ISABE-2009-1166

Towards the Powerhouse for More Electric Aircraft – Dedicated Engine Concepts

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Abstract

Investigations on the requirements for future More Electric Engine concepts are presented in this paper. These refer to both overall system studies as well as candidate subsystems. Investigations in system architectures refer to aircraft power supply, and the interaction with engine power generation, further the impact on engine performance. Referral to proper power generation and power management is made, leading to HP- and LP- power extraction. Investigations in LP-generators are presented and, further, additional more electric engine accessories. One of these is the Electromechanical Fuel System, offering the most benefits for the engine.

Nomenclature

AC	alternating current
AGB	accessory gearbox
APU	auxiliary power unit
DC	direct current
ECS	environmental control system
ECU	engine control unit
FCOC	fuel cooled oil cooler
FMU	fuel metering unit
FSP	first stage pump
GPU	ground power unit
HP	high pressure (spool)
HPT	high pressure turbine
LP	low pressure (spool)
LPT	low pressure turbine
MEA	more electric aircraft
MEE	more electric engine
PMU	power management unit
RAT	ram air turbine
SFC	specific fuel consumption
SSP	second stage pump
TEC	turbine exit case
VGV	variable guide vane

Introduction

During the past years, aircraft on-board systems have seen a steady rise with respect to power requirements. The increasing demand is driven by additional and enhanced avionics systems, the increased use of electromechanical and/or electro-hydrostatical actuation [1], plus the higher passenger comfort, such as in-flight entertainment systems, for example. In the past, power demand increments could be compensated through more powerful generators and thus increased power off-take from the engine accessory gearbox. However, power off-take has reached a level that, if further increased, will significantly affect engine overall performance, and, additionally will take negative influence on engine operability.

State-of-the-art turbofan engine configurations serve all required mechanical power from the high pressure spool, providing electrical power through one or more generators and mechanical power for the hydraulic and the fuel system. Additionally, customer bleed ports provide pressurized air mainly for the anti-ice- and environmental control system (ECS). In the past, mechanical power could be taken from the high pressure spool exclusively. With the continuous ramp up in power demand, however, this leads to engine performance issues, mainly given through the HPC stability. This causes problems mainly with engine acceleration requirements, and forces the raise of flight idle speed in order to cope with the lack of HPC surge margin.

This problem can be overcome by including the LP-spool with the power generation strategy. Performance studies show that a power off-take, split between HP- and LP-spool, generates notable fuel burn benefits, when compared to the standard configuration [2]. This effect results from the possibility to lower the engine idle speed, being a consequence of a lower HPC working line. Further, extracting power from the LP-spool improves the yield due to the higher LPT efficiency (in comparison to the HPT). In order to properly distribute the power required by the airframe among these HP- and LP-spool mounted generators, an interface unit between airframe (consumer) and engine (provider) has been investigated, optimizing the load for the respective generators for overall engine performance, i.e. depending on the actual operating conditions.

Besides the increasing utilization of electrified general systems on the airframe side, electrically driven accessories can be beneficial for future engines as well. First, these can be placed in optimized positions within the nacelle in contrast to gearbox-mounted ones, second they can be optimized in capacity due to the additional degree of freedom gained through the electrical motor speed. MTU has investigated in a number of accessories possibly showing benefits for the engine.

On-Board Power-Supply Systems

Currently, aircraft feature different kinds of power for on-board system operation. Pneumatic power taken from engine customer bleed air feeds the ECS and the wing and nacelle de-icing system. Hydraulic power is required for use in the airframe actuation system, as well as for the landing gear and wheel brakes, for example. Further, electrical power is generated for all aircraft avionics and cabin consumers. Hydraulic and electrical power generation systems are located at the engine accessory gearbox (AGB), together with fuel and oil pumps. On a two-spool turbofan engine, the AGB usually is driven by the HP-spool.

Using different media for energy transport requires a complex wiring and piping system. With the Boeing B-787 "Dreamliner", a first step is made in the direction of a more electric aircraft (MEA), using electrical power for the ECS and de-icing, as well as for engine starting. By this, the concept of bleed-less engines is enabled, offering benefits for overall engine efficiency.

Current power-supply systems in civil aircraft usually feature a voltage of 115V AC. The frequency can vary between 300Hz and 800Hz, depending on the actual application. Thus, the power is provided in a certain frequency band, and the actual frequency may change depending on engine rating and operating condition. The 115V system is powered from the engine mounted generators during normal aircraft in-service operation, in state-of-the-art systems one generator per engine (see Fig. 1). While the aircraft is on ground without the auxiliary power unit (APU) or engines running, the system can be fed by an external power supply, a ground power unit (GPU).

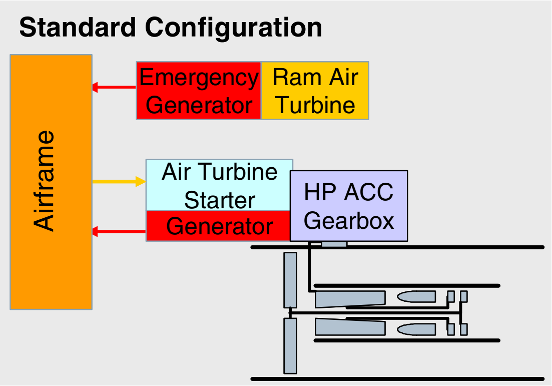

Fig 1: Standard Power Off-Take Configuration

Wherever it may be required by the particular system, the power is converted locally to the special needs. This may apply to different voltages and frequencies, including a conversion to DC. The relatively low voltage of 115V will in the future lead to higher currents, necessary to fulfill the power requirements, since the electrical power is given as the product of voltage and electrical current. Further, an increase of the current requires wiring with rather large cross-sections for safe operation. This finally has a negative effect on the resulting wiring weight as well as the cost.

In contrast to the power supply, common avionics systems use DC power, requiring local conversion to the particularly desirable power format. As a consequence, each subsystem features its own power conversion device, increasing the avionics system gross weight.

In addition to the 115V AC system, civil aircraft use a 28V DC system, mainly for startup and emergency purposes. This power supply serves the basic aircraft systems. It is used to e.g. start up the APU and to operate crucial avionics systems both before the engine startup and in case of emergency after engine failures. In case of emergency, the 28V net is powered either from on-board batteries or from an emergency generator, a ram air turbine (RAT). This device is activated after failure of all main engines due to fuel shortage or other events, and keeps alive the essential aircraft systems. While smaller and business aircraft use batteries, for larger commercial aircraft the RAT is common.

On-Board Power-Generation and Power Management Systems

With the increased demand for electrical power, the use of distributed generators, extracting not only from the HP-spool, but also from the LP-spool is becoming more and more attractive, and drives operability and SFC benefits. Otherwise the airframe power requirements could not be fulfilled using state-of-the-art generator technology. With the possibility of providing power off-take from the LP-spool additionally, the operating line of the HPC can be lowered, and this way the surge margin can be increased for critical operating points. This is important for part load operation range, where the compressors tend to develop surge margin deficits and require the use of handling bleed valves. Further, increased surge margin allows lowering the idle speed and thus the fuel burn during the approach segment, with significant impact on the mission fuel burn, especially during short- and mid-range missions. Additionally, MTU studies show that, with a power off-take split, more power can be extracted from the engine with the same performance and operability properties. This is given through the generally better efficiency of the LPT, compared to the HPT. This applies in particular to the surge margin requirements. Fig. 2 shows a power generation system, using HP- and LP-spool generators.

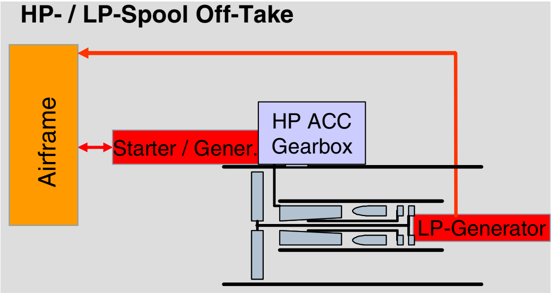

Fig 2: HP / LP Power Off-Take Configuration

The use of both HP- and LP-spool for electrical power generation requires tight integration of the power split management with the engine control as well as with the airframe power management. This is mandatory in order to provide optimized operating conditions with respect to engine performance on the one hand, and engine operability on the other hand. This task requires a dedicated system, providing not only performance optimization, but also safety governor functionality. This power management unit (PMU) is placed at the interface between the power consumption (airframe) and the power generation (engine generators) part of the on-board power supply system. It shall guarantee a proper load proportion between HP- and LP-spool in order to maintain optimum fuel burn conditions during cruise phases and approach. This may mean part of the load for both of the generators during cruise, since surge margin issues usually do not occur in that flight phase. In approach, the load may be shifted more towards the LP-spool, since operability is affected if too much power is taken off the HP-spool, and optimized performance would mean to lower the idle thrust of the engine as far as possible without violating the surge margin requirements. During engine high rating operation, lowering LP-spool power off-take can be beneficial in order to optimize engine thrust output. The provision of satisfactory functionality of the PMU demands extensive information exchange between the airframe system and the engine control unit (ECU). From the airframe, the request for power levels needs to be addressed to the PMU in order to judge the overall power demand required for the actual situation. The ECU shall provide actual engine operating data, helping the PMU to determine the desirable load proportions for the generators. Starting from this, the PMU shall calculate necessary the load distribution according to the actual situation. Depending on the architecture and complexity of the airframe power supply system, the PMU may be either just an additional controller with inherent intelligence, just governing the load distribution in form of control commands, or house both the controller functionality and, further, part of the necessary power electronics, i.e. voltage converters, capacitors, etc.

Since power off-take from the LP-spool is not state-of-the-art so far, relevant pre-requisites and requirements need to be identified in order to find a proper power supply system architecture. Requirements for LP-generators differ considerably from state-of-the-art HP-generators, since the operating range is wider. Because of the bigger speed band the LP-generator has to cover, applicable machine concepts are to be developed, allowing for sufficient power capabilities at all operating conditions, even at ground idle speed. Additionally, the absolute speed for a LP-spool mounted generator is lower than for an HP-generator. The speed ratio required for a LP-generator is around 1 to 5, compared to a ratio of 1:1.5 for a HP-generator. Due to these restrictions, LP-generators require more powerful electrical machines, in order to deliver enough power throughout the whole envelope, and at low idle speed in particular. This is mandatory in order to utilize the fuel burn benefit through lowering idle thrust.

The challenge for generator design is to develop an electrical machine, that can feed the same power supply system together with the HP-generator, although the speed band is much larger through the high speed ratio. This makes necessary the use of new technology, enabling machine designs with sufficiently high power density. MTU has investigated new machine concepts, including integration studies. The compact design is intended to integrate the complete generator, electrical machine and power electronics compartment in the turbine exit case (TEC) to drive it from the LPT. This LPT-generator can be operated by the LP-spool without additional tower shaft and gearbox. Since the machine sees an extremely harsh environment, the generator features its own lubrication and cooling system to deduct the dissipation energy from operation. In order to survive heat soak back conditions after engine shutdown and thus stop of the lubrication fluid circulation, the whole generator is insulated with a dedicated heat shield. In order to prevent the generator from fire after a short circuit in the windings, a special circuit layout keeps the short circuit currents low during this failure condition.

Besides the option to take off power efficiently from the LP-spool, optimizing the engine performance, the LPT-generator further gives the opportunity to generate electrical power during windmilling conditions. By this, the RAT could be replaced, generating further weight- and maintenance cost benefit.

More Electric Engine Architecture – Candidate Accessories

With establishing electrical power as main energy transmission medium, more electric architectures are promising for engines as well, since they show advantages for the engine in combination with the overall system aircraft. Provided the availability of electrical power plus the effort to eliminate other sources, like customer bleed air and hydraulic power, utilization of electrical engine accessories offers various benefits. Harness around the engine can be simplified dramatically, once there is no need any more for hydraulic and bleed air pipes. Especially costly maintenance for pipes and seals can be saved by this, plus the elimination of potentially dangerous flammable fluids from the engine outside and its vicinity. The use of electric components further more eases the generation of redundancies, in case there is the need, e.g. for safety purposes. The use of electric accessories as well allows for easy life and health monitoring, e.g. through sensing and monitoring of motor currents or actuator travel times. Accessories usually driven by the AGB, i.e. fuel system and oil system, can be optimized in size through the decoupling of pump speed and engine speed (originally given through the gearbox). So, an electrically driven fuel system can be designed with smaller dimensions, since the requirement for windmilling restart does not apply here. This has a very positive effect on the heat sink capacity. Similarly advantageous is the application of an electric oil system, additionally offering the option of circulating engine oil even after engine shutdown, in order to avoid or minimize oil coking due to heat soak back effects. In general, the interface between engine and airframe can be simplified significantly, if there is no need to connect hydraulic and pneumatic power, but only electrical power. As well, the additional degree of freedom by electrification allows to relocate accessories to places where they fit better in the engine installation envelope, or see less harsh environment in terms of e.g. temperature or vibrations. In the future, this may be important for military applications, where the engine is completely embedded in the fuselage, and needs to fit into a tight installation envelope. During MTU studies concerning MEE configurations, a variety of more electric accessories and components has been investigated.

An electromechanical variable guide vane (VGV) actuator has been developed to validate the dynamics and the mechanical feasibility on the one hand, and to judge the complexity of the control algorithms for driving the electrical machine on the other hand. Extensive simulations have been conducted in advance to design the control system and to set up the system architecture. Two actuators have been manufactured and rig tests were performed. First, tests were conducted with a single actuator to validate the dynamic behavior, and, second the two-actuator system was tested in order to validate the system behavior with the given master/slave architecture.

Preliminary studies of an electromechanical oil system have revealed similar benefits as with a more electric fuel system. Especially the optimized heat sink capacity allows for reduction of both the overall engine oil amount and the size of the respective oil cooler.

Active magnetic bearings allow for accurate support of spools without the need for lubrication and without friction and thus without excessive dissipation energy generation. However, aero-engine application would require rather large and heavy bearings, together with complex control systems [3]. Therefore, entry into service in the foreseeable future seems unlikely.

Besides the LPT Generator already introduced in the previous section, MTU has conducted preliminary investigations concerning an internal HP-starter/generator, placed directly on the HP-spool in the region of the HPC. This concept would allow for completely eliminating the AGB in case other engine accessories already are driven electrically. However, a variety of technical issues is not properly addressed so far, one being the electrical concept of the machine and the power electronics, given the harsh environment in this engine region. Additionally, reliability requirements for this generator would be rather demanding, due to the high effort for maintenance actions.

Among the investigated accessories, the electrically driven fuel system has turned out to be the most promising candidate for a first engine application. Due to the large benefit expected with respect to the heat sink capacity, the electromechanical fuel system has been investigated in detail. The decoupling of the fuel flow rate from the engine speed is realized through the electrically driven fuel pumps. Several fuel system concepts have been validated including different second stage pump types. The investigations on the electromechanical (smart) fuel system are presented in the following section.

Electromechanical Fuel System

A standard fuel system (see Fig. 3) usually consists of two pumps sitting on a common spool that is driven by an AGB output. The first stage pump (FSP) is designed as a centrifugal pump, generating a sufficient pressure rise for the second stage pump (SSP), a gear pump. In order to prevent the FSP from cavitation, booster pumps provide proper pressure rise. The SSP essentially provides the fuel mass flow that is introduced to the main burner nozzles. Between the FSP and the SSP a filter is located, and often as well a fuel cooled oil cooler (FCOC) using the heat sink capacity of the fuel to cool down the engine oil. Downstream the SSP, part of the fuel mass flow is separated to feed the fuel-draulic drive of the VGV actuators. Due to the fact that the fuel system is gearbox-driven, the speed is directly connected to the HP-spool speed. Additionally, the output of the fuel system must be sufficient to restart the engine from windmilling speed. Through this, for most engine operating conditions the fuel flow rate is higher than the one required by the burners. In order to properly dose the fuel flow to the given operating point, a dedicated Fuel metering unit (FMU) is located between the SSP and the main burner nozzles. The excessive fuel is re-circulated and fed into the fuel system downstream the FSP. The circulation

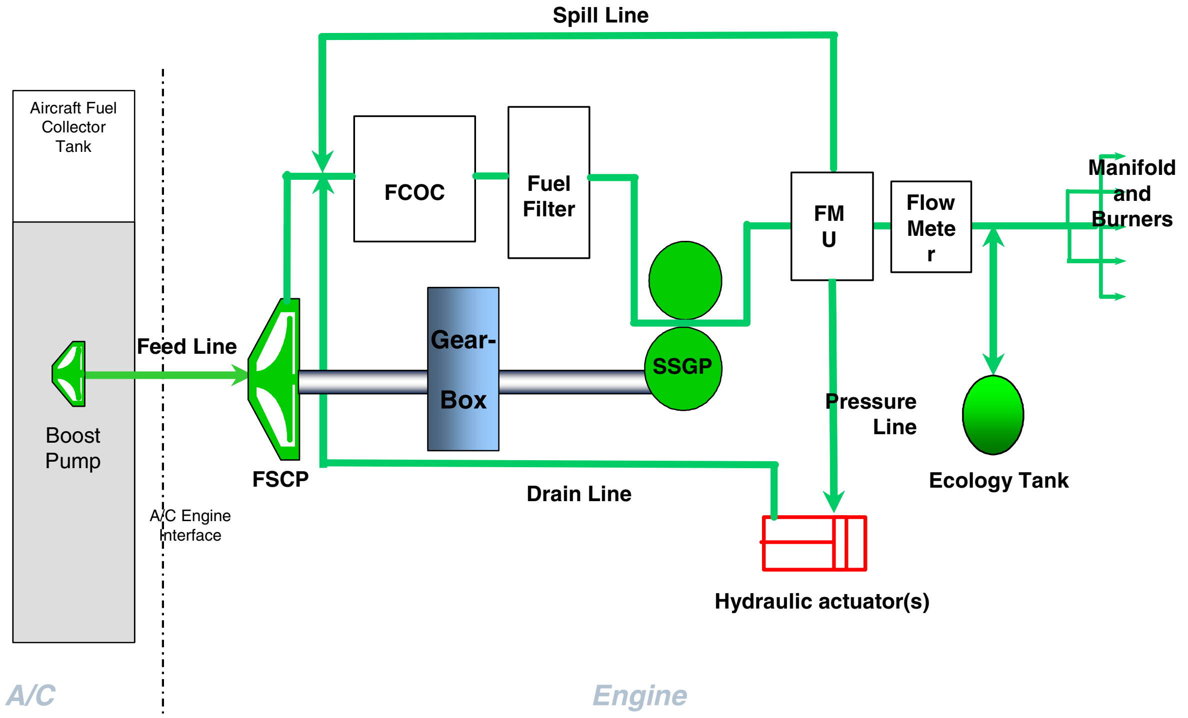

Fig. 3: Conventional Fuel System Schematic

lowers the heat sink capacity of the fuel, therefore requiring a rather large FCOC.

The utilization of an electromechanical fuel system opens the possibility to improve the safety for the engine by use of fault tolerant motor concepts with inherent redundancies. This can be achieved through parallel motor windings in different circuits, that enable to keep the fuel system alive in case of a partial motor failure. According to the number of parallel windings, the drop in maximum output can be minimized for the case of degraded operation. Such a behavior can be important for single engine applications in particular, such as future UAV concepts.

By replacing the AGB drive with an electrical motor, the fuel system delivery rate can be decoupled from the engine speed. This enables the design of the fuel system (see Fig. 4) to be optimized with respect to the capacity. The maximum flow rate can be adapted to the maximum take-off fuel flow instead of a minimum windmilling fuel flow, giving an excessive maximum capacity. So realization of additional heat sink capacity in order to reduce the capacity and therefore weight of the FCOC is made possible. Investigations have revealed, that in some cases there might be minor problems with the pressure ration necessary for operation of a standard fueldraulic VGV actuator. However, for most of the relevant operating points, the pressure drop over the actuator is sufficient. Depending of the concept for the SSP type, with the electromechanical fuel system, the replacement of the FMU, by fuel metering through the pump flow is possible, while a fuel shut-off valve still is needed for save operation of the fuel system in combination with ecological requirements.

MEE Configurations

Configurations for future more electric engine concepts may differ from case to case, depending on the respective application. For civil aircraft, configurations seem beneficial, that introduce electrical fuel and oil systems, while still using the AGB for driving HP-spool generators. This is driven by the fact that the need for full more electric concepts will be not immanent that soon. Therefore, only such systems will be electrified, that show significant advantages for the subsystem engine. As long as the operability can be maintained with HP-spool generators, no LP-spool generators will be introduced to the MEE concepts. Electrified VGV actuation may be employed where it is advantageous, i.e. where the effort for a dedicated fuel-draulic piping can not be justified.

In contrast to civil applications, for military engines, especially for highly integrated UAV and UCAV engines, one will see a more radical electrification of engine system architectures. Through the

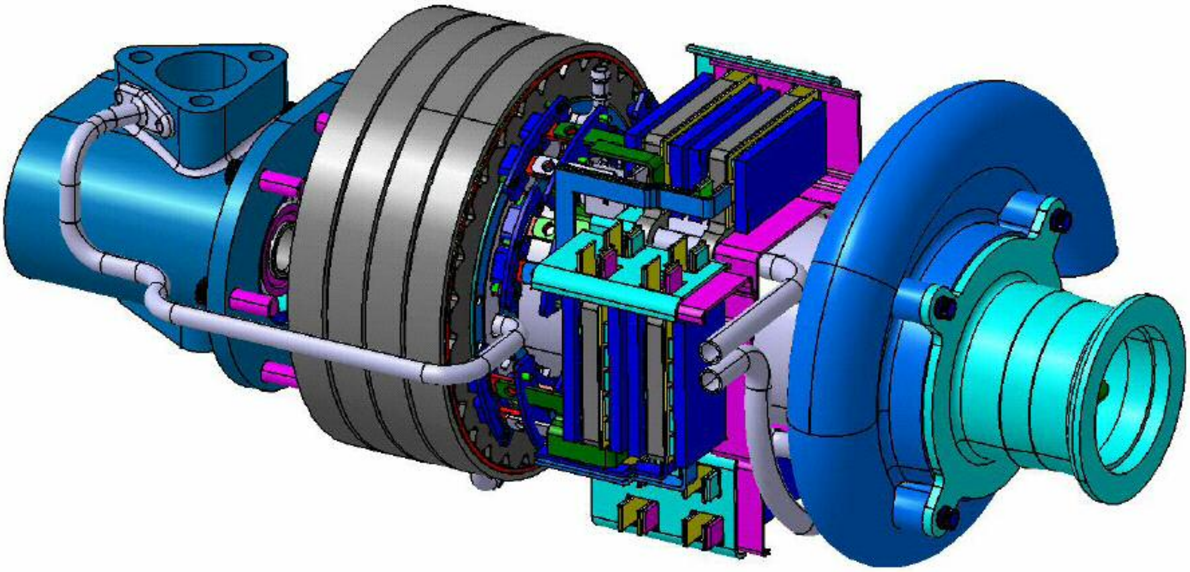

Fig. 4: Electromechanical Fuel System

tight installation envelope of an unmanned vehicle, electric components bear the potential of optimizing the accessories round the engine cross-section, in order to use free installation space where available, and to place accessories in less harsh environmental conditions. This may lead to engine architectures completely missing an AGB, using internal HPC mounted starter/generators, and thus fully electrical accessories. Due to the increased power demand through avionics, etc., military engines will utilize LP-spool generators in order to positively influence engine performance even with high electrical power off-take levels. Additionally, the requirement for long term storage periods with short re-activation times will need minimizing amount of different fluids on the engine and will ask for electrical components.

Conclusions

The demand for electrical power will dramatically increase with future aircraft configurations, due to the changing system and subsystem architectures. As a consequence, proper aircraft power plants will have to cope with changed pre-requisites, bearing the potential to negatively affect engine propulsion performance. Therefore, a re-distribution of power generation will be required, resulting in the utilization of both HP-spool and LP-spool for driving electrical generators on the one hand, and an extensive use of electrical power for engine accessory operation, instead of a rather even split between hydraulic/fueldraulic, pneumatic and electric power, as applied in state-of-the-art systems. MTU has investigated in both HP- and LP-spool generator concepts, and revealed fuel burn and operability benefits, and furthermore identified the major design boundaries that are relevant for future applications. Candidate accessories for more electric engine architectures have been examined. It has turned out that only few systems directly add benefits to the engine by their inherent properties, while some only improve engine performance or life cycle cost through their interaction with other engine or aircraft systems. Some accessories, like the electric VGV actuator are only attractive through the potential to eliminate complex piping. Most interesting candidate for a near-term engine application is the electric fuel system, that first allows to increase the fuel heat sink capacity, and second can improve engine controls reliability by elimination of the FMU.

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