DYNAMICAL BEHAVIOUR OF A FAN PROPULSION UNIT FOR AN UNCONVENTIONAL ULTRA-LIGHT AIRCRAFT

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Abstract. This paper covers the procedure and results of calculation of natural frequencies of torsional and circular vibration of an aircraft propulsion unit consisting of a motorcycle piston engine, a composite transmission shaft and a ducted fan. This propulsion unit will be used in an ultra-light aircraft UL-39 which is being developed at the Institute of Aerospace Engineering, Faculty of Mechanical Engineering, CTU in Prague. The reasons for choosing a composite transmission shaft instead of one made of aluminium are presented. Later on, the methods of computing the natural frequencies of torsional and circular vibrations are discussed along with the results of the calculation. In the end, further development of the UL-39 project is chalked out.

Keywords. torsional vibration, circular vibration, natural frequencies, fan propulsion unit, UL-39, composite transmission shaft.

1 Introduction

The UL-39 is a two-seated ultra-light aircraft which is being developed by the Institute of Aerospace Engineering, Faculty of Mechanical Engineering, CTU in Prague. All parts of its primary structure are made of carbon fibre-reinforced composites. The propulsion unit of the UL-39 aircraft (seen in Figure 1) consists of a motorcycle piston engine, a transmission shaft (also made of composite), and a ducted fan.

Figure 1: Model of the UL-39 aircraft [1]

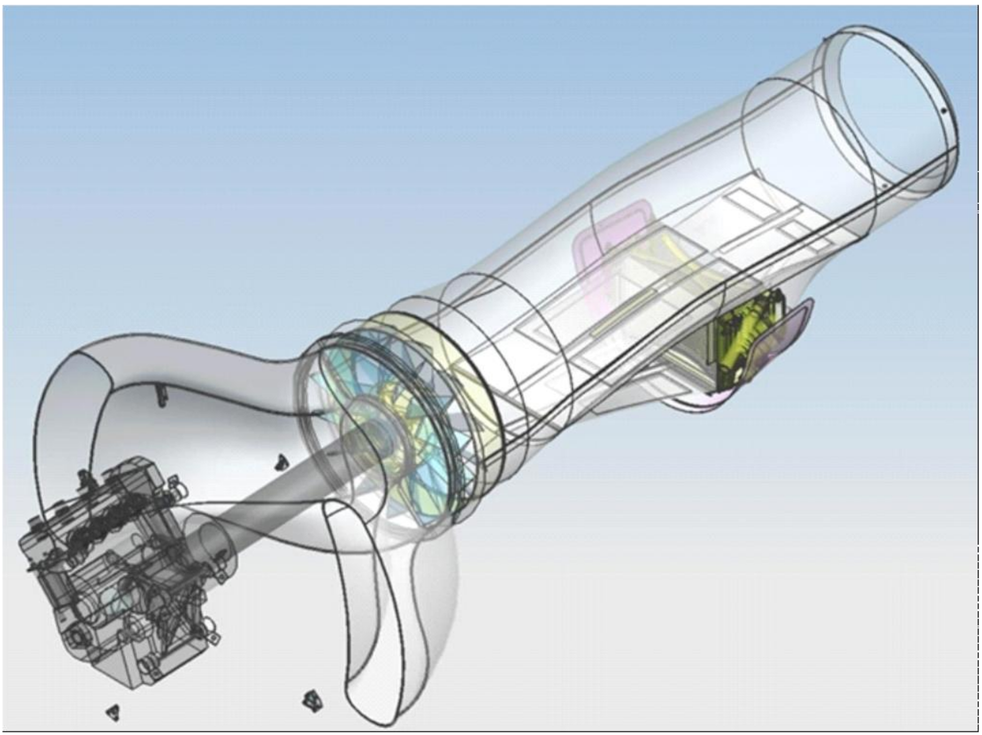

Figure 2: The fan propulsion unit of the UL-39 [1]

1.1 The Propulsion Unit

A model of the mechanical parts of the UL-39 propulsion unit is pictured in Figure 3. The mechanical system which was considered during the calculations presented in this paper incorporates parts of the engine (crankshaft and input shaft of the motorcycle transmission, modified motorcycle clutch), a composite clutch which acts as a safety element so that in event of an accident the aircraft structure is not damaged, and, of course, the transmission shaft and the fan rotor disk.

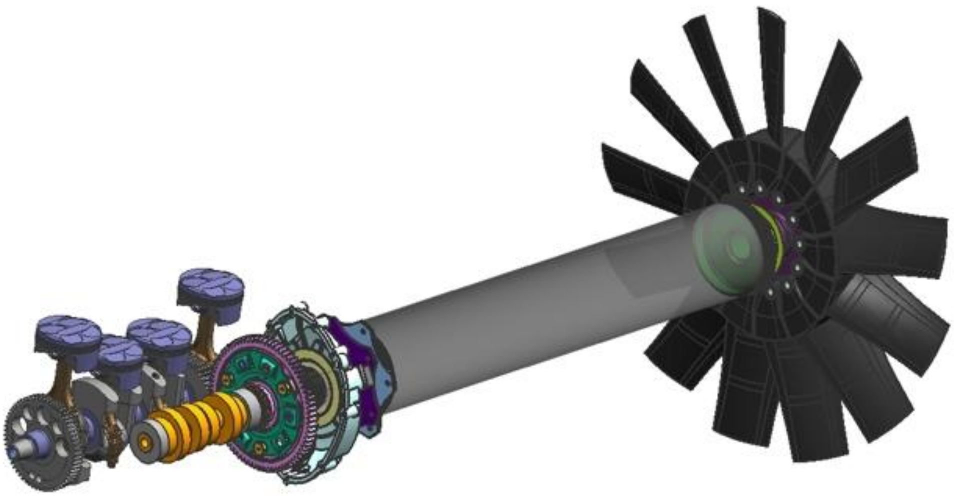

Figure 3: Moving mechanical parts of the fan propulsion unit [2]

1.2 The Transmission Shaft

The transmission shaft consists of a composite tube with aluminium flanges on both ends. Apart form transmitting power from the engine to the fan, it should also act as a torsional vibration damper. Therefore, during its development, small torsional stiffness and high bending stiffness was demanded while its weight should have been made as light as possible.

Figure 4: The transmission shaft undergoing bending stiffness test [4]

Various composite and aluminium shaft prototypes were compared using the above-mentioned criteria and one of the composite shafts was chosen This was done by Mr Ondřej Vích [4]. The issues of fatigue were not taken into account at this stage and will be subject to further calculations and experiments.

The experiments made so far have shown that the response of the shaft to external forces is linear.

2 Calculation of Natural Frequencies – On Collecting the Data

For the calculations it was necessary to convert the components of the propulsion unit to dynamical models. For torsional vibration, the propulsion unit was converted to a system of rotating disks connected to each other by shafts (see Figure 6). For circular vibration, the transfer matrix method was used.

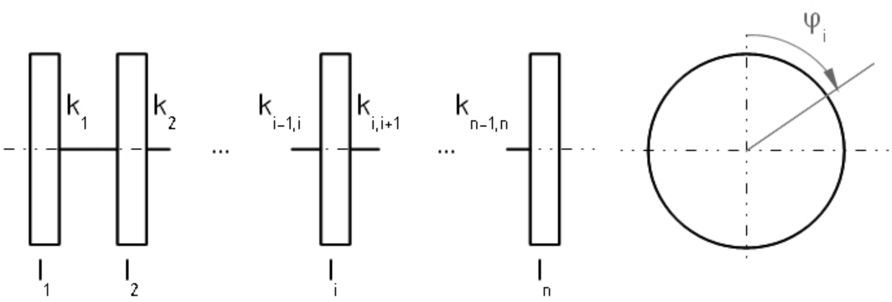

Figure 5: Dynamical model for the calculation of torsional vibrations [2]

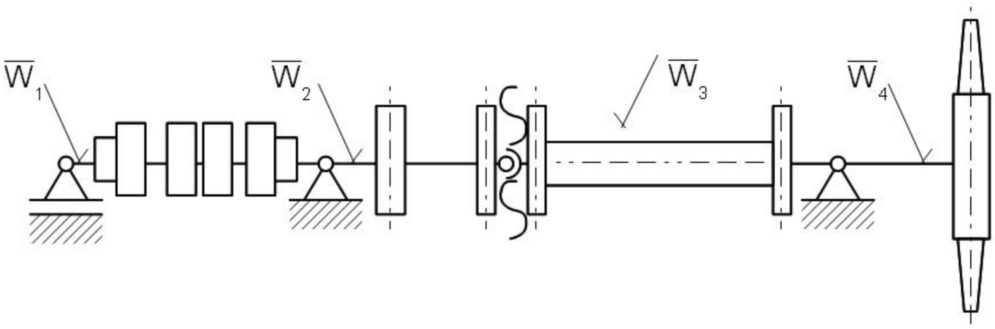

Figure 6: Model for the calculation of circular vibrations [2]

For both of these methods, the components of the propulsion unit had to be weighed, measured or modelled in CAD software. This way, the values of masses, moments of inertia, torsional and bending stiffnesses of the components were found out. For the torsional vibrations, it was also necessary to determine the driving torque produced by the piston engine (the circular vibrations are only driven by centrifugal forces).

Figure 7: The components of the crank mechanism of the BMW S1000RR engine [2]

2.1 Determination of the Piston Engine Driving Torque

The basic quantity required to calculate the time behaviour of torque is the dependency of cylinder pressure on crank angle.

The cylinder pressure may be determined either experimentally or computationally. The experimental way is of course more accurate but for an aircraft engine it is also vital to know the cylinder pressure at higher altitudes. The computational methods prove to be helpful at this point, not mentioning that they are much less expensive than the experiments.

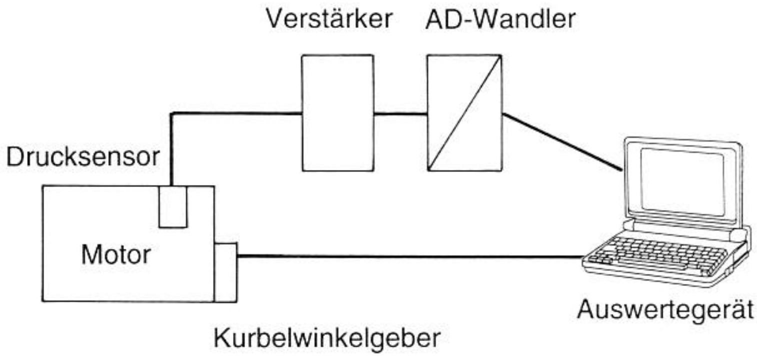

Figure 8: The appliances needed for the experimental evaluation of cylinder pressure [3]

For the experiment, the following equipment is needed (as shown in Figure 8): cylinder pressure sensor (in our case, a spark plug was used), a crank angle sensor, a charge amplifier (to convert the electric charge given by the spark plug to voltage), an A/D converter, and special software (based on LabView in our case).

During the experiment, the engine, still on the motorcycle, was loaded by a dynamometer (see Figure 9).

The cylinder pressure was both measured and calculated by the GT-Power software. The dependence of engine torque on crank angle was then converted to a Fourier series. Since a four-cylinder four-stroke engine is used only even-numbered components of the Fourier series are greater than zero. In the preferred range of operation regimes, the 2nd and 4th component are of the greatest value.

Figure 9: The BMW S1000RR motorcycle during cylinder pressure measurement [2]

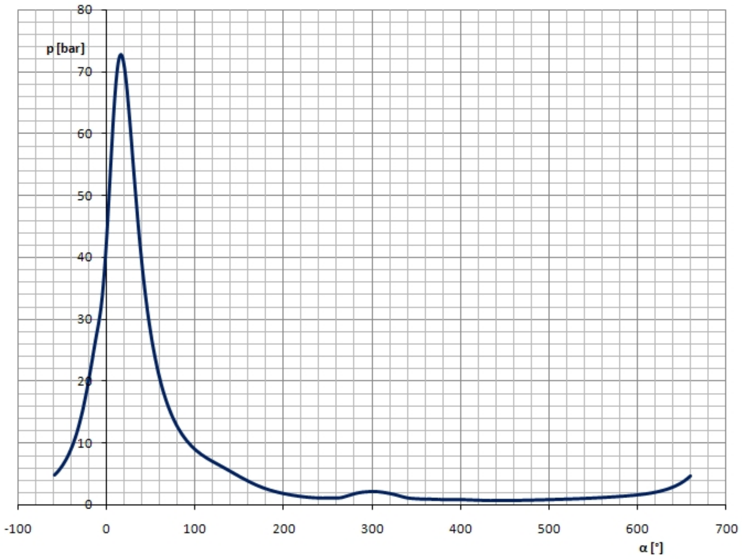

Figure 10: An example of a cylinder pressure diagram (calculated by GT-Power at 14,000 engine rpm) [2]

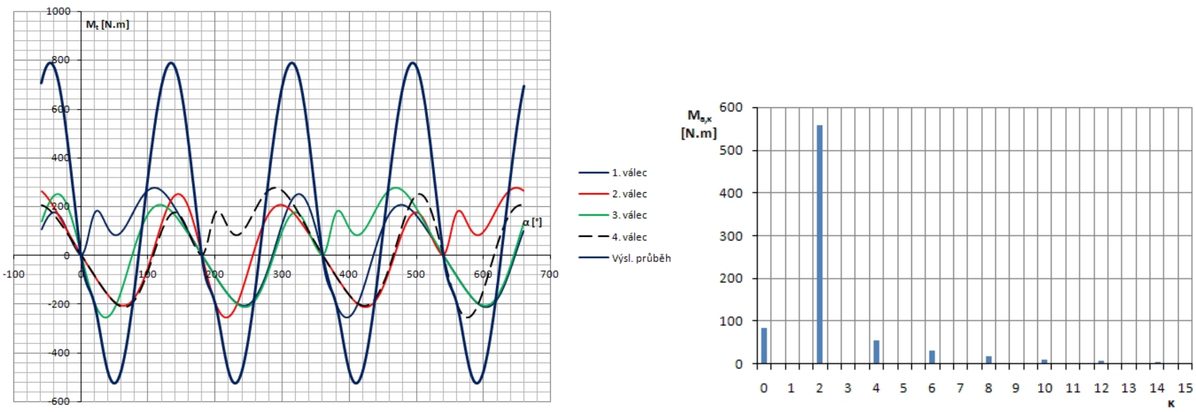

Figure 11: Examples of engine torque and its Fourier components (calculated by GT-Power at 14,000 rpm) [2]

3 Calculation of Natural Frequencies – The Results

3.1 Torsional Vibrations

The dynamical response of the motorcycle clutch proved to be non-linear. This means that all of the natural frequencies depend on the amplitude of the respective mass and hence the amplitude of the piston engine moment. Three constant values of torsional stiffness of the motorcycle clutch were considered. Therefore, three values of each natural frequency depending on the load of the clutch were obtained by the calculation (see Figure 12).

After the natural frequencies were calculated, it was necessary to compare their values to frequencies of the most dangerous Fourier components of the engine driving torque (2nd, 4th and, at lower engine speeds, 6th). This was done with the help of Campbell diagrams (Figure 13).

The Campbell diagram for one of the load cases (Figure 13) shows that dangerous conditions are to be expected at approx. 6,000 and 8,000 engine rpm and over 14,000 rpm (which would influence speeds lower that 14,000 rpm as well). The regimes of resonance within the operation range (which lies at 8,000 to 14,000 engine rpm) are highlighted in the diagram by dots. The other two regimes, on top of the diagram, were not found to be dangerous. This was done by a calculation of mechanical energies in the resonance regimes. It was discovered that with the transmission shaft of current torsional stiffness, the safe operation of the propulsion unit is only possible at approx. (10,000 to 12,500) rpm. Further calculation showed that the dependence of torsional natural frequencies on torsional stiffness of the transmission shaft is only weak.

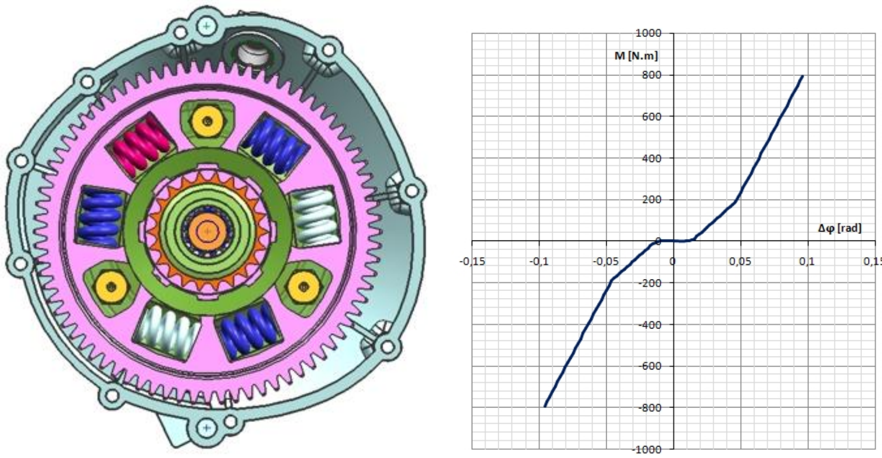

Figure 12: Model of the motorcycle clutch and its characteristic diagram [2]

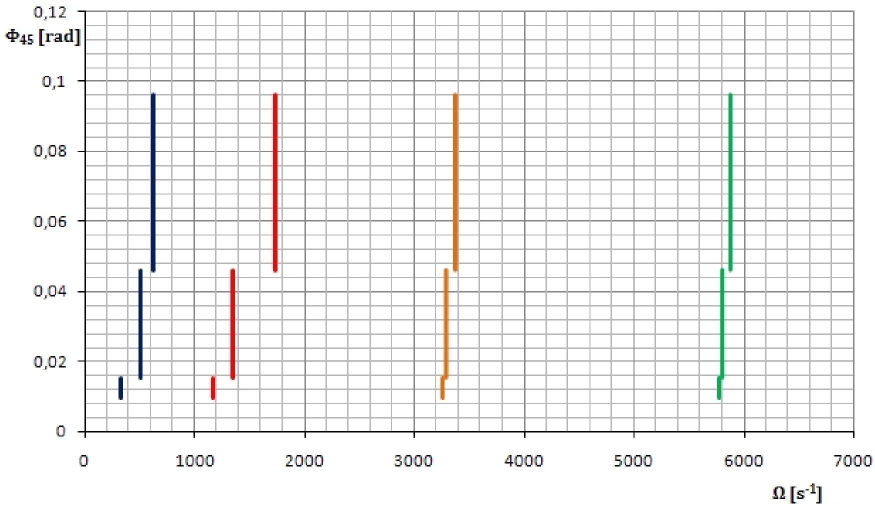

Figure 13: The first four natural frequencies of torsional vibrations [2]

3.2 Circular Vibrations

Unlike in the case of torsional vibrations, the dynamical behaviour of all the parts under the cimcumstances of circular vibration is linear. Hence all of the natural frequencies of rotational vibrations are independent on any amplitude.

The calculation showed that, due to the 6th natural frequency, safe operation with the current shaft is impossible. The 6th natural frequency equals approx. 11,000 engine rpm.

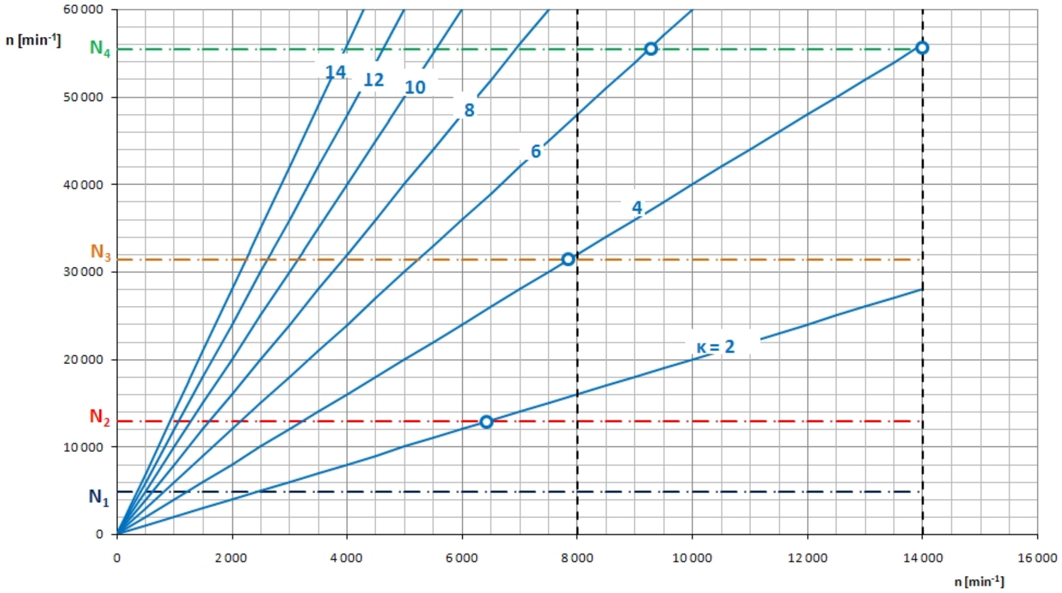

Figure 14: A Campbell diagram for one of the three load cases [2]

Therefore, it is necessary to change the bending stiffness of the transmission shaft. It was chosen to increase it since due to possible problems concerning strength, the bending stiffness should not be reduced. It is obvious that the increment of bending stiffness will inevitably lead to the increment of torsional stiffness as well.

The dependence of natural frequencies of circular vibrations (3rd to 8th) is displayed in Figure 15. The operational range of engine speeds is highlighted by horizontal dashed lines, the current value of natural frequency is highlighted by the vertical dashed line.

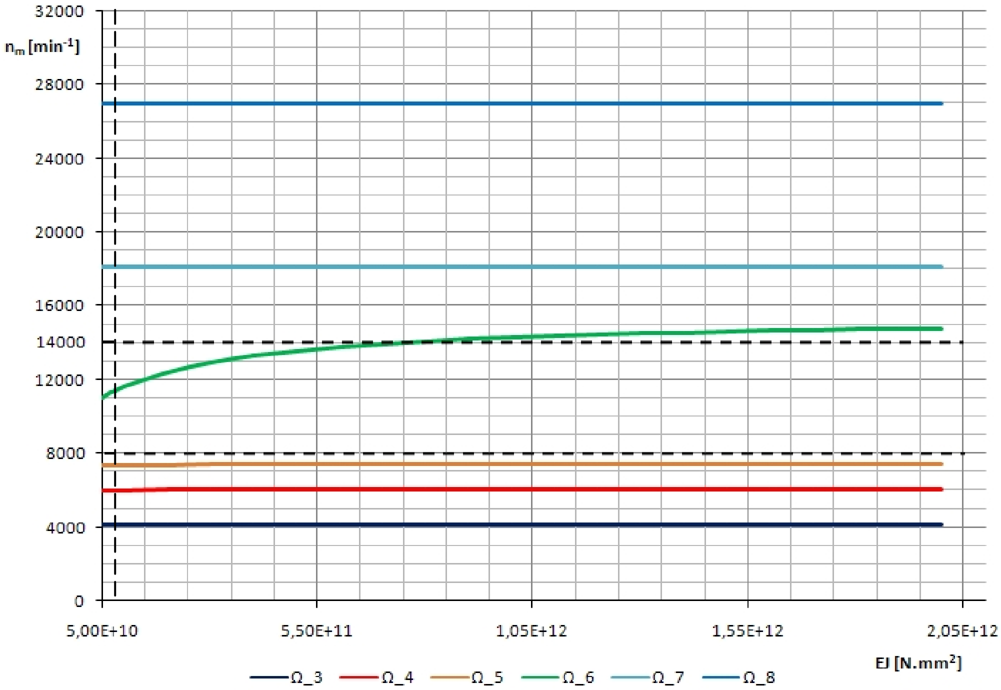

Figure 15: The dependence of natural frequencies of circular vibrations on the bending stiffness of the transmission shaft [2]

3.3 Further Development of the Project

With respect to the results of the calculation of natural frequencies, it was decided that a new transmission shaft be made. Then, along with an experimental evaluation of torsional and bending stiffness, an experimental computational investigation of its damping properties will be carried out. Based on its results, a new, more accurate calculation of natural frequencies of the whole propulsion unit will be made. The natural frequencies will then be verified by experiment.

According to the schedule of the whole project, the UL-39 aircraft should be able to fly in 2014.

4 Conclusion

In this paper, the UL-39 aircraft was briefly introduced, with special attention to its fan propulsion unit. The main topic discussed in this paper was the calculation of natural frequencies of torsional and circular vibrations of the propulsion unit. The methods used for the calculation were presented, including determination of the piston engine driving torque and of stiffnesses of the transmission shaft. In the end of the paper, the next steps of the project are outlined.

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