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ANALYSIS OF AN AIRCRAFT ENGINE START-UP PROCESS ON THE EXAMPLE OF THE PZL-130 TC-II „ORLIK" TRAINING AIRCRAFT

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Abstract

The paper discloses the analysis of processes that take place during the start-up operation of the driving unit for the training aircraft of the TZL-130 TC-II Turbo-Orlik type. The aircraft is designed for selective and initial trainings at the Air Force School of "Little Eagles" in Dęblin. The driving unit comprises the PT6A-25C turbo-propeller engine from Pratt & Whitney combined with the four-bladed airscrew from Hatzell. It is specifically mentioned that data for the analysis were sourced from the S2-3a on-board recorder of flight parameters manufactured by the Air Force Institute of Technology (AFIT). The analysis was carried out both during ground and flight tests. The paper briefly outlines general structures and operation principles of typical start-up systems with the focus to their key components. Attention is paid to how important it is to select an appropriate start-up system to match the specific aircraft type and the guideline parameters for selection that should be adhered to are specified. Also there are disclosed the key mathematical relationships that are indispensable to design start-up systems and to find out their basic characteristics. It is emphasized that the start-up operation must be considered as a non-stationary process that lasts from the standstill state of the engine until the moment when the minimum required rpm is reached, sufficient to generate necessary power of the engine. In addition, the attention is paid to the fact that the value of the engine acceleration is crucial to the achievable start-up time that is deemed as one of key parameters for all start-up systems. It is demonstrated that to achieve the required level of acceleration, it is necessary to secure the so called overhead of the engine power which needs constant flow of fuel and air into the combustion chamber of the engine. The last part of the paper comprises selected characteristic curves that were obtained from the analysis of the engine start-up processes both on ground and in flight. The final conclusions emphasize that the start-up system for the presented driving unit is really efficient and guarantees correct operation of the engine under any conditions.

Keywords: *diagnostics of aircraft engines, qualification tests of aircraft driving units*

1. Introduction

Very common use of turbo-propeller and turbojet engines has also led to equally dynamic development of subsystems that are responsible for the processes of engine start-up (set in motion). During the entire lifetime of aircraft engines, the start-up systems are in operation only for a very small portion of time. However, efficiency of the engine start-up process is an extremely important factor, since it determines technical availability of aircrafts and is also essential for safety of flights, reliable operation and overall lifetime of engines [3].

The design of the start-up system for a specific engine is very often (due to operational considerations) an upshot of possible application areas where individual aircrafts can be used.

Regardless its type and design, the engine start-up system is made up of three key components: the automatic control circuit that also monitors the start-up process, the main starter and the source of electric power (for instance, a rechargeable battery) (Fig. 1).

The sources of electric power may form either an independent part of an aircraft or its engine (combined starter and generator), or an external power unit of the ground equipment on the airfield. For this case, study of the PZL-130TC-II "Orlik" aircraft, the start-up system is powered by a combined starter and generator installed on board as a part of the PT6A-25C turbo-propeller engine from Pratt & Whitney.

For modern turbo-propeller engines, the start-up process runs automatically according to purposefully adjusted schedule designed to switch on and off the starter, the ignition system and the fuel supply devices.

Selection of the start-up system is also crucial for its weight and overall dimensions, which is particularly important for small aircrafts, such as the PZL-130TC-II "Orlik" training airplane.

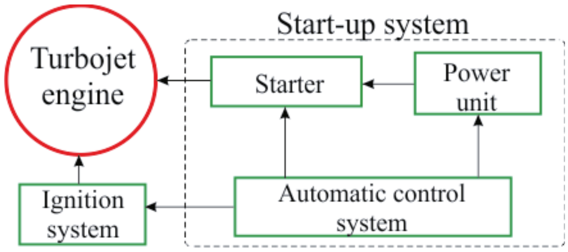

Fig. 1. Schematic diagram of the start-up system [3]

In addition, selection of an appropriate start-up system is also governed by a series of other factors that include but are not limited to technical parameters, cost efficiency and operational performance, including also reliability and lifetime.

2. Theoretical background

The key task of the start-up system for any engine is to enforce necessary rpm of the engine shafting (the compressor and turbine unit). The engine rpm must be high enough, so that the power N_t delivered by the turbine exceeds the overall power N_s consumed by the compressor and other subassemblies of the engine, according to the turbine power balance that is expressed by the relationship:

$$N_t > N_s + N_{agr}, \tag{1}$$

where: N_{agr} - power necessary to drive energy generators and to overcome friction resistance.
The power necessary to drive the engine compressor can be calculated from the formula:

$$N_s = \frac{\dot{m}_{pow} \cdot T^*_{pow}}{\eta_s}\left(\pi_s^{*\frac{k-1}{k}} - 1\right), \tag{2}$$

where:
$\dot{m}_{pow}$ – mass flow rate of air stream that passes through the compressor [kg/s],
T^*_{pow} – air temperature at the compressor inlet [K],
η_s – efficiency factor of the compressor,
π_s^* – compression ratio of the compressor,
k – isentropic exponent for air.

The engine start-up is a non-stationary process that begins, in ground conditions, at the engine standstill and ends when the minimum rpm of the engine is reached. During flight, the process starts from the minimum rpm of "autorotation" and lasts to the minimum rotation speed (frequently referred to as the minimum flight rpm).

The engine start-up within the range up to the minimum rpm must be carried out in a continuous way with the necessary acceleration. The acceleration value is crucial for the duration of the start-up process. Due to that condition, the power of the engine starter must be increased by the overhead that is necessary to gain acceleration. Thus, the total power of the starter is defined by the formula:

$$N_r = N_s + \Delta N_E, \tag{3}$$

where:
N_r – power of the engine starter,
ΔN_E – power overhead necessary to gain acceleration of the engine shafting.

To provide that surplus of engine power it is necessary to guarantee continuous flow of fuel and air.

One important tool that is used to evaluate dynamics of engine operation during the start-up process are the so called phase diagrams that represent momentary increments of individual parameters as a function of these parameters, which is defined by the general formula:

$$\frac{dX}{dt} = f(X), \tag{4}$$

where:
X – parameter in question,
t – time [s].

3. Analysis of the start-up process for the M601t engine

The PT6A-25C turbo-propeller engine (Fig. 2) with the power of 750 HP was designed by the Canadian company Pratt & Whitney Canada. It was installed on the PZL-130 TC-II Turbo-Orlik aircraft together with a four-bladed airscrew from Hartzell to enable extended training of aircraft pilots. The engine has unlimited time resource, which means that it is operated and maintained according to its technical condition.

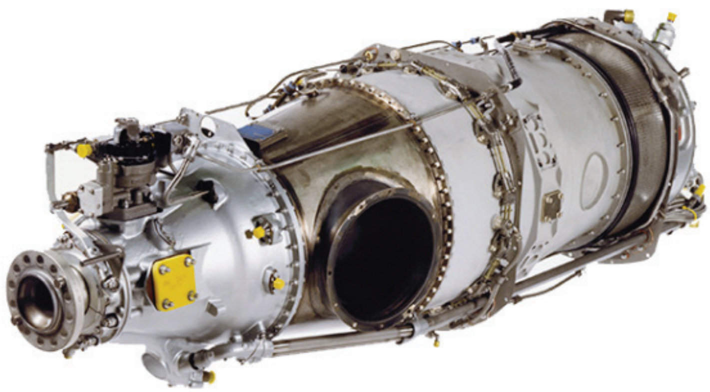

Fig. 2. PT6A turbo-propeller engine from Pratt & Whitney [4]

The objective of completed investigations and experiments was to determine key characteristics of the engine and the airscrew during the start-up process. Therefore the range of measured and evaluated parameters included the engine power *N,* rotation speed of the turbine generator n_g, rotation speed of the airscrew *RPM,* temperature between turbines *ITT*, etc.

3.1. Engine start-up on the ground

The curves of the engine parameters for the start-up process are presented in Fig. 3. The curves clearly show a delay of the airscrew rpm gain with respect to rpm of the turbine generator, which is the consequence of aerodynamic coupling between the turbine generator rotor and the free turbine rotor. It is the typical effect for turbo-propeller engines of that type. The data for this analysis were acquired from the S2-3a recorder of flight parameters manufactured by the Air Force Institute of Technology (AFIT).

Another very important curve that characterizes the start-up process of such engines is the one that shows which rpm of the turbine generator is necessary to achieve such power overhead that is necessary to spin up the free turbine, and therefore to set the aircrew in motion. Fig. 4 presents such a curve that demonstrates that the airscrew is actuated when rpm of the turbine generator reaches about 20% of its rated speed. It is a typical threshold and meets requirements for such types of driving units.

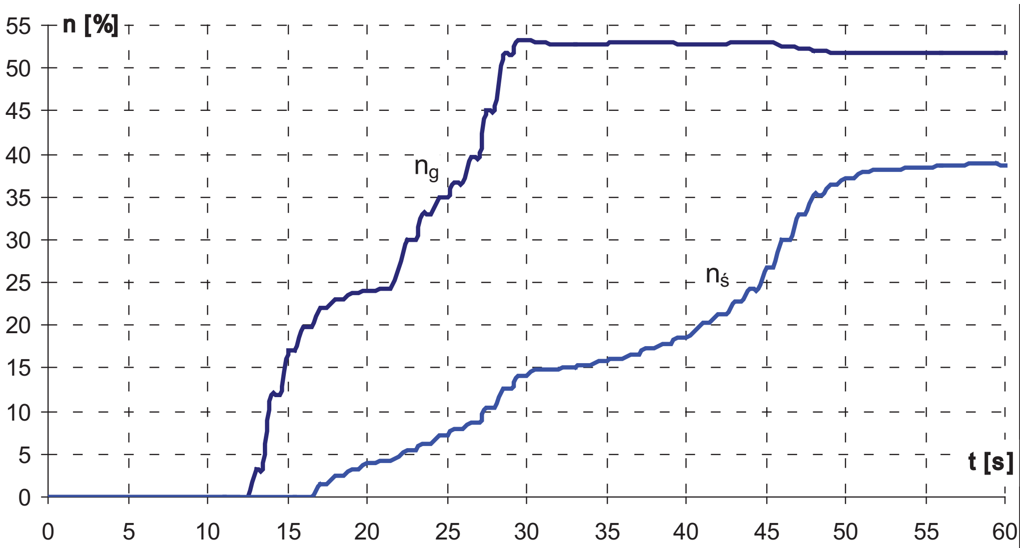

Fig. 3. Characteristic curves that depict rpm changes for the turbine generator and the airscrew during the start-up process as the function of time

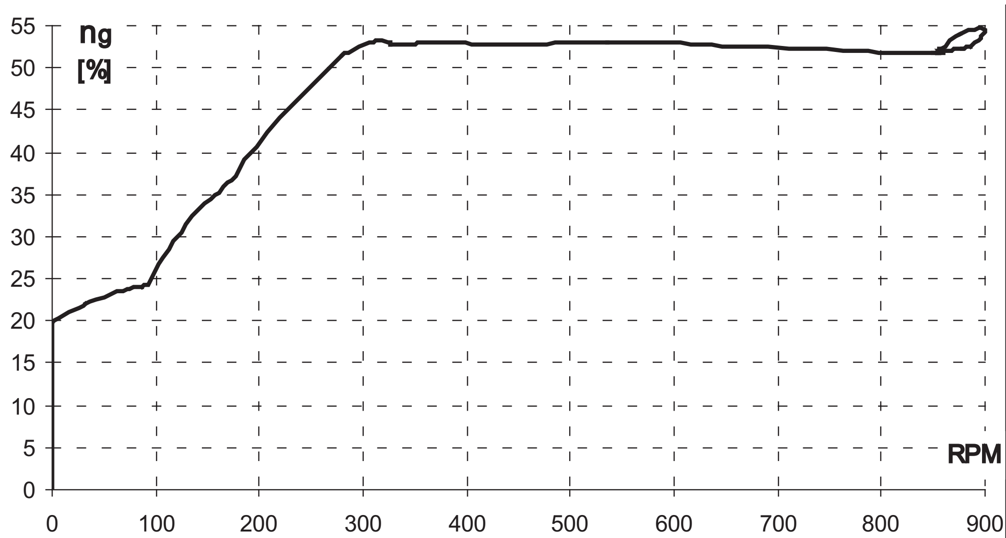

Fig. 4. Characteristic curves for variation of the turbine generator rpm as a function of the aircrew rpm

According to the conventional approach, the start-up procedure can be structured into three phases:

– 1st phase – the rpm range from the standstill state to the rpm threshold when fuel supply is activated. For that phase the motor is revolved exclusively by the starter,
– 2nd phase – the rpm range when the ignition system is activated and fuel is kept supplied, which initiates autonomous operation of the turbine, but the turbine is still assisted by the starter. The phase ends when operation of both the starter and all the start-up support system is ceased (i.e. spark plugs, supply of extra fuel to supply the starter). It is the moment when the working point is reached, i.e. the moment when the torque necessary to drive the compressor is equal to the torque that is produced by the turbine. Theoretically, upon crossing that threshold the torque produced by the turbine exceeds the totalized torque of all resistances,
– 3rd phase – the rpm range when rotation speed keeps growing automatically due to the turbine effort. It is the growth up to the value of minimum operational rpm that is referred to as the idle run rpm for each engine type when assistance of the start-up system is no longer necessary.

These phases are best visible on the characteristic curve that shows course of the start-up as variation of the engine torque as a function of the engine rpm – see Fig. 5.

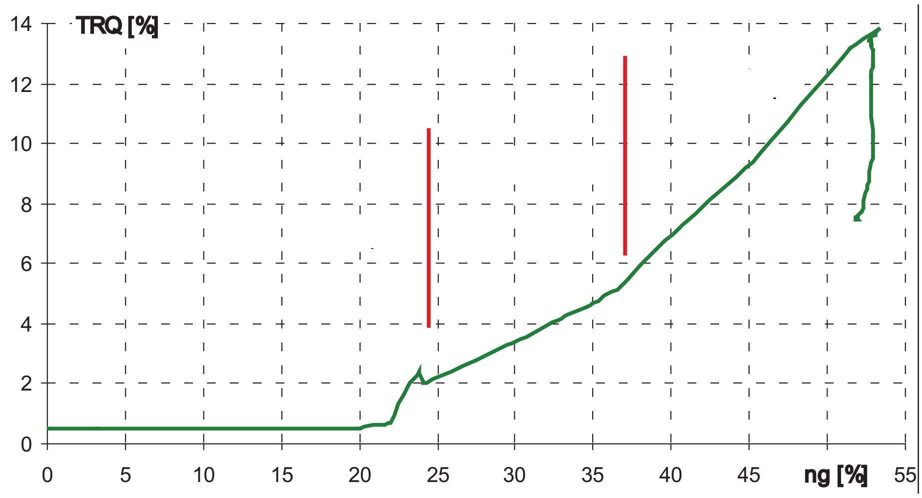

Fig. 5. Variations of the engine torque as a function of the turbine generator rpm during the engine start-up

Variations of the output torque during the start-up process as a function of time indicates that the highest gain of the torque is achieved during the 2nd phase – see Fig. 6.

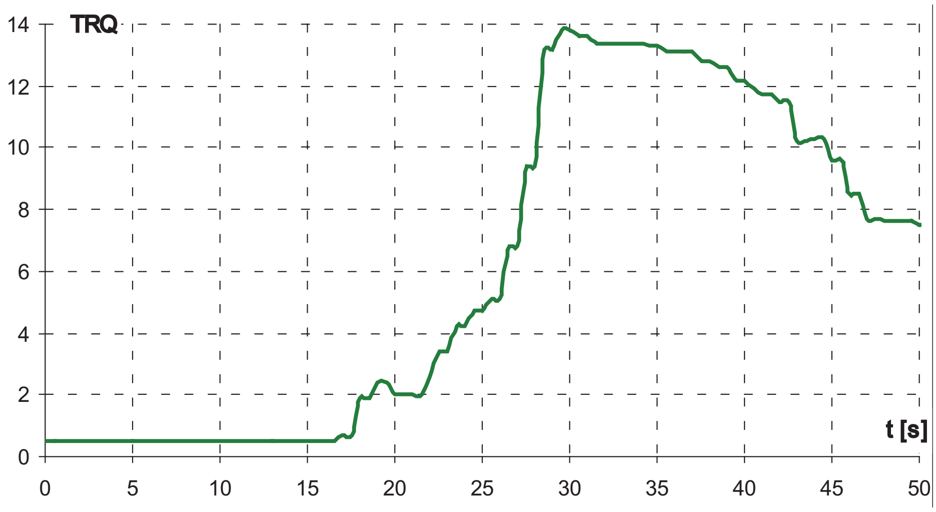

Fig. 6. Variations of the engine torque as a function of time during the engine start-up

Such image of the torque variations leads to variations of the engine power – Fig. 7.

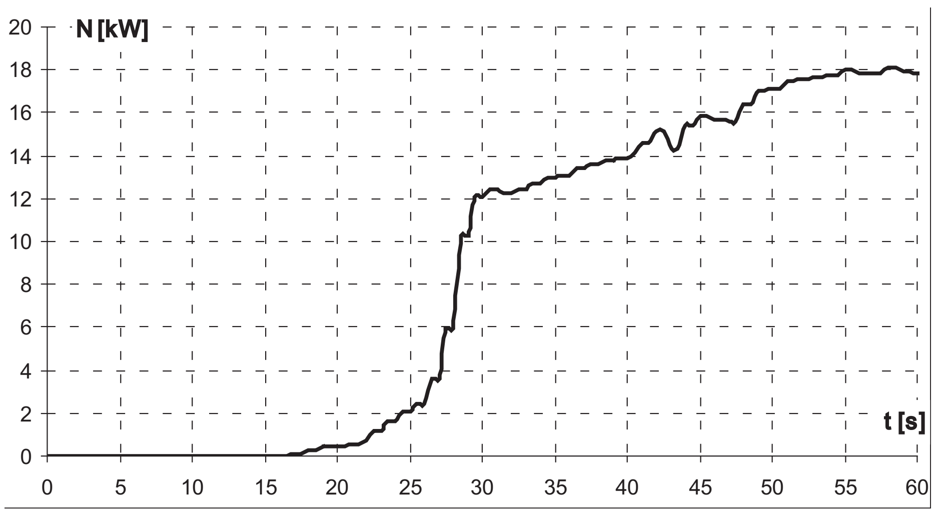

Fig. 7. Curve for power variations of the driving unit during start-up of the - PT6A-25C engine

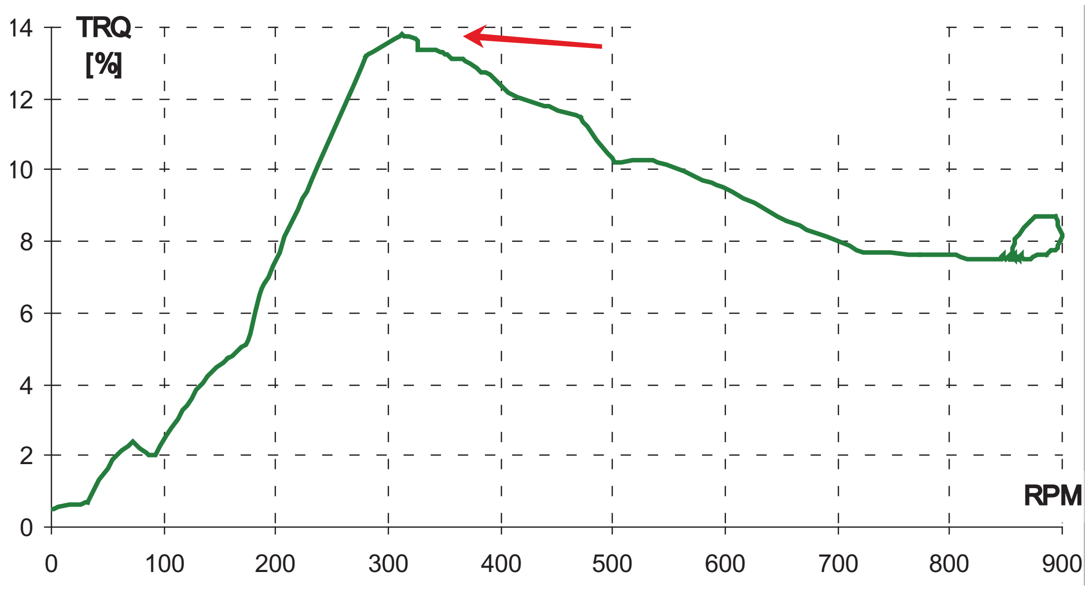

Fig. 8. Variations of the torque as a function of the airscrew rpm

A very rapid change of the engine parameters, in particular its torque, is also entailed by the fact that the airscrew blades are set to the position of a flag during the initial phase of the start-up process and the loads begins to be gradually released only at about 300 rpm – see Fig. 8. It corresponds to 25-30% of the turbine generator rpm – compare against Fig. 3.

The dynamic properties of the torque variations demonstrate that it is also the moment, when differentials of the torque gain change from positive to negative ones, i.e. any further gain if the torque is stopped at the level of the rated torque for idle run – see Fig. 9.

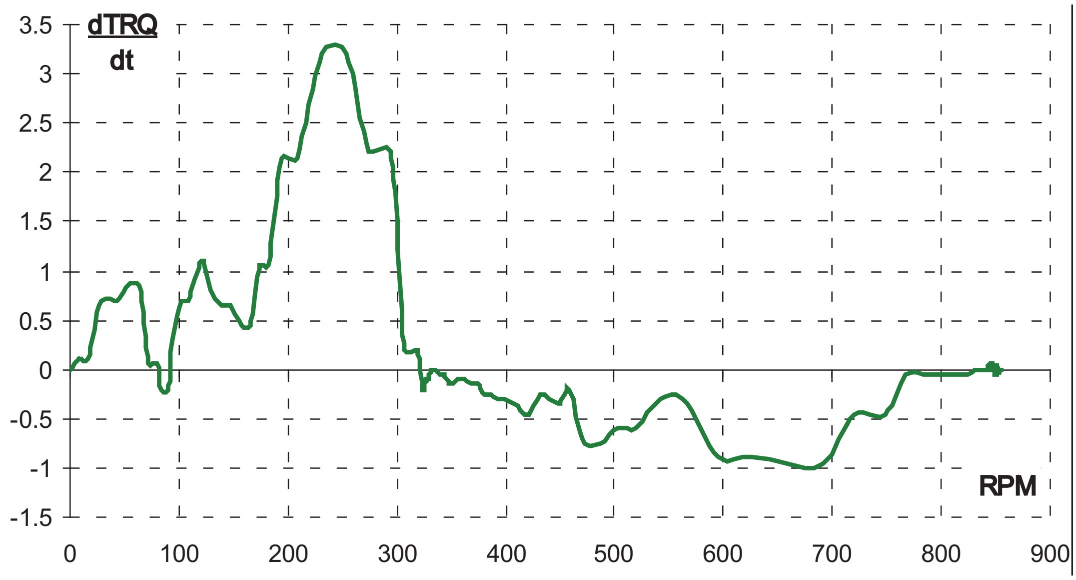

Fig. 9. Dynamics (acceleration) of the engine torque as the function of the airscrew rpm during the start-up process

Figure 10 shows temperature variations of exhaust gas in between the turbines. The highest peak of temperature occurs somewhere between 28^{th} and 29^{th} second, which is also confirmed by comparison against Fig. 3. It is the moment when the engine rpm reaches the threshold of idle run.

Dynamic properties for variations of selected operational parameters for the driving unit as functions of the turbine generator rpm are shown in subsequent graphs. These curves are rather typical for aircraft engines of that type. However, the depicted curves should be considered merely as a rough estimation due to the acquisition frequency of the on-board data recorder.

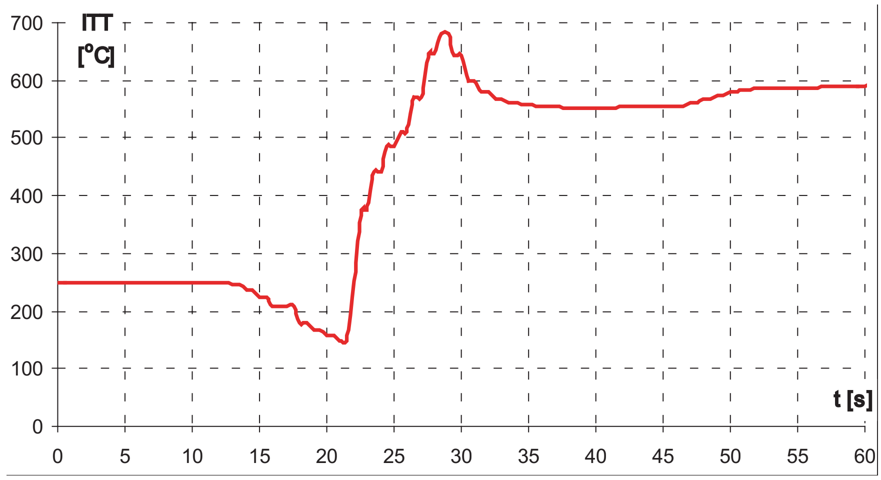

Fig. 10. Temperature variations in the area in between the turbines during the engine start-up

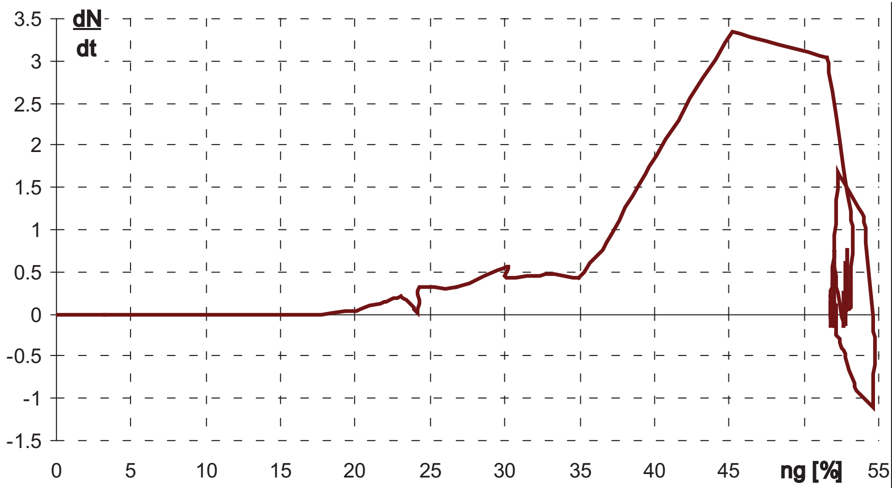

Fig. 11. Dynamic variations of the engine power as a function of the turbine generator rpm during the engine start-up

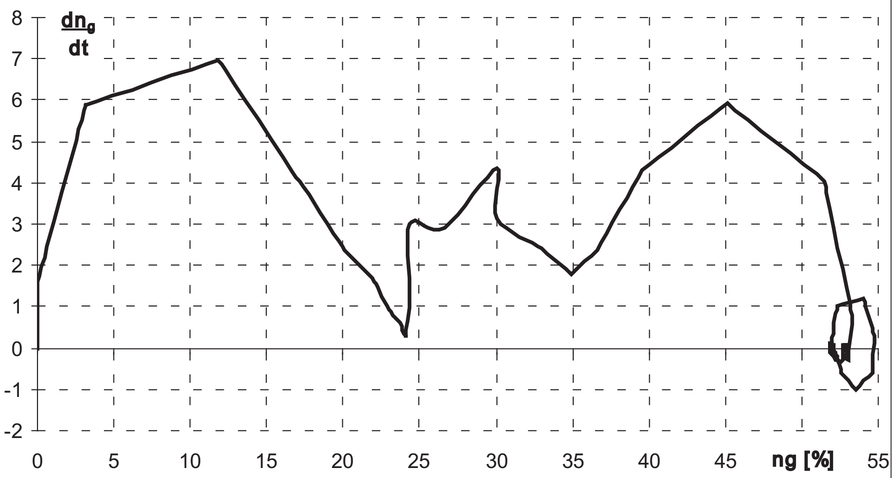

Fig. 12. Phase diagram for variations of the turbine generator rpm during the engine start-up

3.2. Start-up of the aircraft engine in air

When an aircraft engine is operated in air, there is the possibility of the engine being spontaneously killed (engine flameout). Even if the fuel supply system is in healthy condition, there may be a number of reasons for such an engine failure, e.g. rapid maneuvers preceded by reduction of engine rpm that may lead to unsymmetrical flow around the jet intake, incorrect adjustment of inlet diffusers, disturbances of air flow due to such events as launching of missiles, icing of the jet intake, etc. After such a spontaneous engine flameout, the aircraft speed and altitude are reduced to the values that are considered as the most suitable for the engine restart. However, one has to remember that the start-up procedure for the turbo-propeller engine is slightly different that the turbojet one. It results from the fact that the specific rotation speed of the turbine and the compressor is predominantly caused by autorotation of the airscrew that is set to the specific angles of attack. Depending on the setting angles of propeller blades, there are several options of collaboration between the airscrew and the engine. The most convenient option is when blades are set "as a flag," which means that the angle of attack with respect to the rotation plane is nearly 90º, which minimizes the aerodynamic resistance.

The driving unit of the PZL-130TC-II "Orlik" aircraft is not provided with the option for automatically reposition the airscrew to the "flag" position. On the contrary, pilots have for accurately set the engine control lever (DSS) to the range of idle run to activate the microswitch that is responsible for repositioning of airscrew blades to the "flag" position. Such a solution is not the most convenient, since it fails to guarantee appropriate reaction of the aircraft crew under extremely stressful circumstances (as it frequently happens, in particular to young pilots, when the aircraft engine spontaneously goes off).

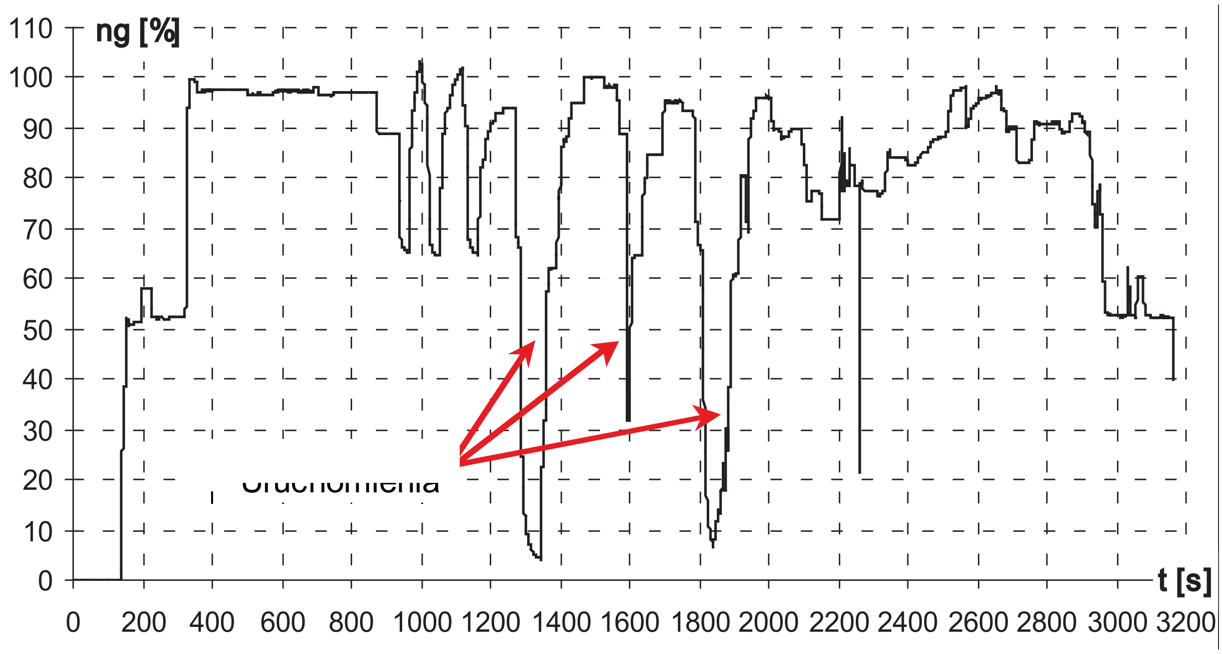

Fig. 13. Variations of the engine rpm during a test flight to check the functionality of restart in air

During the qualification tests, three subsequent restarts in air were carried out at the altitude of 3000 m and with the speed ranging from 230 to 260 km/h. The first restart was carried out 30 seconds after the engine flameout, the second one when the engine rpm dropped below 50% of the ratings, and the third one – also 30 seconds after the engine flameout in the emergency mode. The graphs that show variations of the aircraft altitude and speed during the test flight are presented in Fig. 15 and 16.

When the engine is started-up in air, the airscrew, within a specific range of attack angles, serves as an additional source of substantial torque that is much higher than the maximum torque of the engine starter. It is why the time that is necessary for the engine to reach the rotation speed of idle run (low throttle) is slightly shorter than for start-up procedures on ground. Waveforms for variations of engine rpm during the mentioned restarts in air demonstrate slight reduction of the restart process duration, except for the emergency restart (the third one).

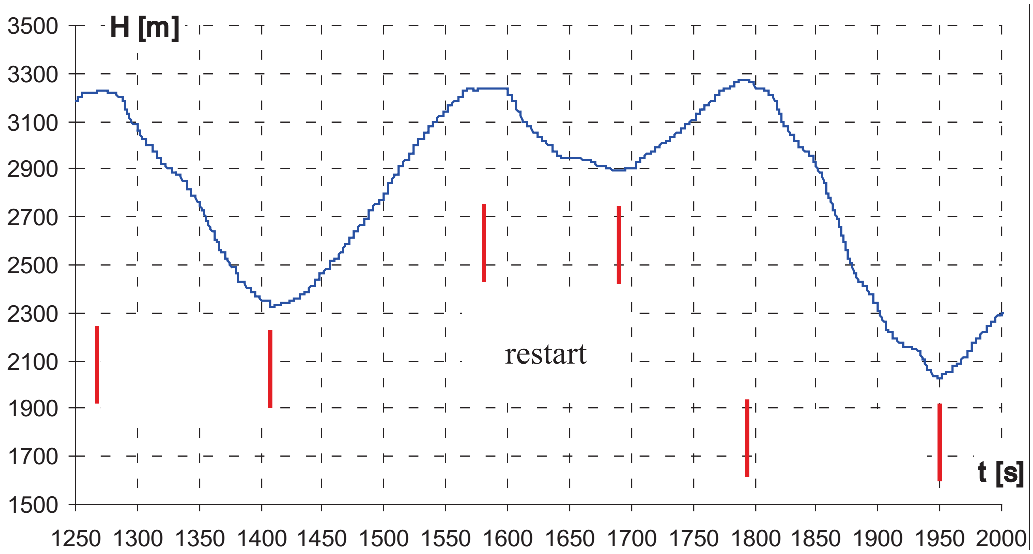

Fig. 14. Variations of the flight altitude associated with engine restart in air

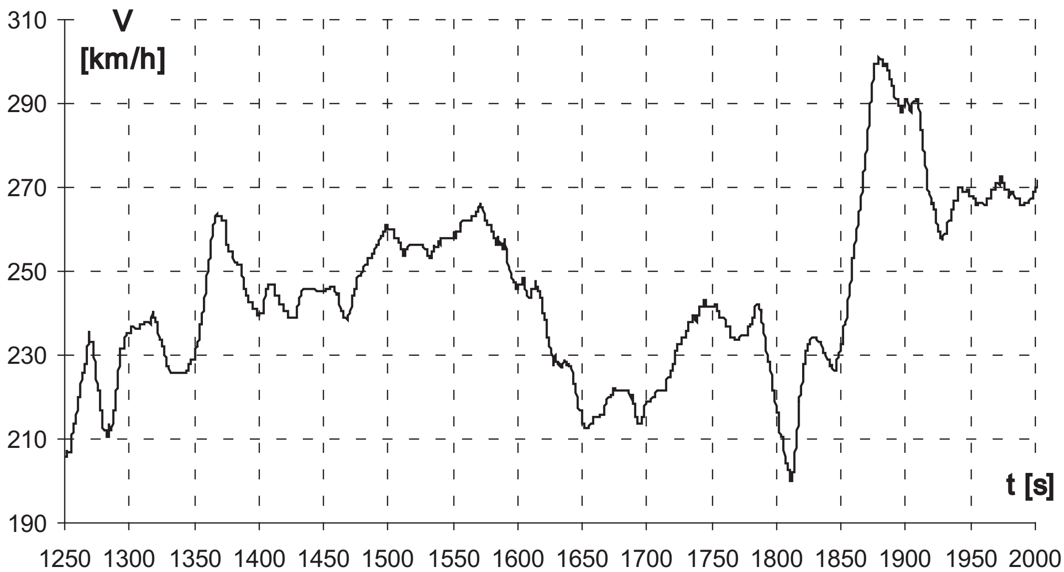

Fig. 15. Variations of the aircraft flight speed associated with engine restart in air

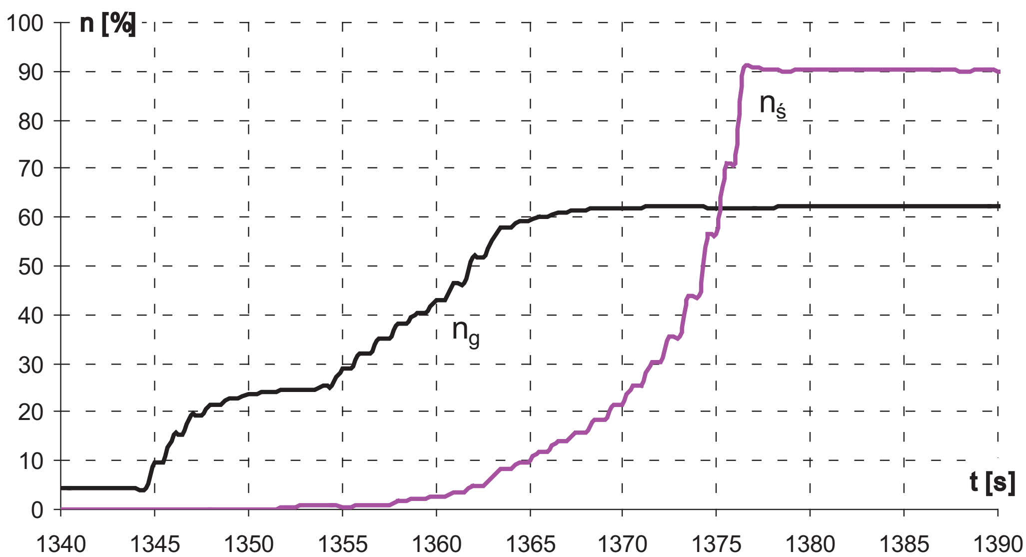

Fig. 16. Variations of the engine and airscrew rpm during the first restart

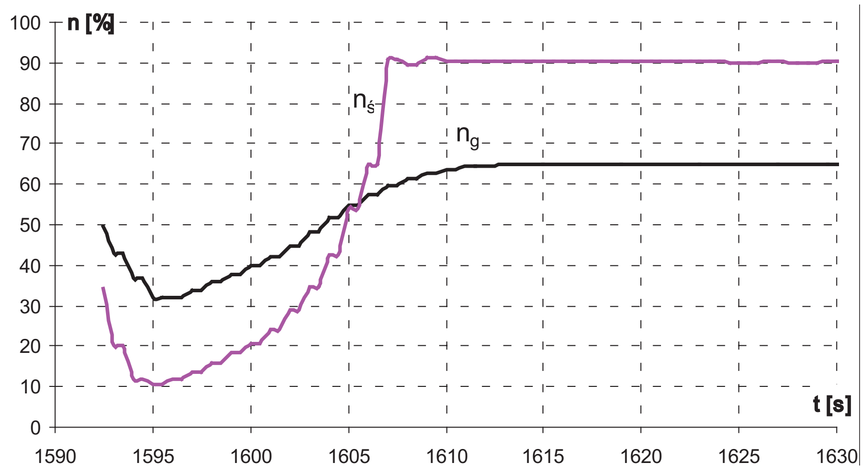

Fig. 17. Variations of the engine and airscrew rpm during the second restart

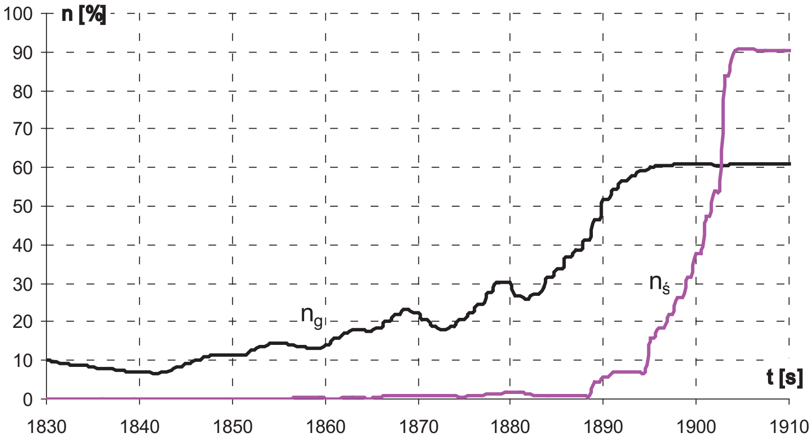

Fig. 18. Course of changes in engine speed and propeller during start of the third (emergency)

Graphs that depict how key parameters of the aircraft driving unit vary during subsequent restarts make it possible to find out which start-up procedure is the most efficient and runs in the smoothest manner.

The following graphs present the variations of the engine torque and serve as evidence that both regular and emergency restarts of the engine lead to substantial jumps of the measured parameters when the restart procedure is in progress. On the contrary, for the second restart (virtually "in flight") the torque jump is not existent, and a momentary drop of the engine torque is recorded instead – Fig. 21.

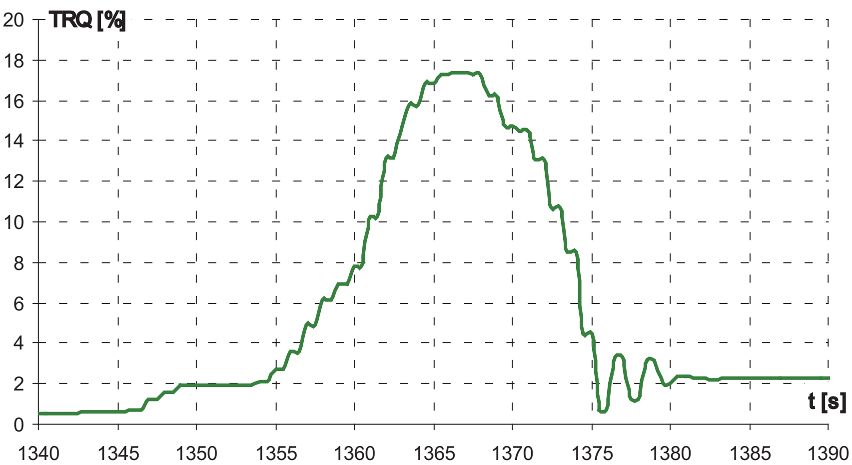

Fig. 19. Variations of the engine torque during the first restart

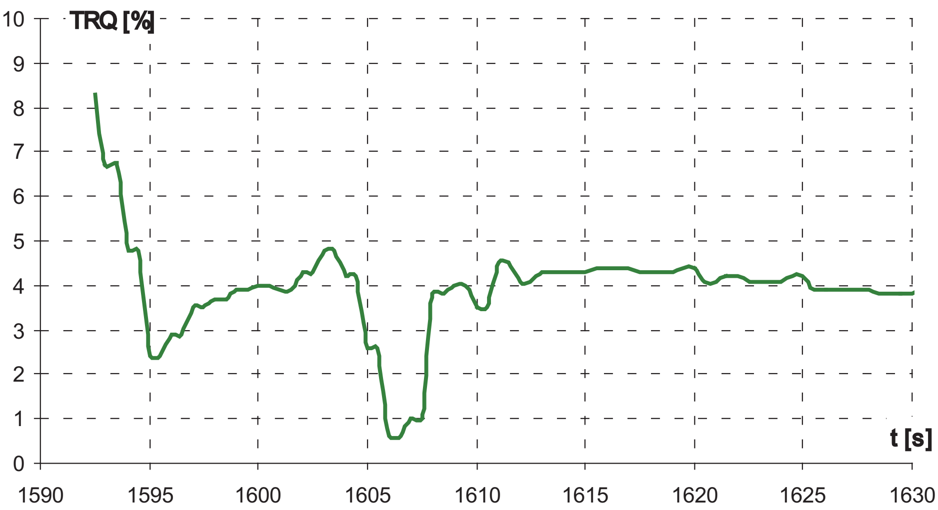

Fig. 20. Variations of the engine torque during the second restart

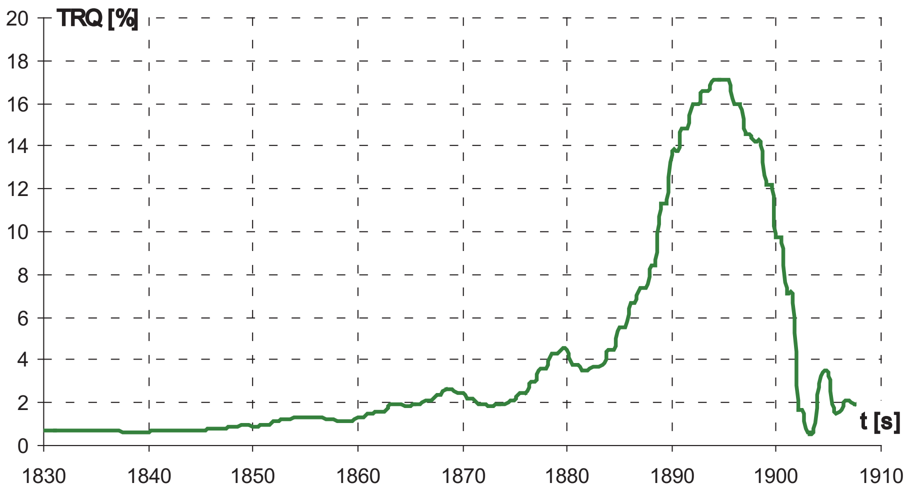

Fig. 21. Variations of the engine torque during the third restart

With regard to waveforms of power developed by the driving unit during subsequent restarts, the highest jump of the power is achieved for regular start-up (the first restart). It chiefly results from the torque that is developed when the airscrew is spun up and the rates of the rpm gain for the engine – Fig. 22.

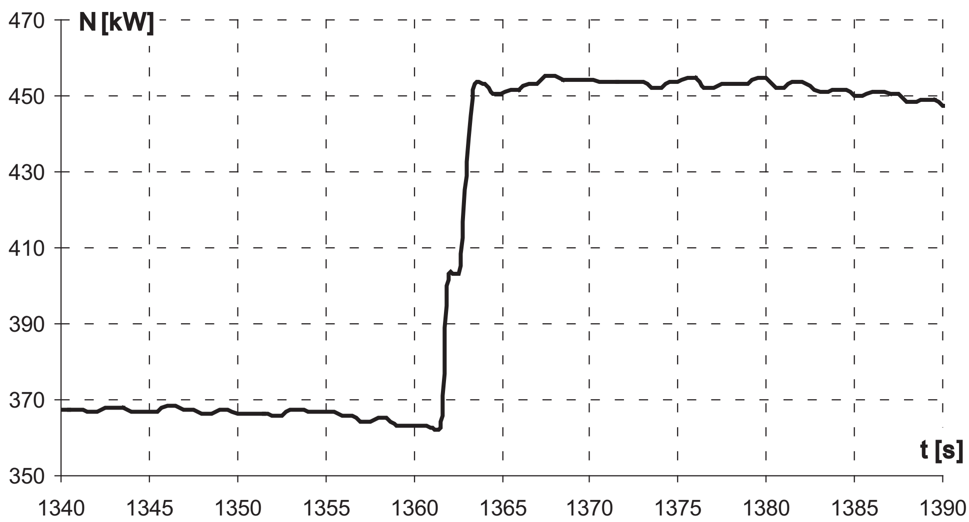

Fig. 22. Variations of the engine power during the first restart

The variations of the exhaust gas temperature in the space between the turbines, during engine restarts in air are virtually the most important parameter, determining the engine failure tolerance and overall lifetime. The analysis has demonstrated that the smoothest restart procedure in terms of the temperature reached by exhaust gas in between the turbines is the regular start-up procedure (the first restart) – Fig. 23.

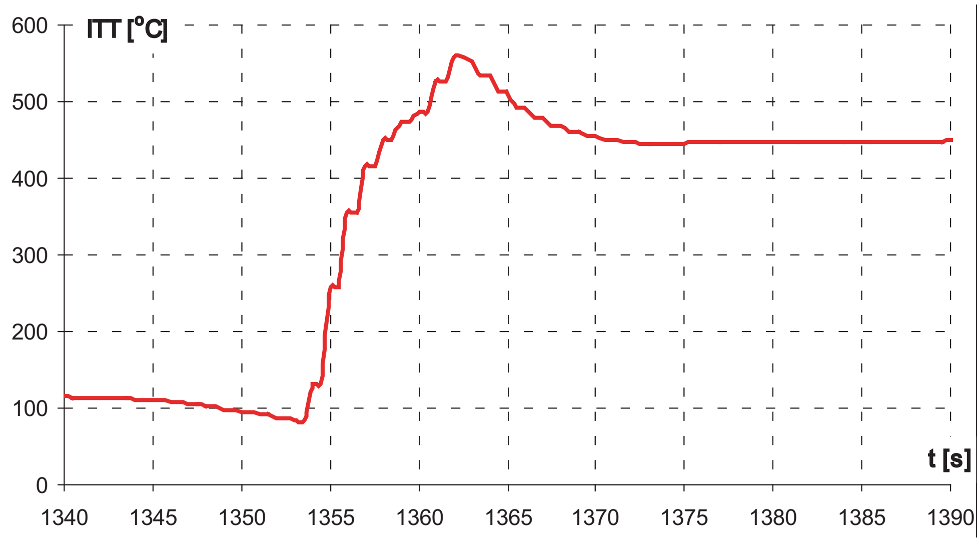

Fig. 23. Variations of exhaust gas temperature in between the turbines during the first restart

With regard to dynamics of gain for individual parameters, the scope of this paper is limited merely to the presentation of phase diagrams for gain of engine rpm. These diagrams present rates of the engine rpm growth, which is directly mapped onto efficiency of the start-up process -Fig. 24.

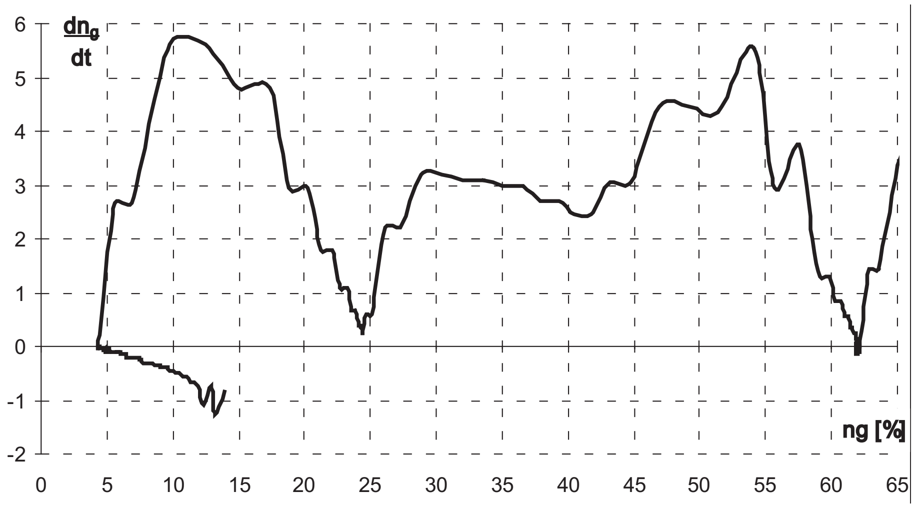

Fig. 24. Phase diagram for gain of the engine efficiency during the first restart

4. Conclusions

The investigations and analyses carried out for variations of key parameters that illustrate operation of aircraft engines and dynamic properties of these parameters have demonstrated that the start-up system installed on-board of the PZL-130TC-II "Orlik" aircraft is correct and perfectly performs its tasks.

Under nearly all circumstances, the system enables start-up of the aircraft engine, whilst dynamics for variations of individual parameters demonstrate no tendency to exceed the maximum permissible thresholds.

The only inconvenience of the system is the need to correctly move back the engine control lever (DSS) by the pilot to the range of rpm that corresponds to the low throttle mode at the specific flight altitude in order to actuate the microswitch that enables engine restart in air. From the standpoint of the flight safety, it is the operation that should be excluded under such stressful circumstances for the pilot as a spontaneous flameout of the engine during a flight. It is particularly dangerous at flights at low altitudes, which is a quite frequent component of trainings provided to young pilots.

References

[1] Boliński, B, Stelmaszczyk, Z., *Operation of turbine engines*, WKiŁ Publishing House, Warsaw 1981.

[2] Kowalski, M., *Phase mapping In diagnosing of the two – rotor turbojet engine*, Journal of Theoretical and Applied Mechanics, Vol. 50, No. 4, 2012.

[3] Kowalski, M., *An analysis of failure symptoms of the airscrew drive in PZL-130 TCI Orlik Aircraft*, VETOMAC VIII International Conference on Vibration Engineering and Technology of Machinery, pp. 127-140, Gdansk, Poland 2012.

[4] Kowalski, M., *Use of data from on-board date recorders for acceptance tests of avionic driving units,* Journal of KONES Powertrain and Transport, Vol. 20, No. 2, Warsaw 2013.

[5] Kowalski, M., *Issues of diagnostics for turbine avionic engines with use of data acquired by on-board recorders of flight parameters,* Scientific Journals of ITWL, No. 31, Warsaw 2013.

[6] Kowalski, M., Kozakiewicz, A., *Unstable operation of the turbine aircraft engine*, Journal of Theoretical and Applied Mechanics, Vol. 51, No. 3, pp. 719-727, 2013.

[7] http://www.pt6nation.com/en/articles/article/best-of-the-pt6-nation-the-legend-tells-its-story/.