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PHYSICS-BASED THERMAL MODEL FOR POWER GEARBOXES IN GEARED TURBOFAN ENGINES

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ABSTRACT

Ultra-High Bypass Ratio Geared (UHBRG) turbofan technology allows a significant reduction in fuel burn, noise and emissions – key metrics for aircraft engine performance. However, one of the main challenges in this technology is the large amount of waste heat generated by the Power Gearbox (PGB). Therefore, having a practical tool for precise prediction of the PGB-generated thermal loads in UHBRGs is becoming a necessity. Such a tool would assist in analyzing engine performance, as well as ensuring that engine physical limitations/restrictions are not breached (e.g. over-temperature in fuel and oil, cocking, etc.). This paper presents a methodological approach to mathematically model the waste heat generated by a PGB on a UHBRG for different points on a typical flight profile. To do this, the total power loss in a PGB system is firstly defined as the summation of load-dependent and load-independent losses. Physics-based equations for each heat loss mechanism are introduced and, through a combination of the associated equations, a simulation model for the thermal loads calculation in PGBs is developed. In addition, the heat losses and efficiency of the PGB has been analyzed across a simulated flight. The developed PGB model calculates the main power losses generated in a gear reduction system of a turbofan engine. It was found that in a typical flight, the heat loss generated by the PGB can reach about 80% of the total waste heat generated by the engine. The values of the mechanical efficiency calculated by the tool at different flight points are above 97% which is in good agreement with publicly available data for planetary gearboxes. This tool is intended to be utilized by engine thermal management system designers to predict and analyze the heat loads generated by the PGB at different flight conditions.

INTRODUCTION

With the demand for air transport evolving at an ever-increasing rate, along with high jet fuel prices and stricter regulations regarding emissions, there is a need for the development of new technologies and solutions to improve aircraft performance. From turbojets, aircraft gas turbine engines evolved towards turbofans, followed by Ultra-High Bypass Ratio Geared (UHBRG) turbofan engines. As the fan diameter increases in this technology, the air mass flow increases as well and therefore, the engine produces more work [1]. This technology can be improved with the implementation of a gearbox system between the fan and the intermediate pressure compressor (IPC), decoupling their rotational speeds. This allows the fan to run at a lower rotational speed and to decrease the number of compressor and turbine blades and stages, reducing the fuel consumption and noise emissions. Finally, by decreasing the rotational speed of the fan, the blades tip speed decreases, which in turn reduces the appearance of shock [2]. This effect allows the fan blade diameter and therefore the bypass ratio, to increase even more. However, there is a limit for the extent to which the fan diameter can be increased. As the diameter increases, the size and therefore the mass of the gearbox needs to be increased as well in order to withstand the higher loads and vibrations generated by the rotation of the fan. The nacelle diameter is a key parameter in the design of an aircraft, and is limited by the required ground clearance [3-4]. It is therefore desired to have the gearbox, which is located in the nacelle, to be as small as possible. Finally, because the loads on the gearbox increase when the Bypass Ratio (BPR) increases, while the size of the gearbox is limited, the heat rejected by this gearbox and other components such as the bearings, increase as well. The maximum allowable heat rejected can be defined as the maximum heat that a defined system can withstand without compromising its performance or structural integrity. Furthermore, with the increase in thrust and power generation on new engines, there is a natural increase in temperature of certain components and fluids [5]. This can be combined with the requirement of higher temperatures in other sections of the gas turbine requires to limit losses and increase efficiency [6]. Therefore, thermal management becomes a center of interest of paramount importance for aircraft manufacturers, aiming to minimize losses. Since the gearbox is designed to be as small as possible in order to fit into the nacelle, while big enough to withstand the high loads and vibrations induced by a larger fan, the heat rejected by these components becomes a critical aspect for the performance analysis of an aircraft [7].

Power loss in PGBs is associated primarily with tooth friction and lubrication churning losses. The frictional losses are related to the gear design. These losses are difficult to calculate.

Therefore, either correlations based on experiments or mechanical efficiency formula (equation 1) are often used in the literature.

$$\eta = \frac{output\ shaft\ power}{input\ shaft\ power} \quad (1)$$

The aim of this paper is to develop a physic-based tool to calculate the heat rejected by the power gearbox in UHBRG turbofan technology, the main source of heat generation, for a complete mission profile. This tool enables the engine system designers to analyze and optimize the design procedure of PGBs. These results can be used in future work to optimize the design procedure of new and next generation of geared turbofan engines. The heat rejected by the gearbox is not constant throughout the flight. Indeed, inputs in the power loss model include parameters such as the shaft rotational speed and the transmitted power. It is therefore necessary to assess the overall performance of an aircraft throughout a specific flight cycle. For this purpose, two 2-spool geared turbofan engines are modelled as case studies by using a tool called TURBOMATCH (TM), an in-house gas turbine simulation tool developed at Cranfield University. The aircraft performance is modelled by using HERMES, another in-house simulation tool, in which the mission profile was introduced using a model based on the Airbus A320 and A350 aircraft. By utilizing the power loss calculation methods, a power loss model to calculate the heat generated by the gearbox on a UHBRG turbofan engine is developed and simulated in different flight points to confirm the effectiveness of the proposed approach in thermal management system design and development of next generation of civil aero-engines. The results of the two case studies are also compared together to discuss the capabilities and limitations of the developed tool as well as to explore the current challenges and future work.

HEAT LOSS MECHANISMS IN POWER GEARBOXES

The PGB is a planetary reduction gearbox between the fan and the Low Pressure (LP) shaft allows the latter to run at a higher rotational speed thus enabling fewer stages to be used in both the LP turbine and the LP compressor, increasing efficiency and reducing weight. However, some energy will be lost as heat in the bearings, gears, and seals of the PGB. The total power loss in a PGB system could be divided into load-dependent and load-independent (non-load dependent) losses. The load-dependent loss is the sum of the bearing friction loss and the gear mesh loss. These losses are linked to the mechanical losses generated by the friction at the contact surfaces between the teeth of mating gears. The load-independent loss is the sum of the bearing churning loss, gear windage loss, and oil seal loss. The latter is usually being neglected as its contribution is very small in comparison with those of other mechanisms of heat generation. These losses are all linked to fluid-dynamic effects, bearing viscous losses, and fluid compressed and trapped between meshing gear teeth. The physic-based equations for calculation of thermal load in each mechanism will be presented in this section.

Non-load dependent losses

The load-independent losses could be calculated by adding the gear windage loss to the bearing churning loss as shown in equation (2).

$$P_{non-load\ dependent} = \Sigma P_{gear\ windage} + \Sigma P_{bearing\ churning} \quad (2)$$

In order to estimate the gear windage loss, the Dudley model is suggested as a suitable formula for small diameter gears, say up to approximately 20 inches in diameter with an L/D ratio of approximately 0.5 [8].

$$P_w = \frac{n^3 t^5 L^{0.7}}{1.683 \times 10^{-8}} \quad (3)$$

Where
P_w – Power loss due to windage (kW)
n – Rotational speed (rpm)
D – Diameter of rotating element (m) – can be approximated as pitch diameter of the gear
t – Disk thickness (m)

It should be mentioned that other methods for calculating the windage loss have also been proposed in [9-13] and applied for several case studies. However, the Dudley method is more accurate than others and more acceptable by the researchers in the field of thermal management.
The bearing oil churning losses depend on bearing speed, oil supply conditions, oil kinematic viscosity and size. The expression for the planet spherical roller bearings is [14-15]:

$$P_{BO} = \frac{2\pi M_0 n_B}{60000} N_{CP} \quad (4)$$

Where:
M_0 - No-load torque of planet bearing [Nm]
n_B - Planet bearing rotational speed about its axis [rpm]

Note that the planet bearing rotational speed is equal to the planet rotational speed (n_B=n_P). Moreover, the procedure of calculation of the no-load torque is described in detail in [15]. Equation 4 also confirms that the bearing oil churning loss could be calculated for one planet and then it should be multiplied by the number of planets to return the total bearing churning loss in the PGB.

Load dependent losses

The load-dependent losses could be calculated by adding the gear mesh loss to the bearing friction loss as shown in equation (5).

$$P_{load\ dependent} = \Sigma P_{bearing\ friction} + \Sigma P_{gear\ mesh} \quad (5)$$

The following approach could be used to the bearing-loss problem which consists on calculating the torque loss in the bearing and then estimating the power loss as follows [8]:

$$P_{BL} = \frac{2\pi T_{BL} n_B}{60000} N_{CP} \quad (6)$$

Where:
TBL - Torque loss per bearing [Nm]
The torque loss TBL can be found simply by the use of a constant coefficient of friction for each type of bearing, f.

$$T_{BL} = f \frac{d_I}{2} P \quad (7)$$

Where:
dI - Planet bearing bore diameter [m]

Finally, the mesh loss in the gears could be calculated by utilizing the following formula [16]:

$$P_{ML} = (P_{MLE} + P_{MLI}) N_{CP} \quad (8)$$

Where:
PMLE - Friction power loss at sun/planet (external) mesh [kW]
PMLI - Friction power loss at planet/ring (internal) mesh [kW]

Both loss components are calculated with similar expressions with only small differences in the formulation as follow.

➢Sun/planet mesh losses
The losses in the external mesh are evaluated using the expression below:

$$P_{MLE} = \frac{2\pi f_e n_s Cos^2 \beta_e}{60000 M_e} \quad (9)$$

Where:
fe - External mesh coefficient of friction [-]
βe - Sun/planet helix angle [degree]
Me - External mesh mechanical advantage [-]

➢Planet/ring mesh loss
In the internal mesh the expressions to be used are:

$$P_{MLI} = \frac{2\pi f_i T_P n_P Cos^2 \beta_i}{60000 M_i} \quad (10)$$

Where:
fi - Internal mesh coefficient of friction [-]
TP - Planet gear torque [Nm]
βi - Planet/ring operating helix angle [degree]
Mi - Internal mesh mechanical advantage [-]

The tables for selecting the coefficients values for different types of bearings and gears could be found [17-19].

Finally, by adding the equations 3, 4, 6, and 8, the total heat load generated by the power gearbox could be estimated.

SIMULATION RESULTS

By applying the above-mentioned equations on each element (sun, planet, ring) and adding all values together, the total heat load generated by the PGB could be calculated at each flight point. The equations with all associated coefficients and tables are implemented in MATLAB/Simulink environment and a toolbox is developed to analyze the thermal behavior of the PGBs in UHBRG turbofan engines. This toolbox gets the engine rotational speed and LP power as the input and gives the PGB heat loss and the PGB mechanical efficiency at any flight condition as the outputs. Moreover, the oil temperature difference through the PGB could be calculated by having the oil flow rate. The geometry and components size of the PGB could also be set in the module. Therefore, the module could be used for design and optimization reasons as well. The snapshot of the generated module is shown in figure 1.

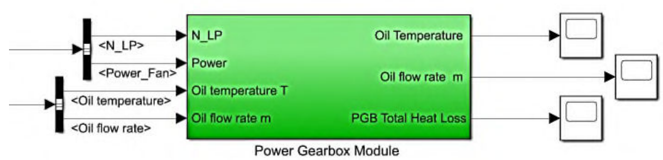

Figure 1 – PGB toolbox

In order to simulate the thermal behavior of the PGB in a pre-defined mission, the engine data will be provided to the module from TURBOMATCH (TM), an in-house gas turbine simulation tool developed at Cranfield University. TM is a 0-D simulation tool being used for many years in the Centre for propulsion engineering at Cranfield University in several industry-linked and academic projects. Its validity and effectiveness have been confirmed against experimental results. The aircraft performance is also modelled by using HERMES, another in-house simulation tool, in which the mission profile can be introduced to calculate the required thrust which is an input for the engine simulation tool (TM).

Therefore, the steps for simulation procedure could be described as follow:

1. Definition of a mission.

2. Based on the pre-defined mission, the aircraft simulation toolbox (HERMES) calculates the required thrust that should be provided by the engine.
3. The engine simulation toolbox (TM) gets the required thrust from the HERMES and calculates the engine performance parameters.
4. Based on a pre-set geometry, the PGB module will get the rotational speed and the shaft power from TM and calculates the heat load value generated by the PGB during the mission.

The schematic of the simulation process has been shown in figure 2.

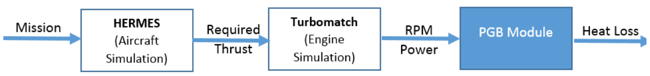

Figure 2 – Simulation Procedure

The above-mentioned procedure could be extended in the future by adding more toolbox like accessory gearbox, bearings, heat exchangers, etc. to generate the system level thermal management model for the engine and aircraft.

Case studies:

In order to confirm the effectiveness of the proposed approach in predicting the thermal behavior of the PGB, two different case studies will be considered in this paper for different engine sizes.

- The first case study would be the PW1100G engine, a high-bypass geared turbofan engine, currently selected as the exclusive engine for the Airbus A220, Mitsubishi SpaceJet, and Embraer's second-generation E-Jets, and as an option on the Irkut MC-21 and Airbus A320neo. The engine has the Bypass Ratio (BPR) of 12.5:1, and the thrust range 110–160 kN (112.5 has been selected as the design point (take-off) in this paper). The aircraft has been selected as A320neo for the HERMES simulation. The mission is defined as shown in table 1.
- The second case study is to replicate the Ultrafan engine PGB thermal behavior. The Rolls-Royce Ultrafan is one of the best possible candidates for the future air travel systems by reducing the noise and emission respect to the Advisory Council for Aeronautics Research in Europe (ACARE) Flighpath 2050 requirements. The BPR of 15:1 and thrust level of 360 kN has been selected for this case study. The aircraft has been selected as A350 for the HERMES simulation. The mission is also the same with the first case study for comparison purpose.

The results of simulations for both case studies are presented and analyzed in this section:

PW1100G PGB

The first case study focuses on the power gearbox being used by P&W in the PW1100G engine. It utilizes a star-style gear system in which the carries is fixed and the ring is the output. The values of the heat loads generated by the PGB in different flight points have been shown in figure 3. It can be seen that the PGB generated heat loads varies from 25 kW at the ground idle to 225 kW at the beginning of climb. These heat loads should be inserted to the oil to guarantee the safe and optimal operation of the PGB and the engine. Therefore, the results of the tool will be essential for design and optimization of thermal management system of the engine.

Table 1- Mission data

		Ground idle / taxi	Take off	Begin climb	Climb	End climb	Start of cruise	End of cruise	Begin descent	End descent	Approach	Ground idle / taxi
Flight phase index		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Altitude	m	0	0	457.2	6,096	10,000	10,000	11,100	11,278	457.2	457.2	0
Flight Mach number	-	0	0.222	0.388	0.589	0.78	0.78	0.792	0.78	0.388	0.233	0
Time	s	0	618	668.4	1973.4	2580	2580	20400	21600	24180	24600	25200

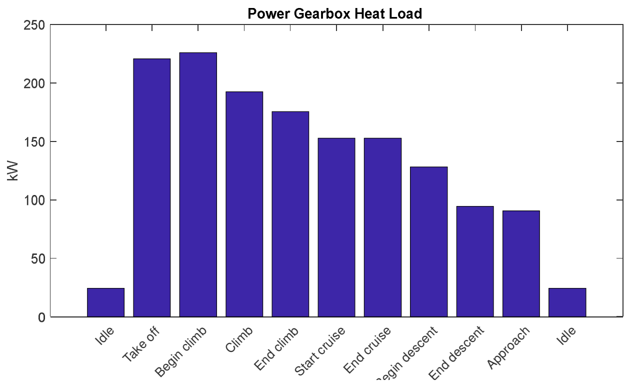

Figure 3 – Heat loads generated PGB – the first case study

Figure 4 shows the heat loads generated by different heat sources of the engine. This figure confirms that the PGB is the main source of excess heat at all flight points. For instance, at the take-off, bearings generate around 6 kW, accessory gearbox (AGB) generates 42 kW and the PGB generates 225 kW of heat. It means that around 80% of the generated heat at the take-off condition is coming from the PGB itself. So, having a precise tool to calculate the thermal loads generated by the PGB at different flight points enables the engine systems and sub-system designers to achieve an optimal design for the gearbox system.

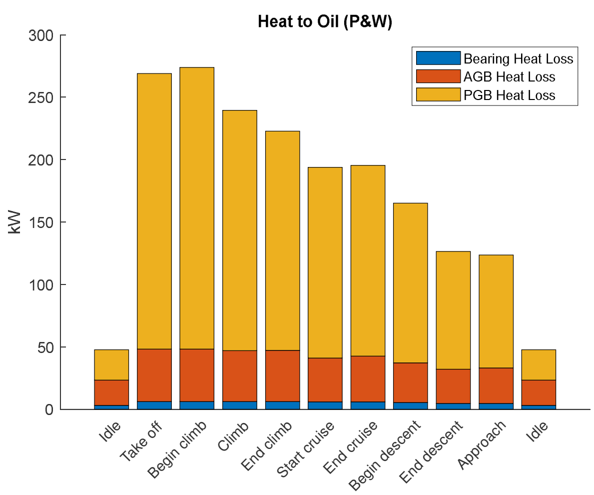

Figure 4 – Heat loads generated by engine heat sources – the first case study

Ultrafan PGB

The second case study is to replicate the thermal behavior of the PGB of Rolls-Royce Ultrafan. The Ultrafan PGB is a planetary-style gearbox with a ring gear on the outside and five planet gears inside rotating around a central sun gear. The design, with a gear ratio around 4:1, drives the fan from a centrally mounted planet carrier, unlike the star-style gear system used in Pratt & Whitney's geared turbofan. As all data was not available for the Ultrafan engine, the designed engine is scaled to deliver the same level of thrust. That's why it is called "scaled engine" in the results and figures. Figure 5 compares the generated heat by the Ultrafan PGB with those of PW1100G engine. The generated results are in a very good agreement with a quote by Paul Stein, Chief Technology Officer at Rolls-Royce: "I can't tell you exactly the levels of efficiency we achieved in this gearbox, but if you can imagine 53 megawatts at 99% efficiency, we'd have 500 kW of excess energy—which is a pretty sizable gas turbine in its own right."[20].

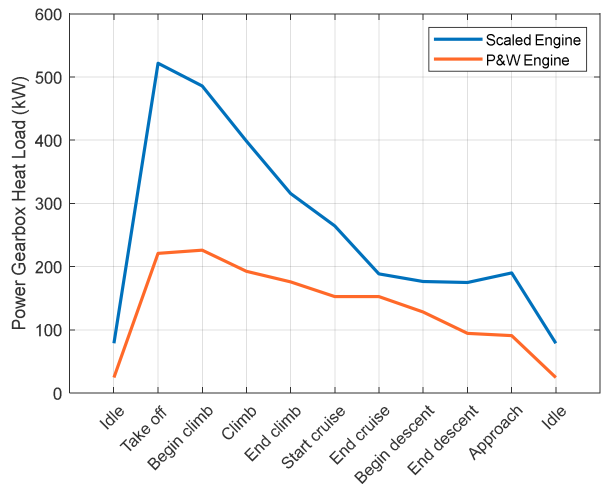

Figure 5 – Heat loads generated PGBs – both case studies

In order to check the range of the mechanical efficiency for the sized PGBs, the variation of mechanical efficiency for both case studies are plotted in figure 6. This figure confirms that the efficiency of the designed PGBs are in the acceptable band of planetary gearbox efficiencies (above 97%) [21]. The maximum efficiency is achieved at the take-off condition where the PGBs are designed at.

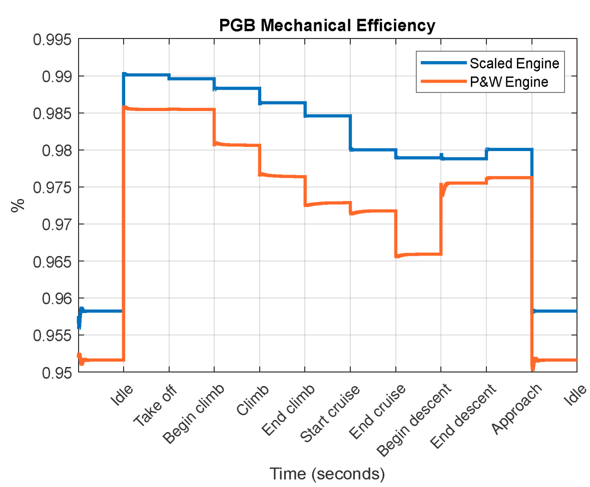

Figure 6 – Mechanical efficiency of PGBs – both case studies

DISCUSSION

Comparison between the heat loads generated by PGBs (figure 5) as well as variation of efficiency during the mission figure 6) shows that the trends of variation of heat loads for both cases are not the same. Therefore, it is fruitful to explore the reason. Figures 7 and 8 compare the inputs from engine simulations to the PGB module in normalized feature. As it can be seen from these figures, the trends of engine rotational speed and the LP shaft power (inputs for the PGB module) are not the same. The maximum values are not achieved at the same flight point and the normalized values are not the same at different flight points. It confirms the capability of the generated module to do sensitivity analysis on the engine inputs for design and optimization purpose. In figures 7 and 8 X-axes numbers are corresponded with the flight points presented in table 1.

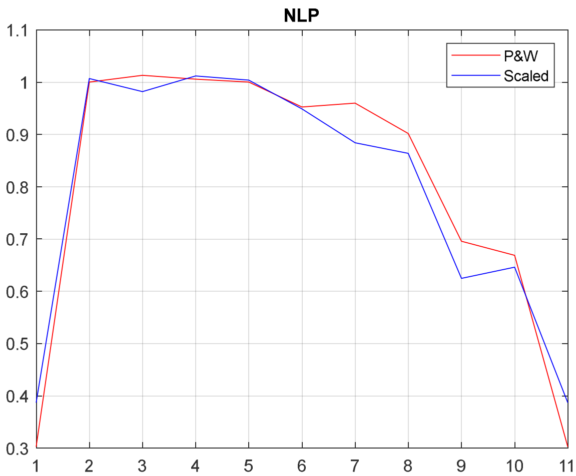

Figure 7 – Comparison of normalized LP rotational speed in both case studies

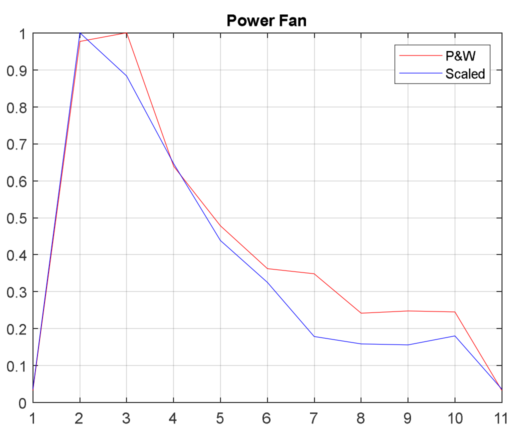

Figure 8 – Comparison of normalized input power in both case studies

Finally, the capabilities, advantages, disadvantages, and limitations of the developed tool could be concluded as follow:

Capabilities and advantages:

- Different heat loss mechanisms could be modelled and analyzed.
- Effects of size and geometry could be explored for design and optimization purpose.
- Effects of oil properties, temperature, and oil flowrate could be studied in detail.
- Sensitivity analysis could be done on effects of geometry, input power, input rotational speed, and cooling fluid on the heat loads generated by the PGB and the mechanical efficiency of the PGB.
- Different style of gear systems (planetary, star, etc.) could be modelled and effects of them can be studied on the engine and aircraft performance.

Limitations and disadvantages:

- Lots of coefficients and correlations should be studied and implemented to have the model up-and-running.
- All values for geometry, size, and architecture parameters should be set to run the model.
- The tool needs some experimental/ real-world data to be validated for industrial applications.

The future work will be focused on more case studies, validation, sensitivity analysis, and design challenges for PGBs to enhance the performance of UHBRG turbofan technology as one of the best candidates for next generation of aircraft engines.

CONCLUSIONS

A physic-based module for thermal analysis of power gearbox in ultra-high bypass ratio geared turbofan technology has been developed in this paper. Equations of different heat loss mechanisms are presented and discussed to form the total heat loss calculation method in PGBs. The developed module has been tested in a pre-defined mission on two case studies replicating the PW1100G engine with star-style gearbox and Ultrafan engine with planetary-style gearbox. In-house 0-D tools for engine and aircraft simulations have been used to provide inputs for the PGB module during the mission. The results of the case studies confirm the effectiveness of the proposed approach in thermal analysis of PGBs in UHBRG turbofan technology. The developed tool can be used for design, optimization, and sensitivity analysis purpose in geared turbofan engines.

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