upon how balanced the different portions are at providing motive power. In some cases, the combustion engine is the dominant portion (the electric motor turns on only when a boost is needed) and vice versa. Others can run with just the electric system operating. But because current parallel hybrids are unable to provide all-electric (ICE=OFF) propulsion, they are often categorized at mild hybrids (see below).

Because parallel hybrids can use a smaller battery pack as they rely more on regenerative braking and the internal combustion engine can also act as a generator for supplemental recharging, they are more efficient on highway driving compared to urban stop-and-go conditions or city driving. Honda's Insight, Civic, and Accord hybrids are examples of production parallel hybrids.

Series hybrid

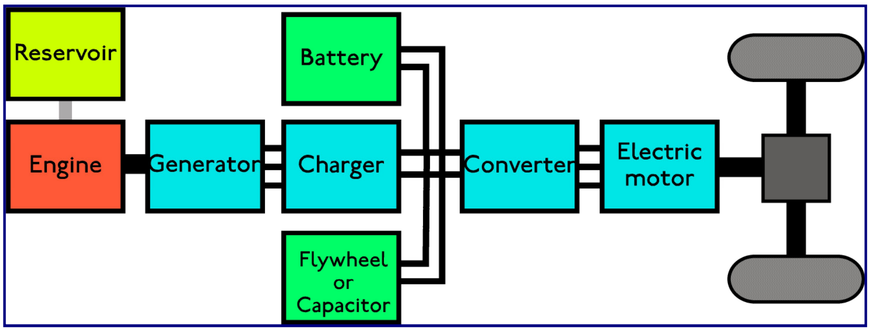

Figure 2 Structure of a series-hybrid vehicle. The grey square represents a differential gear. An alternative arrangement (not shown) is to have electric motors at two or four wheels.

Series hybrids have also been referred to as range-extended electric vehicles (REEV) in order to emphasize that they are electric vehicles with a combustion engine assist. However, range extension can be accomplished with either series or parallel hybrid layouts.

Series-hybrid vehicles are driven only by electric traction. Unlike piston internal combustion engines, electric motors are efficient with exceptionally high power to weight ratios providing adequate torque over a wide speed range. Unlike combustion engines, electric motors matched to the vehicle do not require a transmission between the engine and wheels shifting torque ratios. Transmissions add weight, bulk and sap power from the engine. Mechanical automatic shifting transmissions can be very complex. In a series-hybrid system, the combustion engine drives an electric generator instead of directly driving the wheels. The generator provides power for the driving electric motors. In short, a series-hybrid is simple, the vehicle is driven by electric motors with a generator set providing the electric power.

This arrangement is common in diesel-electric locomotives and ships. Ferdinand Porsche used this setup in the early 20th century in racing cars, effectively inventing the series-hybrid arrangement. Porsche named the system, System Mixt. A wheel hub motor arrangement, with a motor in each of the two front wheels was used, setting speed records. This arrangement was sometimes referred to as an electric transmission, as the electric generator and driving motor replaced a mechanical transmission. The vehicle could not move unless the internal combustion engine was running.

The setup was difficult for production cars being unable to synchronise the electric driving motors with the generator set power, resulting in higher fuel consumption. No longer an issue with modern computer engine management systems optimizing when the generator runs to match the power needed. Electric motors have become substantially smaller, lighter and efficient over the years. These advances have given the advantage to the electric transmission in normal operating conditions, over a conventional internal combustion engine and mechanical automatic transmission. One of the advantages is the smoother progressive ride with no stepped gear ratio changes.

The electric transmission is currently viable in replacing the mechanical transmission. The Chevrolet Volt claims that without using energy from the battery running on gasoline only, fuel consumption is expected to be 4.7 L/100 km on the city cycle of the EPA's test. For such a size of car this is notable fuel consumption. However, the modern series-hybrid vehicles takes the electric transmission to a higher plane adding greater value. There is a difference to an electric transmission. Modern series-hybrids contain:

- Electric traction only - using only one or more electric motors to drive the vehicle.
- Combustion engine - that turns only a generator.
- A generator - turned by the combustion engine to make up a generator set that also acts as an engine starter.
- A battery bank - which acts as an energy buffer.
- Regenerative braking - Driving motor becomes a generator and recovers potential and kinetic (inertial) energies through its conversion to electrical energy, a process which in turn is able to slow the vehicle and thus preventing wasteful transfer of this energy as thermal losses within the friction brakes.

- May be plugged into the electric mains system to recharge the battery bank.
- May have supercapacitors to assist the battery bank and claw back most energy from braking - only fitted in proven prototypes currently.

The electric driving motor may run entirely fed by electricity from a large battery bank or via the generator turned by the internal combustion engine, or both. The battery bank may be charged by mains electricity reducing running costs as the range running under the electric motors only is extended. The vehicle conceptually resembles a Diesel-electric locomotive with the addition of large battery bank that may power the vehicle without the internal combustion engine running. The generator may simultaneously charge the battery bank and power the driving electric motor that moves the vehicle. The battery bank acts as an energy buffer. An advantage is that when the vehicle is stopped the combustion engine is switched off. When the vehicle moves it does so using the energy in the batteries. This reduces kerbside emissions greatly in cities and towns. Vehicles at traffic lights, or in slow moving stop start traffic need not be polluting when stationary.

In some arrangements when high levels of power are required, such as in vehicle acceleration, the electric driving motor draws electricity from both the batteries and the generator. With the Chevy Volt if the battery bank is depleted the vehicle may run entirely with electricity provided only from the generator. Some prototype vehicle designs such as the Volvo ReCharge and Ford F-Series pickup have electric motors in wheel hubs reducing the need for a differential saving weight, space and power being sapped by the differential. Series-hybrids can be also fitted with a supercapacitor or a flywheel to store regenerative braking energy, which can improve efficiency by clawing back energy that otherwise would be lost being dissipated via heat through the braking system.

Because a series-hybrid omits a mechanical link between the combustion engine and the wheels, the engine can be run at a constant and efficient rate even as the vehicle changes speed. The vehicle speed and engine speed are not necessarily in synchronization. The engine can thus maintain an efficiency closer to the theoretical limit of 37%, rather than the current average of 20%. At low or mixed speeds this could result in ~50% increase in overall efficiency (19% vs 29%). However

General Motors have designed the Chevy Volt's engine/generator set to operate between 1,200 and 4,000 revolutions per minute. The Lotus company has introduced an engine/generator set design that runs at two speeds, giving 15 kW of electrical power at 1,500 rpm and 35 kW at 3,500 rpm via the integrated electrical generator.

As the requirements for the engine are not directly linked to vehicle speed, this gives greater scope for more efficient or alternative engine designs, such as a microturbine, rotary Atkinson cycle engine or a linear combustion engine.

There are stages of operation: power from the combustion engine to the generator and then to the electric motor and, depending on the design, may also run through the generator and into the battery pack then to the electric motor further reducing efficiency. Each transformation through each stage results in a loss of energy. However in normal vehicle operating conditions the energy buffer of the battery bank, which stores clawed back energy from braking and the optimum running of the combustion engine may raise overall operating efficiency, despite each stage being an energy loss. The engine to a mechanical automatic shifting transmission efficiency is approximately 70%-80%. A conventional mechanical clutch transmission, has an engine to transmission efficiency of 98%. In a series-hybrid vehicle, during long-distance high speed highway driving, the combustion engine will need to supply the majority of the energy, in which case a series-hybrid may be 20%-30% less efficient than a parallel hybrid.

The use of a motor driving a wheel directly eliminates the conventional mechanical transmission elements: gearbox, transmission shafts and differential, and can sometimes eliminate flexible couplings. This offers great simplicity. If the motors are integrated into the wheels a disadvantage is that the unsprung mass increases and suspension responsiveness decreases which impacts ride performance and potentially safety. However the impact should be minimal if at all as electric motors in wheel hubs such as Hi-Pa Drive, may be very small and light having exceptionally high power to weight ratios. The braking mechanisms can be lighter as the wheel motors brake the vehicle. Light aluminum wheels may be used reducing the unsprung mass of the wheel assembly. Vehicle designs may be optimized to lower the centre of gravity having the heavy mechanicals and battery banks at floor level. If the motors are attached to the vehicle body, flexible couplings are still required. Advantages of individual wheel motors include simplified traction control and all wheel drive if required, allowing lower floors, which is useful for buses. Some 8x8 all-wheel drive military vehicles use individual wheel motors. Diesel-electric locomotives have used this concept (albeit with the individual motors driving axles connecting pairs of wheels) for 70 years.

In a typical road vehicle the whole series-hybrid power-transmission setup may be smaller and lighter than the equivalent conventional mechanical power-transmission setup which liberates space. As the combustion generator set only requires cables to the driving electric motors, there is greater flexibility in major component layout spread across the vehicle giving superior weight distribution and maximizing vehicle cabin space. This flexibility may lead to superior vehicle designs.

In 1997 Toyota released the first series-hybrid bus sold in Japan. Meanwhile, GM hopes to introduce the Chevy Volt by 2011, aiming for an all-electric range of 64 km and a price tag of around 30000 €. Supercapacitors combined with a lithium ion battery bank have been used by AFS Trinity in a converted Saturn Vue SUV vehicle. Using supercapacitors they claim up to 63 Km/l in a series-hybrid arrangement.

Power-split or series-parallel hybrid

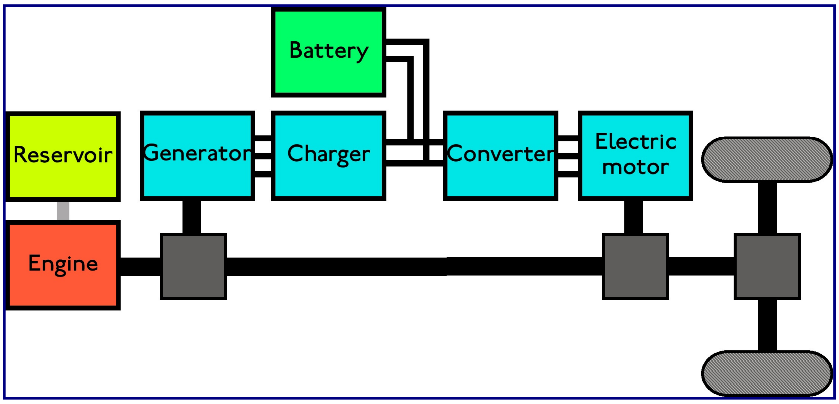

Figure 3 Structure of a combined hybrid electric vehicle

Power-split hybrid or series-parallel hybrid are parallel hybrids. They incorporate power-split devices allowing for power paths from the engine to the wheels that can be either mechanical or electrical. The main principle behind this system is the decoupling of the power supplied by the engine (or other primary source) from the power demanded by the driver.

A combustion engine's torque output is minimal at lower RPMs and, in a conventional vehicle, a larger engine is necessary for acceptable acceleration from standstill. The larger engine, however, has more power than needed for steady speed cruising. An electric motor, on the other hand, exhibits maximum torque at standstill and is well-suited to complement the engine's torque deficiency at low RPMs. In a power-split hybrid, a smaller, less flexible, and highly efficient engine can be used. The conventional Otto cycle (higher power density, more low-rpm torque, lower fuel efficiency) is often also modified to a Miller cycle or Atkinson cycle (lower power density, less low-rpm torque, higher fuel efficiency). The smaller engine, using a more efficient cycle and often operating in the favorable region of the brake specific fuel consumption map, contributes significantly to the higher overall efficiency of the vehicle.

Interesting variations of the simple design found, for example, in the well-known Toyota Prius are the:

- addition of a fixed gear second planetary gearset as used in the Lexus RX400h and Toyota Highlander Hybrid. This allows for a motor with less torque but higher power (and higher maximum rotary speed), i.e. higher power density
- addition of a Ravigneaux-type planetary gear (planetary gear with 4 shafts instead of 3) and two clutches as used in the Lexus GS450h. By switching the clutches, the gear ratio from MG2 (the "drive" motor) to the wheel shaft is switched, either for higher torque or higher speed (up to 250 km/h / 155 mph) while sustaining better transmission efficiency.
- addition of 2 additional planetary gear sets in combination with 4 clutches to create a Two-Mode Hybrid configuration able to operate in all-electric, blended electric and ICE, or ICE alone with 4 fixed gears. Examples of Two-Mode Hybrids include the General Motors Two-Mode Hybrid full-size trucks and SUVs, the BMW X6 ActiveHybrid and the Mercedes ML 450 hybrid

The Toyota Hybrid System THS / Hybrid Synergy Drive has a single power-split device (incorporated as a single 3 shaft planetary gearset) and can be classified as an Input-Split, since the power of the engine is split at the input to the transmission. This in turn makes this setup very simple in mechanical terms, but does have some drawbacks of its own. For example, the maximum speed is mainly limited by the speed of the smaller electric motor (usually functioning as a generator). Also, the efficiency of the transmission is heavily dependent on the amount of power being transmitted over the electrical path, as multiple conversions, each with their own, less than perfect efficiency, lead to a low efficiency of that path (~0.7) compared with the purely mechanical path (~0.98). Especially in higher speed regimes (>120 km/h) the efficiency (of the transmission alone) therefore drops below that of a generic automatic transmission with hydrodynamic coupler.

General Motors, BMW, and DaimlerChrysler have developed in collaboration a system named "Two-Mode Hybrid" as part of the Global Hybrid Cooperation. The technology was released in the fall of 2007 on the Chevrolet Tahoe Hybrid. The system was also featured on the GMC Graphite SUV concept vehicle at the 2005 North American International Auto Show in Detroit.

The Two-Mode Hybrid name is intended to emphasize the drivetrain's ability to operate in all-electric (Mode 1, or Input-Split) as well as hybrid (Mode 2, or Compound-Split) modes. The design, however, allows for operation in more than two modes; two power-split modes are available along with several fixed gear (essentially parallel hybrid) regimes. For this reason, the design can be referred to as a multi-regime design. The Two-Mode Hybrid powertrain design can be classified as a compound-split design, since the addition of four clutches within the transmission allows for multiple configurations of engine power-splitting. In addition to the clutches, this transmission also has a second planetary gearset. The objective of the design is to vary the percentage of mechanically vs. electrically transmitted power to cope both with low-speed and high-speed operating conditions. This enables smaller motors to do the job of larger motors when compared to single-mode systems, because the derived electrical peak power is proportional to the width of the continuous variation range. The four fixed gears enable the Two-Mode Hybrid to function like a conventional parallel hybrid under high continuous power regions such as sustained high speed cruising or trailer towing. Full electric boost is available in fixed gear modes.

Types by degree of hybridization

Full Hybrids

A full hybrid, sometimes also called a strong hybrid, is a vehicle that can run on just the engine, just the batteries, or a combination of both. The Toyota Prius, Toyota Camry Hybrid, Ford Escape Hybrid/Mercury Mariner Hybrid, Ford Fusion Hybrid/Mercury Milan Hybrid, as well as the General Motors 2-mode hybrid trucks and SUVs, are examples of this type of hybridization as they are able to be propelled on battery power alone. A large, high-capacity battery pack is needed for battery-only operation. These vehicles have a split power path that allows more flexibility in the drivetrain by interconverting mechanical and electrical power, at some cost in complexity. To balance the forces from each portion, the vehicles use a differential-style linkage between the engine and motor connected to the head end of the transmission.

The Toyota brand name for this technology is Hybrid Synergy Drive, which is being used in the Prius, the Highlander Hybrid SUV, and the Camry Hybrid. A computer oversees operation of the entire system, determining which half should be running, or if both should be in use. The operation of the Prius can be divided into six distinct regimes.

Electric vehicle mode: The engine is off, and the battery provides electrical energy to power the motor (or the reverse when regenerative braking is engaged). Used for idling as well when the battery State Of Charge (SOC) is high.

Cruise mode: The vehicle is cruising (i.e. not accelerating), and the engine can meet the road load demand. The power from the engine is split between the mechanical path and the generator. The latter provides electrical energy to power the motor, whose power is summed mechanically with the engine. If the battery state-of-charge is low, part of the power from the generator is directed towards charging the battery.

Overdrive mode: A portion of the rotational energy is siphoned off by the main electric motor, operating as a generator, to produce electricity. This electrical energy is used to drive the sun gear in the direction opposite its usual rotation. The end result has the ring gear rotating faster than the engine, albeit at lower torque.

Battery charge mode: Also used for idling, except that in this case the battery state-of-charge is low and requires charging, which is provided by the engine and generator.

Power boost mode: Employed in situations where the engine cannot meet the road load demand. The battery is then used to power the motor to provide a boost to the engine power.

Negative split mode: The vehicle is cruising and the battery state-of-charge is high. The battery provides power to both the motor (to provide mechanical power) and to the generator. The generator converts this to mechanical energy that it directs towards the engine shaft, slowing it down (although not altering its torque output). The purpose of this engine "lugging" is to increase the fuel economy of the vehicle.

The hybrid drivetrain of the Prius, in combination with aerodynamics and optimizations in the engine itself to reduce drag, results in 80%–100% gains in fuel economy compared to four-door conventional cars of similar weight and size.

Mild Hybrids

Mild hybrids are essentially conventional vehicles with some degree of hybrid hardware, but with limited hybrid feature utilization. Typically they are a parallel system with start-stop only or possibly in combination with modest levels of engine assist or regenerative braking features. Unlike full hybrids, Mild hybrids generally cannot provide ICE-OFF all-electric (EV) propulsion.

Mild hybrids like the General Motors 2004-07 Parallel Hybrid Truck (PHT) and the Honda Eco-Assist hybrids are equipped with a 3-phase electric motor mounted within the bell-housing between the engine and transmission, allowing the engine to be turned off whenever the truck is coasting, braking, or stopped, yet restart quickly when required. Accessories can continue to run on electrical power while the engine is off, and as in other hybrid designs, the motor is used for regenerative braking to recapture energy. The large electric motor is used to spin up the engine to operating rpm speeds before injecting any fuel.

The 2004-07 Chevrolet Silverado PHT, was a full-size pickup truck. Chevrolet was able to get a 10% improvement on the Silverado's fuel efficiency by shutting down and restarting the engine on demand and using regenerative braking. However the electrical motor was not used to provide propulsion or assist, rather the electrical energy was used to drive accessories like the A/C and power steering. The GM PHT used a 42 volt systems via a pack comprised three 12V vented lead acid batteries connected in series (36V total) to supply the power needed for the startup motor, as well as to compensate for the increasing number of electronic accessories on modern vehicles.

General Motors followed the parallel hybrid truck with their BAS Hybrid system, another mild hybrid implementation officially released on the 2007 Saturn Vue Green Line. For its "start-stop" functionality, it operates similarly to the system in the Silverado, although via a belted connection to the motor/generator unit. However the GM BAS Hybridsystem has broader hybrid functionality as the electric motor can also provide modest assist under acceleration and during steady driving, and captures energy during regenerative (blended) braking. The BAS Hybrid can result in as much as a

27% improvement in combined fuel efficiency as noted by the EPA in testing of the 2009 Saturn VUE. The BAS Hybrid system can also be found on the 2008-09 Saturn Aura and the 2008-2010 Chevrolet Malibu hybrids.

Another way to provide for shutting off a car's engine when it is stopped, then immediately restarting it when it's time to go, is by employing a static start engine. Such an engine requires no starter motor, but employs sensors to determine the exact position of each piston, then precisely timing the injection and ignition of fuel to turn over the engine.

Mild hybrids are sometimes called Power assist hybrids' as they use the engine for primary power, with a torque-boosting electric motor also connected to a largely conventional power train. The electric motor, mounted between the engine and transmission, is essentially a very large starter motor, which operates not only when the engine needs to be turned over, but also when the driver "steps on the gas" and requires extra power. The electric motor may also be used to re-start the combustion engine, deriving the same benefits from shutting down the main engine at idle, while the enhanced battery system is used to power accessories.

Honda's hybrids including the Insight use this design, leveraging their reputation for design of small, efficient gasoline engines; their system is dubbed Integrated Motor Assist (IMA). Assist hybrids differ fundamentally from full hybrids in that propulsion cannot be accomplished on electric power alone. However, since the amount of electrical power needed is much smaller, the size of the system is reduced. Starting with the 2006 Civic Hybrid, the IMA system now can propel the vehicle solely on electric power during medium speed cruising.

A variation on this type of hybrid is the Saturn Vue Green Line BAS Hybrid system that uses a smaller electric motor (mounted to the side of the engine), and battery pack than the Honda IMA, but functions similarly.

Another variation on this type is Mazda's e-4WD system, offered on the Mazda Demio sold in Japan. This front-wheel drive vehicle has an electric motor which can drive the rear wheels when extra traction is needed. The system is entirely disengaged in all other driving conditions, so it does not directly enhance performance or economy but allows the use of a smaller and more economical engine relative to total performance.

Plug-in hybrid

A plug-in hybrid electric vehicle (PHEV) has two defining characteristics: 1) it can be plugged in to an electrical outlet to be charged and (2) has some range that can be traveled on the energy it stored while plugged in. They are full hybrid, able to run in electric-only mode, with larger batteries and the ability to recharge from the electric power grid. And can be parallel or series hybrid designs. They are also called gas-optional, or griddable hybrids. Their main benefit is that they can be gasoline-independent for daily commuting, but also have the extended range of a hybrid for long trips. They can also be multi-fuel, with the electric power supplemented by diesel, biodiesel, or hydrogen. The Electric Power Research Institute's research indicates a lower total cost of ownership for PHEVs due to reduced service costs and gradually improving batteries. The "well-to-wheel" efficiency and emissions of PHEVs compared to gasoline hybrids depends on the energy sources of the grid (the US grid is 50% coal; California's grid is primarily natural gas, hydroelectric power, and wind power). Particular interest in PHEVs is in California where a "million solar homes" initiative is under way, and global warming legislation has been enacted.

Prototypes of PHEVs, with larger battery packs that can be recharged from the power grid, have been built in the U.S., notably at Prof. Andy Frank's Hybrid Center at University of California, Davis and one production PHEV, the Renault Kangoo, went on sale in France in 2003. DaimlerChrysler is currently building PHEVs based on the Mercedes-Benz Sprinter van. Light Trucks are also offered by Micro-Vett SPA the so called Daily Bimodale.

The California Cars Initiative has converted the '04 and newer Toyota Prius to become a prototype of what it calls the PRIUS+. With the addition of 140 kg of lead-acid batteries, the PRIUS+ achieves roughly double the gasoline mileage of a standard Prius and can make trips of up to 16 km using only electric power.

Chinese battery manufacturer and automaker BYD Auto released the F3DM PHEV-62 (PHEV-100 km) compact sedan to the Chinese fleet market on December 15, 2008.

Types by nature of the power source

Electric-internal combustion engine hybrid

There are many ways to create an electric-Internal Combustion Engine (ICE) hybrid. The variety of electric-ICE designs can be differentiated by how the electric and combustion portions of the powertrain connect, at what times each portion is in operation, and what percent of the power is provided by each hybrid component. Two major categories are series hybrids and parallel hybrids, though parallel designs are most common today.

Most hybrids, no matter the specific type, use regenerative braking to recover energy when slowing down the vehicle. This simply involves driving a motor so it acts as a generator.

Many designs also shut off the internal combustion engine when it is not needed in order to save energy. That concept is not unique to hybrids; Subaru and FIAT pioneered this feature in the early 1980s, and the Volkswagen Lupo 3L is one example of a conventional vehicle that shuts off its engine when at a stop. Some provision must be made, however, for accessories such as air conditioning which are normally driven by the engine. Furthermore, the lubrication systems of internal combustion engines are inherently least effective immediately after the engine starts; since it is upon startup that the majority of engine wear occurs, the frequent starting and stopping of such systems reduce the lifespan of the engine considerably. Also, start and stop cycles may reduce the engine's ability to operate at its optimum temperature, thus reducing the engine's efficiency.

Electric-fuel cell hybrid

Fuel cell vehicles are often fitted with a battery or supercapacitor to deliver peak acceleration power and to reduce the size and power constraints on the fuel cell (and thus its cost); this is effectively also a series hybrid configuration.

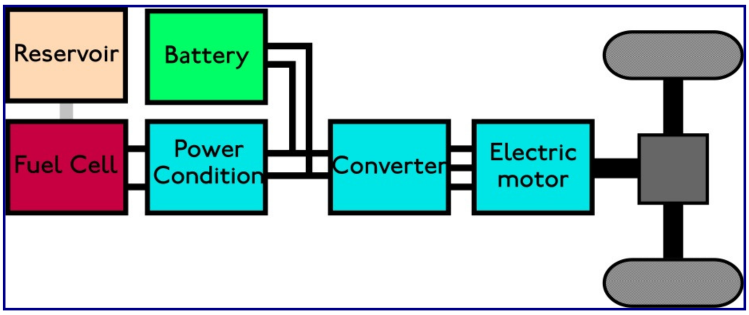

Figure 4 Structure of a fuel cell hybrid electric vehicle

Internal combustion engine-hydraulic hybrid

A hydraulic hybrid vehicle uses hydraulic and mechanical components instead of electrical ones. A variable displacement pump replaces the motor/generator, and a hydraulic accumulator (which stores energy as highly compressed nitrogen gas) replaces the batteries. The hydraulic accumulator, which is essentially a pressure tank, is potentially cheaper and more durable than batteries. Hydraulic hybrid technology was originally developed by Volvo Flygmotor and was used experimentally in buses from the early 1980s and is still an active area.

Initial concept involved a giant flywheel for storage connected to a hydrostatic transmission, but it was later changed to a simpler system using a hydraulic accumulator connected to a hydraulic pump/motor. It is also being actively developed by Eaton and several other companies, primarily in heavy vehicles like buses, trucks and military vehicles. An example is the Ford F-350 Mighty Tonka concept truck shown in 2002. It features an Eaton system that can accelerate the truck up to highway speeds.

The energy recovery rate is higher and therefore the system is more efficient than battery charged hybrids, demonstrating a 60% to 70% increase in economy in EPA testing. Under tests done by the EPA, a hydraulic hybrid Ford Expedition returned 7.4 L/100 km in urban driving, and 11 L/100 km on the highway. UPS currently has two trucks in service with this technology. While the system has faster and more efficient charge/discharge cycling, the accumulator size and pressure dictates total energy capacity, and requires more space than a battery.

Internal combustion engine-pneumatic hybrid

Compressed air can also power a hybrid car with a gasoline compressor to provide the power. Motor Development International in France is developing such air-powered cars. A team led by Tsu-Chin Tsao, a UCLA mechanical and aerospace engineering professor, is collaborating with engineers from Ford to get Pneumatic hybrid technology up and running. The system is similar to that of a hybrid-electric vehicle in that braking energy is harnessed and stored to assist the engine as needed during acceleration.

Human power and environmental power hybrids

Many land and water vehicles use human power combined with a further power source. Common are parallel hybrids, e.g. a boat being rowed and also having a sail set, or motorized bicycles, or a human-electric hybrid vehicle such as the Twike. Also some series hybrids exist, see in hybrid vehicle. Such vehicles can be tribrid vehicles, combining at the same time three power sources e.g. from on-board solar cells, from grid-charged batteries, and from pedals.

Benefits of a Hybrid

Hybrid vehicles have the potential to be two to three times more fuel-efficient than conventional vehicles, with much lower emission levels. Also, the combination of an engine and electric motor can provide increased power and/or additional auxiliary power for electrical devices. A hybrid vehicle has two main advantages over a battery-operated electric vehicle:

1. Drivers are more comfortable with HEVs because there are no battery range limitations (therefore no fear of being stranded) and the vehicles are refueled in the same way as any gasoline-powered vehicle.
2. A hybrid requires a much smaller battery than a pure EV, which dramatically reduces the vehicle's price. The battery cost in a pure EV can be as much as 25,000 €, whereas the battery cost in hybrids is less than 5000 €.

When comparing the pollution and fuel consumption of EVs and HEVs, it is important to remember that EVs are not completely pollution-free, nor oil-independent. Many of the electric power plants that generate the electricity to charge EVs burn oil, natural gas, or coal. Only electric power produced by hydroelectric dams, wind turbines, solar, or geothermal plants are pollution-free and are renewable (they do not consume any type of fossil fuel). These clean sources, however, produce only a small fraction of the electricity in the United States today, and most electricity is generated by burning a fuel.

Although HEVs still burn gasoline and emit exhaust pollutants, the amount of pollution produced, and gasoline consumed per mile are substantially less than in a typical gasoline-powered vehicle because:

- The gasoline engine can be smaller for the same level of vehicle performance because there is electric motor assist.

- The propulsion system can be designed to allow the engine to run at its most fuel efficient speed.
- The engine can be shut off while the car is stopped at traffic lights, decelerating, or moving at low speed.
- Regenerative braking captures and recycles much of the energy used to accelerate the vehicle.

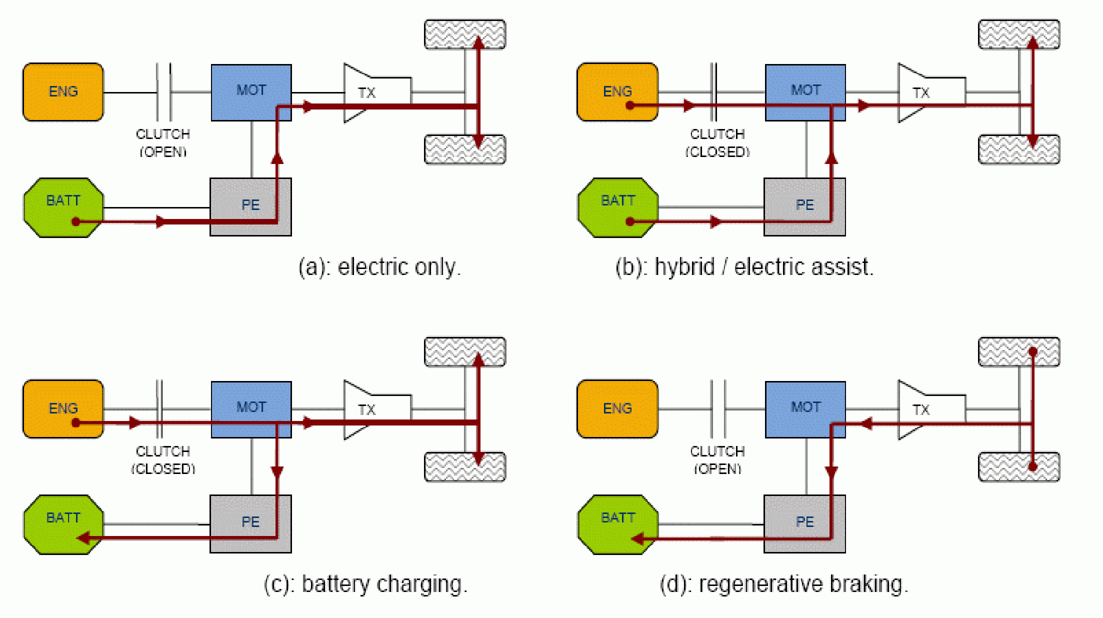

Figure 5 Hybrid vehicle operation modes

Fuel Economy

Hybrids consume significantly less fuel than vehicles powered by gasoline alone. Therefore, they can reduce the country's dependence on fossil fuels and foreign oil. (Fuel economy ratings for hybrid and conventional vehicles can found at www.FuelEconomy.gov) Table compares the performance of a standard Honda Civic to a Civic HEV. As you can see, there is a substantial difference in fuel consumption. Also, notice, although the acceleration times are slightly different, other performance measurements are near identical.

HEVs typically have the same or greater range than conventional vehicles. For example, Honda's Insight has a range of about 1.100 kilometers on a tank of fuel. This extended range certainly offsets the disadvantage of a battery operated electric vehicle, which has been impaired by having very short driving ranges.

Air Pollution

Hybrids can have more than 90% fewer emissions than the cleanest conventional vehicles. HEVs also produce significantly lower total fuel-cycle ("well to wheel") emissions when compared to equivalently sized conventional vehicles.

The low emissions result from the use of smaller and more efficient internal combustion engines. The engine's power is boosted by electric motors that produce zero emissions. Also, the engine can be shut down when it is not needed. In addition, many HEVs can move in an electric-only mode. In this mode, the vehicle has no emissions. Clean electricity is also used to power many accessories and other equipment that typically are driven by the ICE. This means the engine has less work to do and therefore will use less fuel and emit fewer pollutants.

Hybrids will never be zero-emission vehicles, because they rely on an engine for much of its power. However, most are rated as being close to zero emission vehicles.

Using ICEs and electric motors, HEVs also have very low carbon dioxide emissions. Hybrids emit one-third to one-half less carbon dioxide than conventional vehicles.

Cost

HEVS have a higher initial cost than comparable conventional vehicles and tend to be heavier. The added weight decreases fuel economy, which is why some larger hybrid SUVs see little gain in fuel mileage. The additional weight results from the addition of large battery packs and electric motor/generators. These same items contribute to the higher cost, as well. However, the cost of some of these items will decrease as the volume of production increases. Currently, a HEV costs nearly 4000 € more to produce.

Many believe the increased fuel economy of HEVs offsets their higher initial cost. Consumers pay more for a HEV but typically gain a substantial increase in fuel economy. The initial cost can also be partially offset by tax incentives. Some states may provide additional incentives or tax credits for purchasing a hybrid vehicle.

Not all automotive experts believe the savings on fuel does, indeed, offset the higher initial cost of a HEV. These opinions are based on the service life of a HEV. According to *www.edmunds.com,* gasoline would have to cost $5.60 a gallon for a Ford Escape Hybrid owner and $10.10 a gallon for a Prius owner to financially justify the higher initial cost of a hybrid. The debate will undoubtedly continue for quite some time. However, it is safe to say that most who buy hybrids are doing so for other reasons than using less fuel. These reasons are based on the benefits of hybrid vehicles such as lower emissions and decreasing the country's dependence on fossil fuels. Plus, some feel owning a hybrid makes a statement they want to make!

Comparing two Honda Civic

What's the Difference?	Civic EX	Civic HEV
On-Road Fuel Economy (mpg)	40.1	47.8
EPA Fuel Economy (city/highway; mpg)	31/38 (auto)	48/47 (CVT)
Acceleration (0-60 mph)	10.84	12.88
Slalom (cones every 50 ft; average mph)	33.25	33.39
Skid Pad (average G clockwise)	0.69	0.66
Braking (ft from 60-0 mph)	140	136
Passenger/Luggage Volume (ft^3)	88.1/12.9	91.4/10.1
Curb Weight (Ib)	2,615 (auto)	2,732 (CVT)

Source: U.S. Department of Energy Technology Snapshot — Featuring the Honda Civic Hybrid from their website

Start-Stop system

Stop-start systems automatically shut down the engine when the driver applies the brakes and brings the vehicle to a complete stop. This prevents wasting energy while the engine is idling and can increase fuel economy by more than 10%. The benefit of these systems is most evident during stop-and-go driving. With the engine off, the vehicle's heating and air conditioning systems and its electrical systems continue to run using the battery power. The engine is restarted automatically when the drivers releases the brake pedal or when the control system senses the need.

When the engine is restarted is a defining element of mild and full hybrids. Electric components turn off the engine when the vehicle is stopped and is quickly restarted when the brakes are released. Most mild hybrids have a belt-driven starter-generator.

Full hybrids can be powered by only the electric motor, the gasoline engine alone, or both. They have the stop-start feature but the engine does not automatically restart when the brakes are released. Because full hybrid can accelerate with only the electric motor, the engine is not restarted until the engine's power is needed. This is determined by the control system and is based on the vehicle's load and the batteries' state of charge.

Nearly all mild hybrid vehicles are fitted with a flywheel/alternator/starter or a belt-driven alternator/starter hybrid System. These systems provide for stop-start. Strong motors are used to spin the engine fast enough to provide for quick engine restarts. Because most of the vehicle's accessories are powered by the battery, they continue to run when the engine is off. Regenerative braking may be used to supplement the recharging capability of the generator. Fuel consumption is decreased because the engine does not run when it is not needed.

Assist hybrids typically have an electrical motor connected in series with the engine. The motor adds power to the output of the engine when needed. When the motor is not assisting the engine, it may serve as a generator. The motor also provides for stop-start. Fuel consumption is decreased because of the stop-start feature and, with the assist of the motor, smaller and more efficient engines are used.

Flywheel Alternator Starter Hybrid System

The flywheel/alternator/starter assembly replaces the starter and generator on a conventional engine. The assembly is sometimes called an integrated starter alternator damper (ISAD). In most applications, the ISAD is positioned between the engine and the transmission, although it can be mounted to the side of the transmission.

This unit costs about € 1,000 less than a full hybrid System. The compact assembly does not require the very high voltages required by other hybrid systems. Most ISAD systems rely on 42-volt power sources. The ISAD allows for regenerative braking.

General Motors Corp.'s hybrid Chevrolet Silverado and GMC Sierra full-sized pickup trucks are equipped with the ISAD System. The System is designed to provide:

- Quick and quiet engine starting
- Stop-start technology
- Dampening of driveline vibrations
- Charging voltages for the batteries

- Regenerative braking
- Generation of electricity for auxiliary electrical outlets

The ISAD system replaces the conventional starter, generator, and flywheel with an electronically controlled compact AG asynchronous induction electric motor. This unit is housed in the transmission's bell housing. The stator of the starter/generator is mounted to the engine block. The rotor is attached to the end of the engine's crankshaft. As the crankshaft rotates, so does the rotor, or vice versa. Current is sent to the stator when the unit is functioning as a motor. When functioning as a generator, current flows from the stator. When working as a generator, the electrical motor can provide up to 14,000 watts of continuous electric power.

The electricity generated by the System is used to recharge the 12- and 42-volt battery packs, both of which are used to power the various vehicle systems. The electricity can also be used to run power tools or home appliances. These trucks have four 120-volt, 20-amp AG power outlets. The auxiliary outlets can power up to four accessories while driving or when the vehicle is parked, as long as the engine is running. It is claimed the generators can power tools or appliances for up to 32 hours on a full tank of gasoline. The System is also designed to turn off the engine when the fuel level gets low. This feature allows the vehicle to be driven somewhere to be refueled. Ali power supply circuits are protected by a ground fault detection system to prevent overloads and short circuits.

The overall performance of the trucks is the same as non-hybrid models. Both models use the same 5.3-liter Vortec V-8 and 4-speed automatic. Because the electric motor provides no power assist, their power output ratings are also identical. This means these hybrid trucks have the same towing capacity and payload ratings as a conventional pickup.

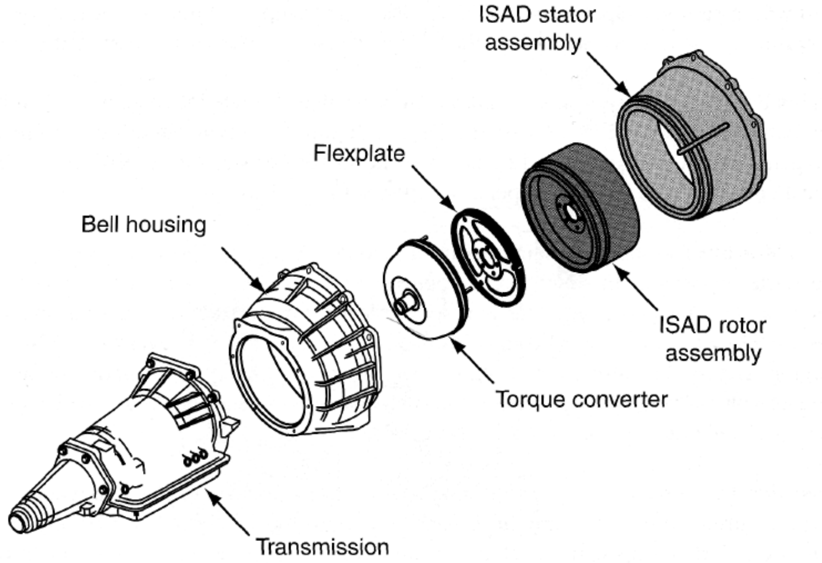

Figure 6 The basic layout of an ISAD assembly

The reduction in fuel consumption of the hybrid pickup is mostly noticeable during city driving, like most hybrids. The EPA mileage ratings for a Sierra 4WD hybrid with an automatic transmission are 17 miles per gallon (mpg) city and 19 mpg highway. The ratings for a similar non-hybrid model are 15 mpg city and 18 highway. This amounts to an approximate gain of 12% during city driving.

The hybrid system improves fuel economy and reduces emissions because it has three primary features. The System allows for regenerative braking, which decreases the amount of load placed on the engine to turn the generator. However, the major contributor to fuel efficiency is the stop-start feature. An additional feature to save fuel is the shutdown of the engine's fuel injection system whenever the vehicle is coasting, decelerating, and braking.

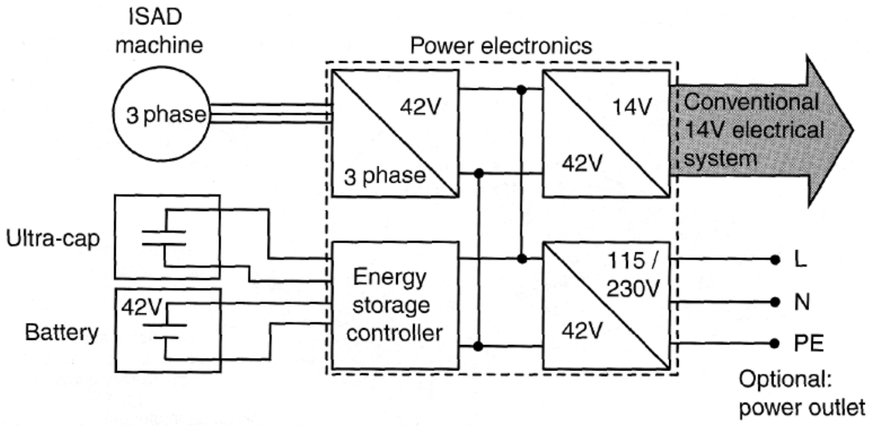

Figure 7 A look at a simplified electrical circuit for an ISAD system

The transmission in the hybrid models has been slightly modified to meet the demands of the system. The torque converter is smaller and has a stronger lockup clutch. The transmission is fitted with a stronger input shaft and an auxiliary oil pump. The pump provides for sufficient line pressure in the transmission when the engine is restarted during the stop-start sequence.

Batteries Energy for ISAD is stored in three 14-volt valve-regulated lead-acid or absorbed glass mat (AGM) batteries. These batteries are used to power the electro-hydraulic power steering System and the starter/generator. A conventional 12-volt under-hood battery supplies the power for all other electrical items, such as lighting, wipers, sound systems, and so on.

Control Module The starter/generator control module controls the flow of electricity in and out of the starter/generator. In doing so, it controls the operation of the hybrid system and the power module. The power module is responsible for all electrical conversion and inversion processes 42-volt DC is converted to AG for starting and the AG is converted to 42-volt DC for recharging. The module also converts 42-volt DC power to 14-volt DC to charge the under-hood battery; 14-volt DC power is converted to 42-volt AG for jump-starting; and 42-volt AG power is converted to 120 volts AG for use at the electrical outlets.

Accessories To maintain the operation of accessories and auxiliary equipment when the engine is shut off during stop-start, many accessories are powered by the 42-volt battery. When the engine is off during stop-start, an electric pump continues to circulate hot water through the heating System during cold weather; in warm weather, cold, dry air is moved through the vehicle's ventilation system. Power steering is provided by an electrically driven hydraulic pump. The electro-hydraulic power steering (EHPS) system operates whether the engine is running or not, and provides fluid under pressure for the Hydroboost power brake system.

Belt Alternator Starter Hybrid System

A Belt Alternator Starter (BAS) system replaces the traditional starter and generator in a conventional vehicle. The unit is located where the generator would normally be, and is connected to the engine's crankshaft by a drive belt. This unit, an electric motor, serves as the starting motor and generator. When the engine is running, a drive belt spins the rotor of the motor and the motor acts as a generator to charge the batteries. To start the engine, the motor's rotor spins and moves the drive belt, which in turn cranks the engine. These systems have the capability of providing stop-start, regenerative braking, and high-voltage generation.

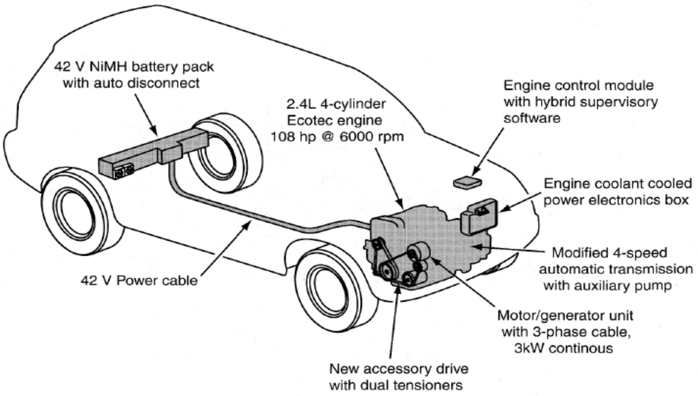

Figure 8 General Motor's BAS hybrid system and key components

A typical BAS includes the motor/generator, electronic controls, and a 42-volt battery. The ability to start the engine quietly and quickly is important to the operation of the stop-start feature, therefore the system uses a rather robust motor. The motor can be either a permanent magnet or induction motor. The required electronic controls for the system depend on the type of motor used. Some systems are also equipped with a conventional starting motor. These are used during extremely cold temperatures. Once the engine is warm, the BAS takes over.

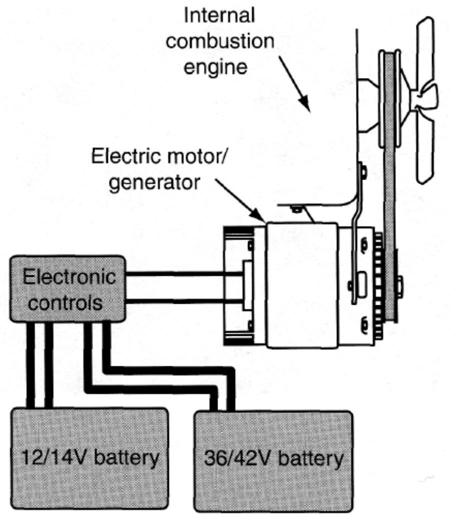

Figure 9 The basic architecture for a BAS hybrid system

“BAS” and “Flywheel Alternator Starter” are practical examples of start-stop systems.

As seen in previous paragraphs, both systems are mainly composed of an electric synchronous or asynchronous motor. Thus, the design of these electric devices is very important to permit the motors to reach appropriate electrical and mechanical characteristics such as torque, speed, acceleration, wear resistance et cetera.

Electric drive is also very important because of the need to change motor’s role when the ICE is started. From initial starting motor function, electric motor become a current generator, reversing its power flow. Knowing resistant torque when the engine is not running is thus important to correctly design electric motor, electric drive and switching time too.

For this reason we decide to create the following mathematical model that evaluate the torque needed to a system composed by a piston, a crank and a piston rod to reach and to maintain imposed values of acceleration and angular velocity.

The model is quite simplified and it considers only the contributions of inertial forces and of the pressure generated by compressed gas inside combustion chamber (considering it a simply “gas container” without valves motion and thus without gas flow). Once the model was conceived, it was then written in MATLAB code and afterwards inserted in a SIMULINK schematic through a “embedded MATLAB function” block in order to perform a dynamic simulation.

An accurate evaluation of starting torque is even more important for design of new conception of hybrid bikes. Indeed, this research field requires compact and lightweight devices.

Engine physical-mathematical model

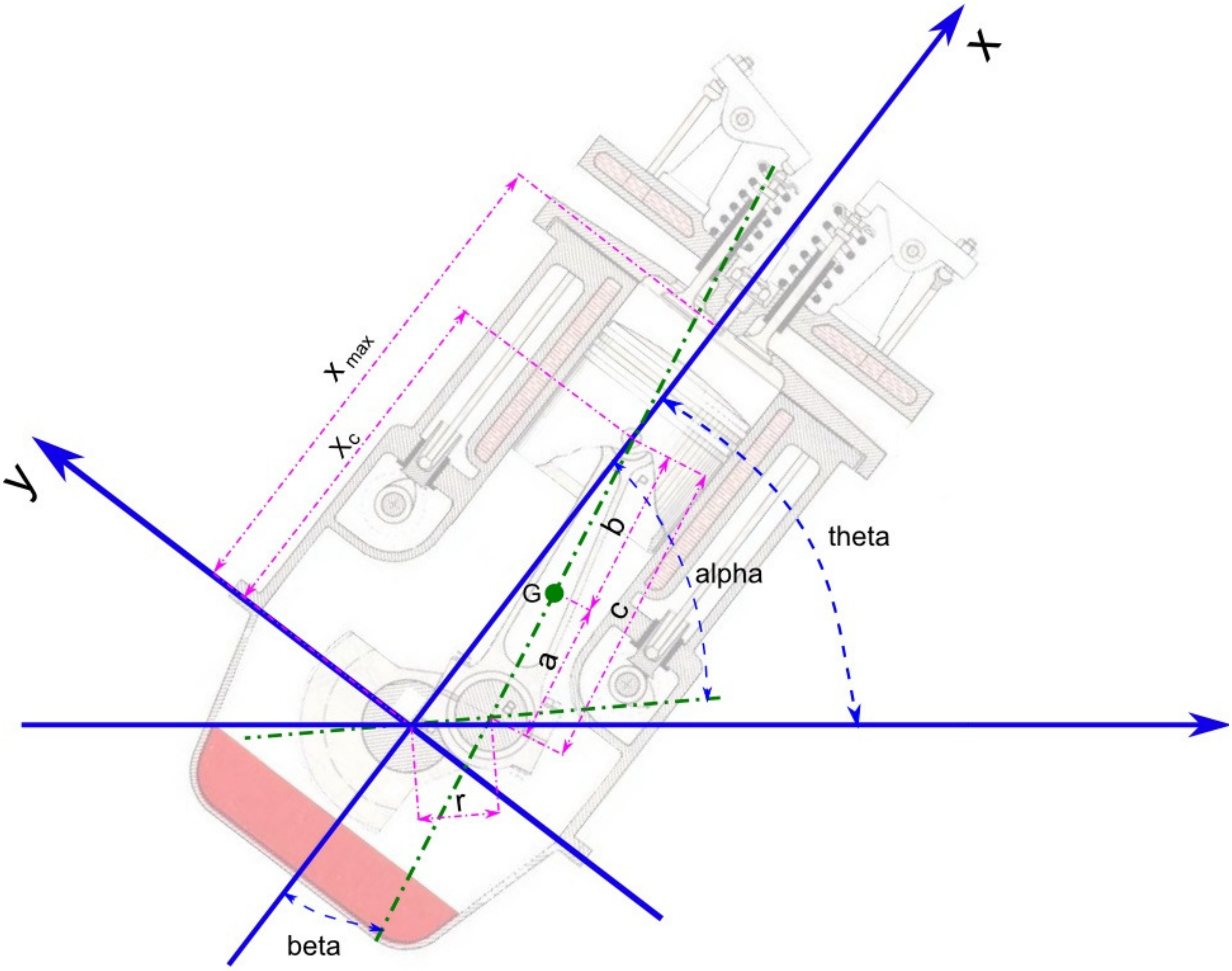

Figure 10 Engine scheme

Trigonometric analysis

As shown in figure, x_c , that is the position of piston on X axis relative to the origin and therefore also relative to the rotation axis of the crank (crankshaft), can be obtained by a simple trigonometric function:

$$x_c = r\cos(\alpha) + c\cos(\beta) \tag{1}$$

Where r is the length of the crank and c is the length of the piston rod.

Defining $\sin(\beta)$ as a function of α :

$$r\sin(\alpha) = c\sin(\beta) \tag{2}$$

$$\sin(\beta) = \frac{r\sin(\alpha)}{c} \tag{3}$$

Therefore number 1 can be written as:

$$x_c(\alpha,\beta) = r\cos(\alpha) + c\sqrt{1-\sin(\beta)^2} \tag{4}$$

And then:

$$x_c(\alpha) = r\cos(\alpha) + c\sqrt{1-\frac{r^2}{c^2}\sin(\alpha)^2} \tag{5}$$

Speed and acceleration of piston over translation axis can be obtained by derivation of previous equation and resulting in:

$$\dot{x}_c(\alpha,\dot{\alpha}) = \left(-r\sin(\alpha) - \frac{r^2\sin(\alpha)\cos(\alpha)}{\sqrt{(c^2)-r^2\sin(\int)^2}}\right)\dot{\alpha} \tag{6}$$

$$\ddot{x}_c(\alpha,\dot{\alpha},\ddot{\alpha}) = \left(-r\cos(\alpha) - \frac{r^2\left(2c^2\cos(\alpha)^2 d r^2\sin(\alpha)^4-c^2\right)}{\sqrt{c^2-r^2\sin(\alpha)^2}^{1}}\right)\dot{\alpha}^2 + \left(-r\sin(\alpha) - \frac{r^2\sin(\alpha)\cos(\alpha)}{\sqrt{(c^2)-r^2\sin(\int)^2}}\right)\ddot{\alpha} \tag{7}$$

Regarding piston rod’s position the following considerations are possible:

$$\sin(\sigma) = -\frac{r}{c}\sin(\alpha) \tag{8}$$

$$\sigma = -\arcsin\left(\frac{r}{c}\sin(\alpha)\right) \tag{9}$$

Coordinates of piston rod’s center of gravity (shown in the figure with G) are given by:

$$x_G(\alpha) = r\cos(\alpha) + a\cos(\sigma) = r\cos(\alpha) + a^2\sqrt{1-\left(\frac{r}{c}\sin(\alpha)\right)^2} \tag{10}$$

$$y_G(\alpha) = -b\sin(\sigma) = b\,\frac{r}{c}\sin(\alpha) \tag{11}$$

It is also necessary to calculate speeds and accelerations of the piston rod’s center of gravity over X and Y axes ($\dot{x_G}, \dot{y_G}$, $\dot{\sigma_G}$ and $\ddot{x_G}, \ddot{y_G}, \ddot{\sigma_G}$) that will be used later

$$\dot{x}_G(\alpha,\dot{\alpha}) = \tau - r\sin(\alpha) - a\frac{r^2}{c^2}\frac{\cos(\alpha)\sin(\alpha)}{\sqrt{1}-\left(\frac{r}{c}\sin(\alpha)\right)^2}\boldsymbol{\sigma}\dot{\alpha} \tag{12}$$

$$\dot{y_G}(\alpha,\dot{\alpha}) = \left(b\frac{r}{c}\cos(\alpha)\right)\dot{\alpha} \tag{13}$$

$$\dot{\sigma}_G(\alpha,\dot{\alpha}) = -\frac{\frac{r}{c}\cos(\alpha)}{\sqrt{1-\left(\frac{r}{c}\sin(\alpha)\right)^2}}\dot{\alpha} \tag{14}$$

$$\ddot{x}_G(\alpha,\dot{\alpha},\ddot{\alpha}) = -\dot{\alpha}^2\left(r\cos(\alpha) + \frac{a\frac{r^2}{c}\left(2c^2\cos(\alpha)^2 d\,r^2\sin(\alpha)^4 - c^2\right)}{\sqrt{c^2-r^2\sin(\alpha)^2}^{1}}\right) - \ddot{\alpha}\left(r\sin(\alpha) + \frac{a\left(\frac{r}{c}\right)^2\cos(\alpha)\sin(\alpha)}{\sqrt{1-\left(\frac{r}{c}sin(\alpha)\right)^2}}\right) \tag{15}$$

$$\ddot{y_G}(\alpha,\dot{\alpha},\ddot{\alpha}) = b\frac{r}{c}\left(\ddot{\alpha}\cos(\alpha) - \dot{\alpha}\sin(\alpha)\right) \tag{16}$$

$$\ddot{\sigma}_G(\alpha,\dot{\alpha},\ddot{\alpha}) = \dot{\alpha}^2\left(\frac{\frac{r}{c}\sin(\alpha)\sqrt{1-\left(\frac{r}{c}\sin(\alpha)\right)^2} - \frac{r^2\sin(\alpha)\cos(\alpha)^2}{c\sqrt{c^2-r^2\sin(\alpha)^2}}}{1-\left(\frac{r}{c}\sin(\alpha)\right)^2}\right) + \ddot{\alpha}\left(-\frac{\frac{r}{c}\cos(\alpha)}{\sqrt{1-\left(\frac{r}{c}\sin(\alpha)\right)^2}}\right) \tag{17}$$

Knowing the position of the piston allows also to define the volume inside combustion chamber. It will depends too by the angle α with the following law:

$$V_c(\alpha) = (X_{\max} - x_c(\alpha)\,)\pi\left(\frac{A}{2}\right)^2 \tag{18}$$

And then, by substituting number 5:

$$V_c(\alpha) = \left(X_{\max} - r\cos(\alpha) - c\sqrt{1 - \frac{r^2}{c^2}\sin(\alpha)^2}\right)\pi\left(\frac{A}{2}\right)^2 \tag{19}$$

Where X_{max} is the distance between crankshaft and the top of the combustion chamber and A is the bore.

Thermodynamic analysis

Due to the extremely rapid transformation that takes place inside the combustion chamber, it is possible to assume that there isn’t any heat exchange with the outside. Therefore the transformation can be considered adiabatic. The mathematic relation obtained from the equation of state for this type of transformation is:

$$pV^{\gamma} = const \tag{20}$$

Where p indicates the pressure of the considered gas, V is its volume and γ is the ratio between specific heat considered at constant pressure and specific heat considered at constant volume that, in this case, assuming a diatomic gas like the air, it will be 1,4.

For every instant i and j we will have:

$$p_i {V_i}^{\gamma} = p_j {V_j}^{\gamma} = const \tag{21}$$

And, in particular, for $\alpha = \pi$ we have:

$V = V_c = V_{max}$ and $p = p_{atm}$

That is the volume of combustion chamber is the maximum volume when the crank is at its lower position and the pressure inside the cylinder is equivalent to the atmospheric.

Solving 21 in p_i and substituting $p_j = p_{atm}$ and $V_j = V_{max}$ we have:

$$p_i = \left(\frac{V_{max}}{V_i}\right)^{\gamma} p_{atm} \tag{22}$$

In this way it is possible to deduce the pressure inside combustion chamber in every instant simply knowing its own volume. Substituting number 19 in number 22 we find:

$$p(\alpha) = \left(\frac{V_{max}}{\left(X_{max} - r\cos(\alpha) - c\sqrt{1 - \left(\frac{r^2}{c^2}\right)\sin(\alpha)^2}\right)\pi\left(\frac{A}{2}\right)^2}\right)^{\gamma} P_{atm} \tag{23}$$

Now, knowing gases pressure inside combustion chamber it is also possible to define the force performed over the piston by themselves

$$p = \frac{F_g}{S_p} \tag{24}$$

Therefore:

$$F_{g(\alpha)} = m_p g \cos\left(\Theta - \frac{\pi}{2}\right) + \left(\frac{V_{max}}{\left(X_{max} - r\cos(\alpha) - c\sqrt{1 - \left(\frac{r^2}{c^2}\right)\sin(\alpha)^2}\right)\pi\left(\frac{A}{2}\right)^2}\right)^{\gamma} P_{atm}\,\pi\left(\frac{A}{2}\right)^2 \tag{25}$$

Which also consider the component of piston weight parallel to the translation axis and where m_p is the piston mass, g is the gravity acceleration and θ is the angle formed by translation axis with the tangent to the earth's surface.

Dynamic analysis

Assuming known the moment of inertia I_m of the crank with respect to its own rotation's axis (crankshaft) and the moment of inertia I_b of the piston rod with respect its own centre of mass, it is possible, trough an energetic approach, to determine the equation of motion of the system composed by crank, piston and piston rod.

The total kinetic energy possessed by a rigid body system is given by the sum of kinetic energy due to pure translations with the kinetic energy due to pure rotations of the elements of the system. Because it is a system with only one degree of freedom it is possible to reduce the real system composed by all the rotating and translating components to a system made of only a single rotating component. The parameters that will describe the new reduced system will be the reduced inertia and the reduced moment.

Reduced inertia Defining with n the number of moving bodies of the system, the equivalence of the reduced system (marked with a *) with the real system is given by the following relation:

$$E_C = \frac{1}{2} I^* \dot{\alpha}^2 = \sum_{i=1}^{n} \left(\frac{1}{2} m_i \dot{x}_i^{\,2} + \frac{1}{2} m_i \dot{y}_i^{\,2} + \frac{1}{2} I_i \dot{\sigma}_i^{\,2} \right) \tag{26}$$

Where $\dot{x}_i, \dot{y}_i, \dot{\sigma}_i$ are respectively the components of the speed of the centre of mass of the i-ith body of the system and its angular rotation velocity.

The only degree of freedom of the system makes it possible to express the velocities $\dot{x}_i, \dot{y}_i, \dot{\sigma}_i$ by functions of the generalized coordinate $\dot{\alpha}$ through speed ratios τ. Speed ratios depend on system configuration and they define the relation that exist through linear or angular velocities of the single component and the only generalized coordinate of the reduced system α, i.e.:

$$\tau_{xi} = \frac{dx_i}{d\alpha} = \frac{\dot{x}_i}{\dot{\alpha}} \qquad \tau_{yi} = \frac{dy_i}{d\alpha} = \frac{\dot{y}_i}{\dot{\alpha}} \qquad \tau_{\sigma i} = \frac{d\sigma_i}{d\alpha} = \frac{\dot{\sigma}_i}{\dot{\alpha}}$$

The reduced inertia I^* can be obtained from 27 through some simple calculation and then substituting the speed ratios. Hence:

$$I^*(\alpha) = \sum_{i=1}^{n} \left(m_i \tau_{xi}^2 + m_i \tau_{yi}^2 + I_i \tau_{\sigma i}^2 \right) \tag{27}$$

In this particular case:

$$I^*(\alpha) = I_m + m_b \tau_{xG}^2 + m_b \tau_{yG}^2 + I_b \tau_{\sigma G}^2 + m_b \tau_{xC}^2 \tag{28}$$

Where m_b is the mass of the crank, m_p is the mass of the piston, $\tau_{xG}, \tau_{yG}, \tau_{\sigma G}, \tau_{xC}$ are the speed ratios of the components extracted from the 6,12,13,14 by division for $\dot{\alpha}$

Reduced inertia calculated through speed ratios is a function of the free coordinate and even of the time too because free coordinate is itself function of time.

Reduced moment The power of the reduced torque applied to the reduced system must equal the sum of all powers generated by the forces, conservative or not, applied to the system. Powers equivalence is therefore:

$$P = M^* \dot{\alpha} = \sum_{i=1}^{m} (F_{xi} \dot{x}_i + F_{yi} \dot{y}_i) + \sum_{i=1}^{r} M_i \dot{\alpha}_i \qquad (29)$$

Where m is the number of forces applied to the system and r is the number of the moments. Introducing speed ratios, like we made before for reduced inertia, the resulting torque is:

$$M^*(\alpha) = \sum_{i=1}^{m} \left(F_{xi} \tau_{xi} + F_{yi} \tau_{yi} \right) + \sum_{i=1}^{r} M_i \tau_{\alpha i} \qquad (30)$$

That in this case become:

$$M^*(\alpha) = M_m(\alpha, \dot{\alpha}, \ddot{\alpha}) + F_{eq}(\alpha) \tau_{xp} + W_{crank\perp} \tau_{yG} + W_{pRod\parallel} \tau_{xG} \qquad (31)$$

Where M_m is the torque applied to the crank, $F_{eq}(\alpha)$ is given by 25, $P_{biella\,\perp}$ and $P_{biella\,\parallel}$are respectively the weight component of the piston rod orthogonal and parallel to the translation axis (X axis) and $\tau_{xC}, \tau_{xG}, \tau_{yG}$ are the speed ratios for the translation over X axis for both the piston and for the centre of mass of the piston rod and for the translation over y axis of piston rod centre of mass. All three can be simply calculated through number 6, 12 and 13 by dividing them for $\dot{\alpha}$.

If forces or torques are motive, their components will be concordant with the velocity and power will be positive (hence introduced into the system); if forces or torques are resistant, their components will be opposite to the velocity and power will be negative (hence outgoing the mechanical system). Even the reduced moment, calculated through speed ratios is function of the free coordinate and thus of the time too.

Equation of motion The equation of the system energy is:

$$E_m + E_r + E_a = E_{c2} - E_{c1} \tag{32}$$

Where E_m, E_r, E_a represent respectively the energy due to motive forces (or torques), the energy due to resistant forces (or torques) and the wasted energy due to friction forces. $E_{c1}$and E_{c2} represent the kinetic initial energy and the kinetic final energy respectively. Using reduced inertia and reduced moment concepts we get:

$$\int_{\alpha_1}^{\alpha_2} M^*(\alpha)d\alpha = \frac{1}{2}I^*(\alpha_2)\dot{\alpha}_2^2 - \frac{1}{2}I^*(\alpha_1)\dot{\alpha}_1^2 \tag{33}$$

The left side of the equation represent the work done by forces that act on the system while the right side is the difference between kinetic energies at ending and starting position.

Similarly, for powers we have:

$$P = P_m + P_r + P_a \tag{34}$$

With the same meaning of the subscripts

Total instantaneous power can be also written as the variation of kinetic energy, i.e.:

$$P = \frac{d7_c}{dt} \tag{35}$$

Relating to 26 is thus possible to write:

$$P = M^*\dot{\alpha} = \frac{d\left(\frac{1}{2}\alpha^*\dot{\alpha}^2\right)}{dt} \tag{36}$$

Then dividing for $\dot{\alpha}$ we obtain:

$$M^* = I^*(\alpha)\ddot{\alpha} + \frac{\frac{1}{2}d\alpha^*(\alpha)}{d\alpha}\dot{\alpha}^2 \tag{37}$$

That is the equation of the motion. Assigning motive and resistant forces and/or torques it is now possible to calculate the time trend of $\dot{\alpha}$ .Expanding the expression $\frac{1}{2}\frac{d\alpha^*(\alpha)}{d\alpha}$ we arrive at:

$$\frac{1}{2}\frac{d\alpha^*(\alpha)}{d\alpha} = \sum_{i=1}^{n}\left(m_i\tau_{xi}\frac{d\tau_{xi}}{d\alpha} + m_i\tau_{yi}\frac{d\tau_{\sqrt{i}}}{d\alpha} + I_i\tau_{\sigma i}\frac{d\tau_{\sigma i}}{d\alpha}\right) \tag{38}$$

Where speed ratio’s derivatives result:

$$\frac{d\tau_{xi}}{d\alpha} = \frac{\ddot{x}_\imath\dot{\alpha} - \dot{x}_\imath\ddot{\alpha}}{\dot{\alpha}^3} \qquad \frac{d\tau_{yi}}{d\alpha} = \frac{\ddot{y}_\imath\dot{\alpha} - \dot{y}_\imath\ddot{\alpha}}{\dot{\alpha}^3} \qquad \frac{d\tau_{\sigma i}}{d\alpha} = \frac{\ddot{\sigma}_\imath\dot{\alpha} - \dot{\sigma}_\imath\ddot{\alpha}}{\dot{\alpha}^3}$$

The equation of motion in this case is differentiable by substituting number 28 and 31 to the equation 38. It results:

$$M_m(\alpha, \dot{\alpha}, \ddot{\alpha}) + F_{eq}(\alpha)\tau_{xp} + W_{pRod\perp}\tau_{yG} + W_{pRod\parallel}\tau_{xG} = \ddot{\alpha}\left(I_m + m_b\tau_{xG}^2 + m_b\tau_{yG}^2 + I_b\tau_{\sigma G}^2 + m_p\tau_{xC}^2\right) + \frac{1}{2}\frac{dI^*(\alpha)}{d\alpha}\dot{\alpha}^2$$

and resolving it in for $M_m(\alpha\ , \dot{\alpha}, \ddot{\alpha})$ we find:

$$M_m(\alpha\ , \dot{\alpha}, \ddot{\alpha}) = \ddot{\alpha}\left(I_m + m_b\tau_{xG}^2 + m_b\tau_{yG}^2 + I_b\tau_{\sigma G}^2 + m_p\tau_{xC}^2\right) + \frac{1}{2}\frac{dI^*(\alpha)}{d\alpha}\dot{\alpha}^2 - F_{eq}(\alpha)\tau_{xC} - W_{pRod\perp}\tau_{yG} - W_{pRod\parallel}\tau_{xG}$$

SIMULINK simulation and results

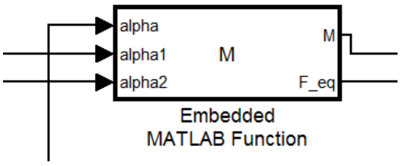

Figure 11 Embedded MATLAB function block

The mathematical model, implemented through a MATLAB embedded function block, was used in 2 different SIMULINK schemes. A first scheme implements an imposed speed profile in which speed and position are consequence of a given acceleration value and the output is therefore the required torque at the crankshaft to follow that speed and that acceleration.

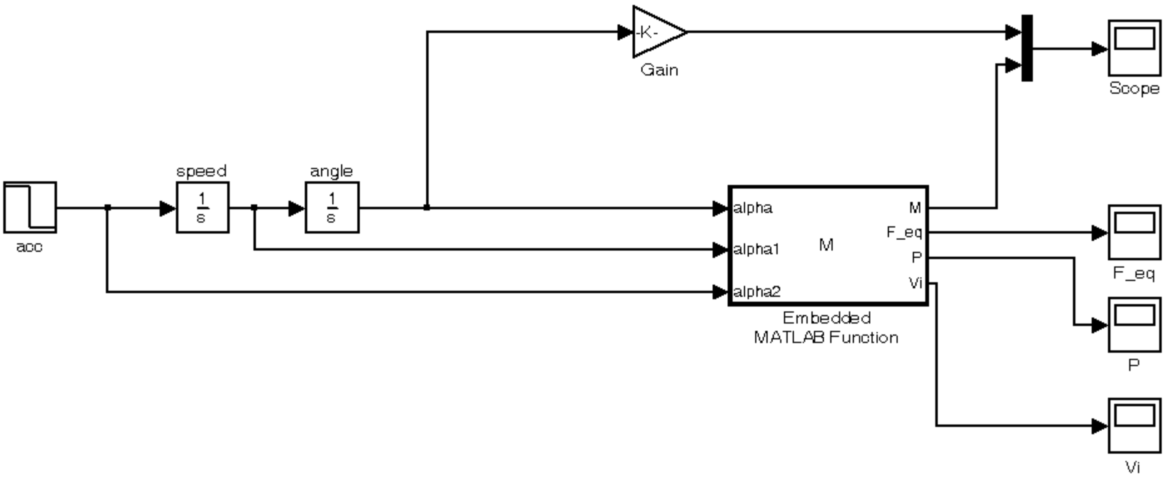

Figure 12 Imposed speed simulation scheme

A second scheme has been indeed implemented with a speed loop. In this scheme is necessary to set a speed value and the system reach the imposed value and maintain it.

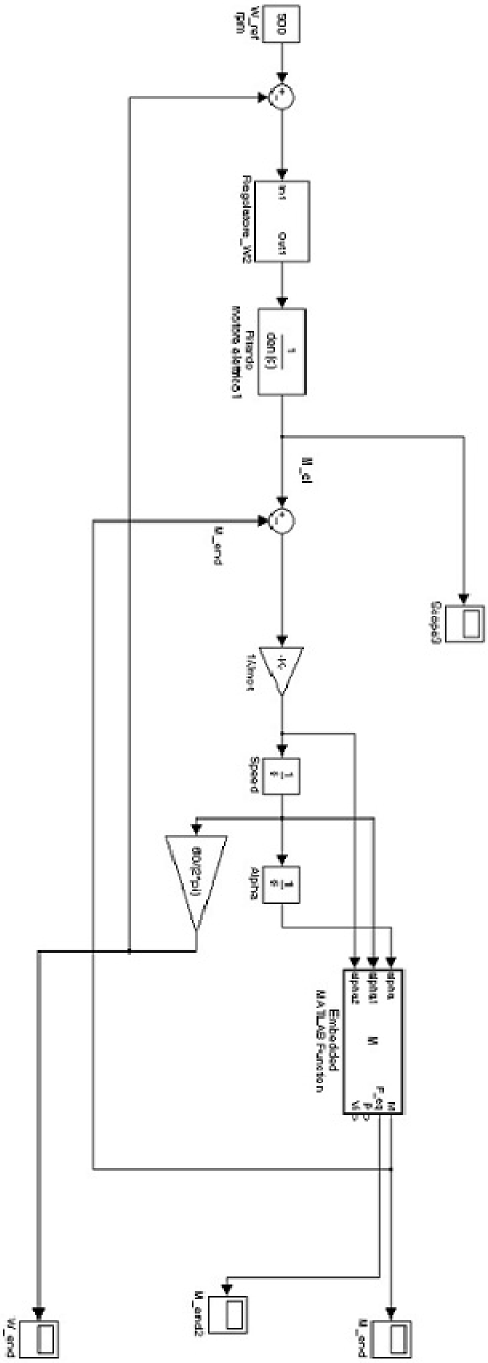

Figure 13 Speed loop scheme

The 2 models were implemented using two different sets of engine specifications. One of the two sets come from a real scooter's engine produced by an Italian manufacturer. Not all needed data was found on technical sheet so missing information was deduced. The second set of specifications was instead supposed to accentuate some aspect of the model, so it does not represent a real system.

To highlight the only effects created by inertial forces, it was also performed a simulation without considering the force generated by compressed gases (which are instead shown in Figure 14). This simulation has allowed to discover that inertial effects in common ICE are unimportant if compared with the other effects depending from other sources.

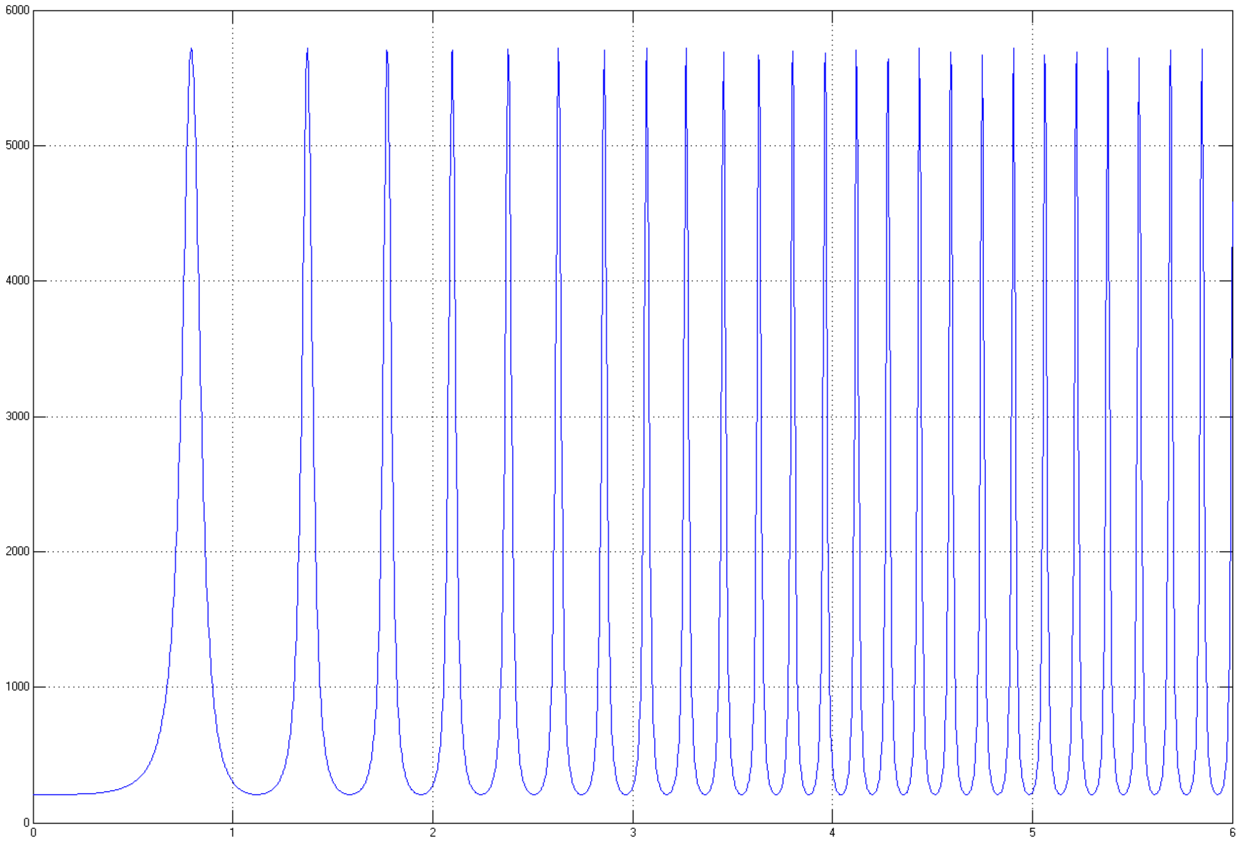

Figure 14 Force applied over the piston

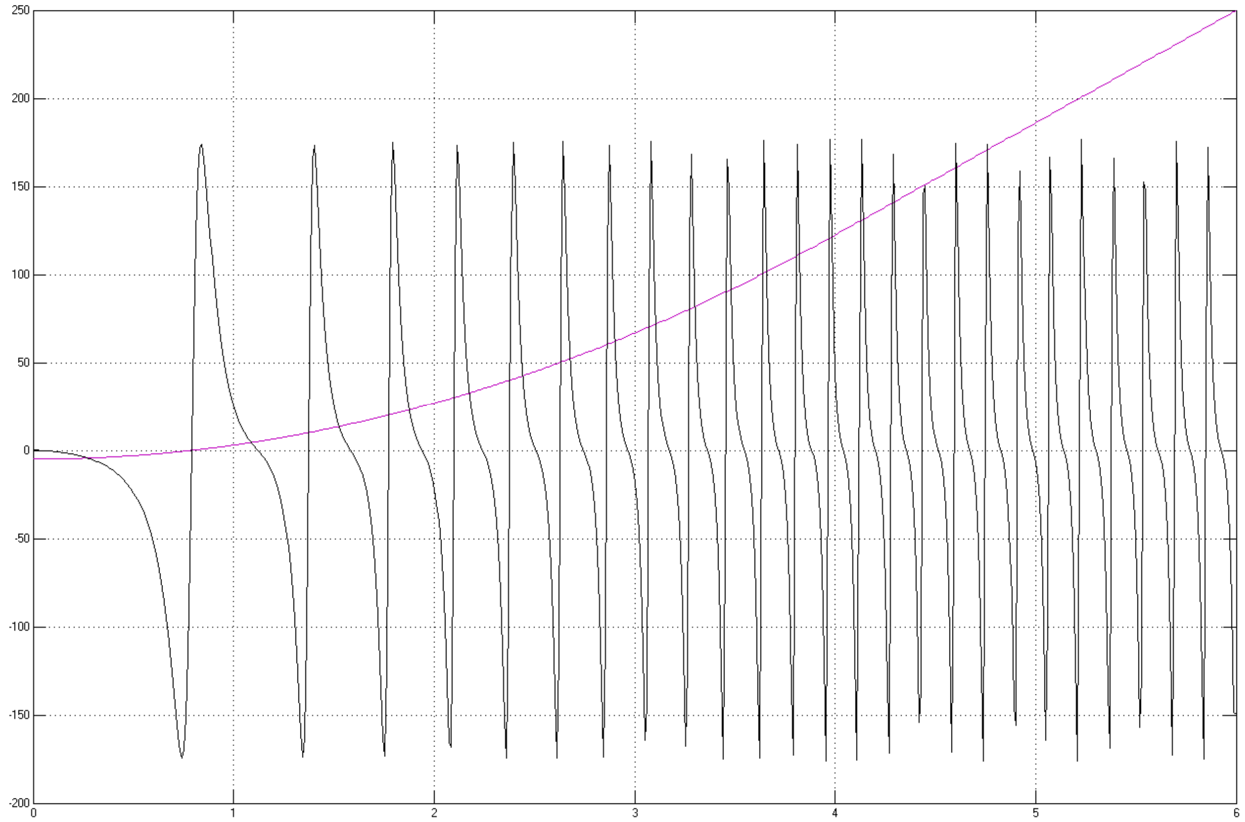

Figure 15 Total torque required to maintain imposed speed

Simulation of real motor shows that pressure caused by gas compression reaches beyond 30 atm and therefore it causes torques of the order of 170 Nm (Figure 15). Pure inertial forces instead cause torques of the order of 3 Nm as shown in Figure 16.

A 4 seconds acceleration was applied to the system so until 4 seconds the engine increases it speed and after removing acceleration stresses become regular. All this tests were run on imposed speed scheme. Due to the step acceleration, the speed increases linearly while the angle in parabolic trend.

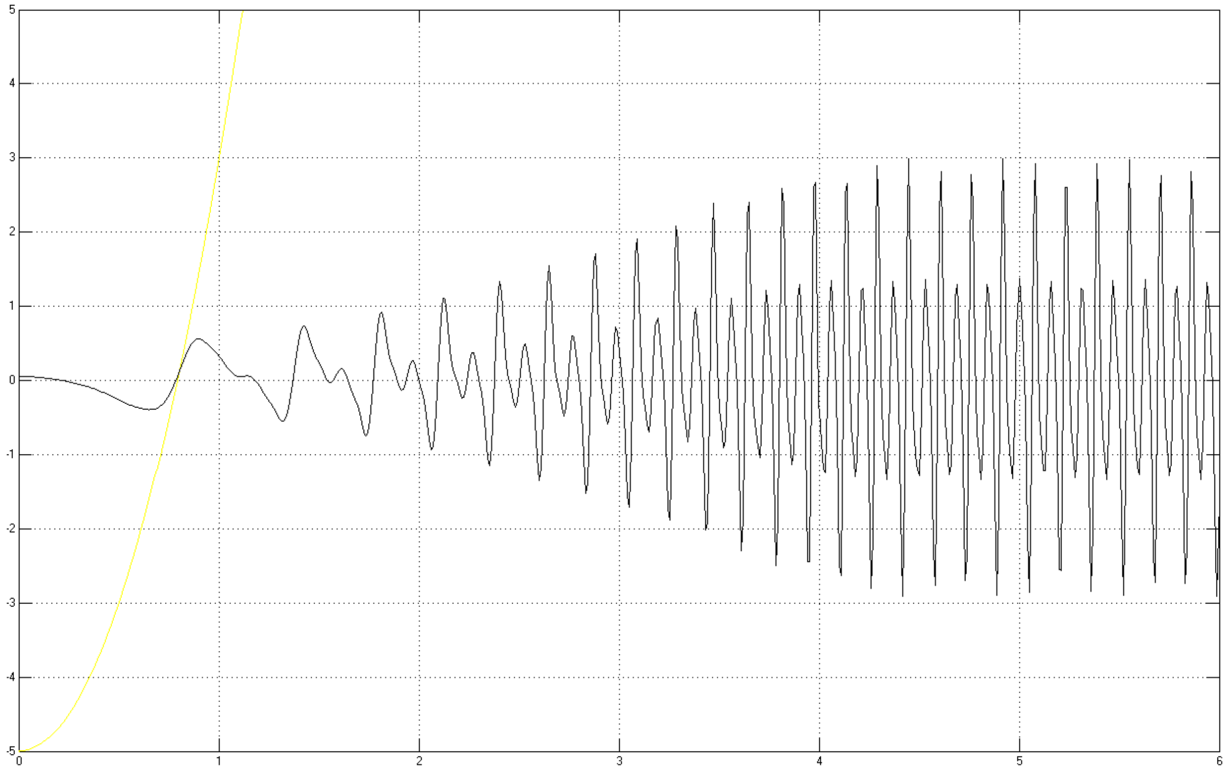

Figure 16 Pure inertial forces effects (imposed speed scheme)

The second simulation (speed loop scheme) does not force a determined acceleration value. Otherwise, as shown in Figure 17 the system reaches rapidly the target speed (set at 500 rpm) and follow it (although the presence of some ripple). These performances are permitted by excellent characteristics of electric motor that, during the simulation, allows torque of several Nm (Figure 18). Despite high torques, we must consider that they are peak torques and therefore the motor should not provides them during normal operation and for a long time, hence we can design the electric machine in a less onerous way.

To conclude, the model in point is fully customable and can be integrated with new solutions in order to reach more accurate and realistic conditions.

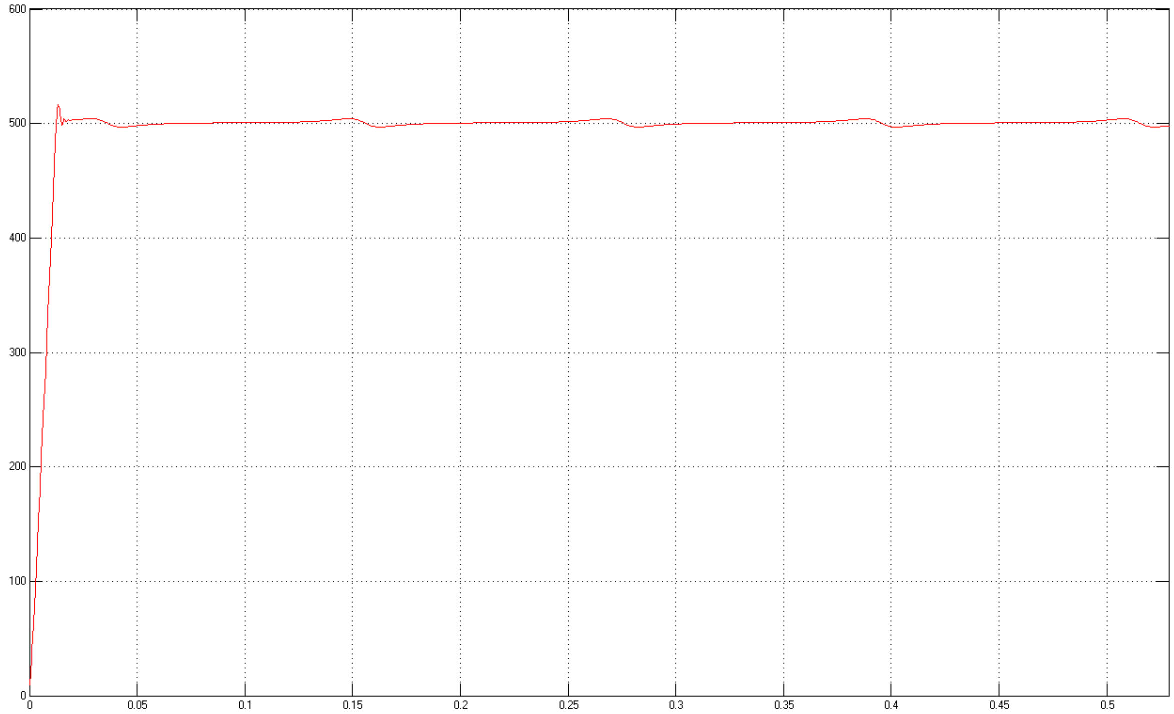

Figure 17 Speed characteristic of closed loop scheme

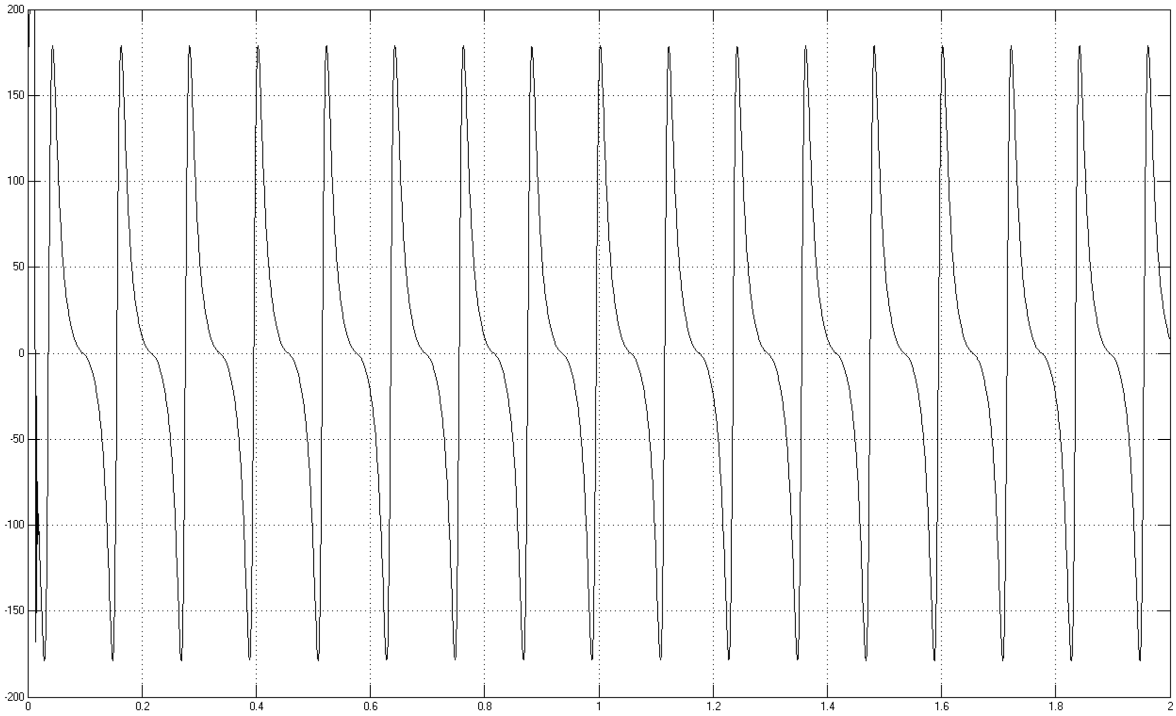

Figure 18 Motor torque (note starting torque)

Appendix A

MATLAB code

```
function [M,F_eq, P,Vi] = M(alpha, alpha1, alpha2)

%MOTORE APRILIA
%lunghezza manovella in m
r=35e-3;
%lunghezza biella in m
c=80e-3;
%distanza baricentro biella da boccola biella/manovella
a=30e-3;
%distanza baricentro biella da boccola pistone/biella
b=c-a;
%alesaggio in m
A=86e-3;
%momento inerzia manovella
I_m=0.005;
%momento inerzia biella
I_b=0.002;
%massa biella in Kg
m_b=200e-3;
%massa manovella in Kg
m_c=300e-3;
%massa pistone in Kg
m_p=1000e-3;
%Distanza albero testa
X_max=122e-3;
%Inclinazione motore
theta=pi/2;
%Volume massimo al PMI
V_max=(X_max +r -c)*(A/2)^2*pi
%Pressione atmosferica in Pa
p_atm=101325;
%Gamma
gamma=1.4;
%Peso biella perpendicolare
Pb_orto=m_b*9.81*cos(theta);
%Peso biella parallelo
```

```
Pb_parallel=m_b*9.81*sin(theta);

% %MOTORE INVENTATO
% %lunghezza manovella in m
% r=100e-3;
% %lunghezza biella in m
% c=250e-3;
% %distanza baricentro biella da boccola biella/manovella
% a=100e-3;
% %distanza baricentro biella da boccola pistone/biella
% b=c-a;
% %alesaggio in m
% A=50e-3;
% %momento inerzia manovella
% I_m=0.005;
% %momento inerzia biella
% I_b=0.002;
% %massa biella in Kg
% m_b=200e-3;
% %massa manovella in Kg
% m_c=300e-3;
% %massa pistone in Kg
% m_p=1000e-3;
% %Distanza albero testa
% X_max=370e-3;
% %Inclinazione motore
% theta=pi/2;
% %Volume massimo al PMI
% V_max=(X_max +r -c)*(A/2)^2*pi
% %Pressione atmosferica in Pa
% p_atm=101325;
% %Gamma
% gamma=1.4;
% %Peso biella perpendicolare
% Pb_orto=m_b*9.81*cos(theta);
% %Peso biella parallelo
% Pb_parallel=m_b*9.81*sin(theta);



%pistone
xc=r*cos(alpha)+c*sqrt(1-(r^2/c^2)*sin(alpha)^2);

xc1=-alpha1*(r*sin(alpha)+r^2*sin(alpha)*cos(alpha)/sqrt(c^2-r^2*sin(alpha)^2));

xc2=alpha1^2*(-r*cos(alpha)-r^2*(2*c^2*cos(alpha)^2+r^2*sin(alpha)^4-
c^2)/sqrt(c^2-r^2*sin(alpha))^3)+alpha2*xc1/alpha1;

%baricentro biella
xg=r*cos(alpha)+a*sqrt(1-(r*sin(alpha)/c)^2);

xg1=-alpha1*(r*sin(alpha)+a*(r/c)^2*cos(alpha)*sin(alpha)/sqrt(1-
(r*sin(alpha)/c)^2));
```

```
xg2=-alpha1^2*(r*cos(alpha)+a*r^2*(2*c^2*cos(alpha)^2+r^2*sin(alpha)^4-
c^2)/(c*sqrt(c^2-r^2*sin(alpha)^2)^3))+alpha2*xg1/alpha1;

yg=b*sin(alpha)*r/c;

yg1=b*r*cos(alpha)*alpha1/c;

yg2=b*r*(alpha2*cos(alpha)-alpha1^2*sin(alpha))/c;

sigmag=-asin(r*sin(alpha)/c);

sigmag1=-r*cos(alpha)*alpha1/(c*sqrt(1-(r*sin(alpha)/c)^2));

sigmag2=alpha1^2*((r*sin(alpha)*sqrt(1-(r*sin(alpha)/c)^2)-
(r^2*sin(alpha)*cos(alpha)^2)/(c*sqrt(c^2-r^2*sin(alpha)^2))))/(c*(1-
(r*sin(alpha)/c)^2)))+alpha2*sigmag1/alpha1;

%Forza agente sul pistone
Vi=((X_max-r*cos(alpha)-c*sqrt(1-(r*sin(alpha)/c)^2))*pi*(A/2)^2);
P=((V_max/((X_max-r*cos(alpha)-c*sqrt(1-
(r*sin(alpha)/c)^2))*pi*(A/2)^2))^gamma)*p_atm;
F_eq=m_p*9.81*cos(theta-pi/2)+P*pi*(A/2)^2;

%Rapporti di velocità
tau_xg=xg1/alpha1;

tau_yg=yg1/alpha1;

tau_sigmag=sigmag1/alpha1;

tau_xc=xc1/alpha1;

%derivate rapporti di velocità
tau_xg1 = (xg2 - tau_xg*alpha2)/alpha1^2;

tau_yg1 = (yg2 - tau_yg*alpha2)/alpha1^2;

tau_sigmag1 = (sigmag2 - tau_sigmag*alpha2)/alpha1^2;

tau_xc1 = (xc2 - tau_xc*alpha2)/alpha1^2;

% 0,5 x dI*/d(alpha)
dI=m_p*tau_xc*tau_xc1+Pb_orto*tau_yg*tau_yg1/9.81+Pb_parallel*tau_xg*tau_xg1/9.8
1+I_b*tau_sigmag*tau_sigmag1;

%Equazione del moto
M=alpha2*(I_m+m_b*tau_xg^2+m_b*tau_yg^2+I_b*tau_sigmag^2+m_p*tau_xc^2) + al-
pha1^2*dI - F_eq*tau_xc - Pb_orto*tau_yg - Pb_parallel*tau_xg;

end
```

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Sitography

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