APPLICATION OF THE PHASE REPRODUCTION METHOD TO THE ANALYSIS OF AN AVIONIC EVENT ON BOARD OF THE W-3 "SOKÓŁ" HELICOPTER

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Abstract

This paper presents a new approach to the study of events/cases of the use of so-called air mapping phase. The examinations were carried out by means of the selective method on the basis of data for basic operational parameters acquired from the both driving units of the W-3 "Sokół" helicopter. The analysis covered quality of information received from the S2-3a on-board recorder of flight parameters, in particular its resolution and recording frequency. Then it was possible to plot waveforms for variation of the recorded parameters associated with operation of the helicopter engines and its rotor. The waveforms were used to determine the most important fragments suitable for detailed analysis of variations exercised by basic parameters and to check them against the Operation Manual for flights of the W-3 helicopter. The selected operation parameters were used for phase imaging (development of phase portraits), which served as the basis to assess dynamic properties of the parameters variations. The final component of the study consisted in discussion of the obtained results with presentation of conclusions. It is infeasible to monitor technical condition of the package joint between the transmission shaft and the PZL-10W aircraft. It is necessary to install additional sensors and gauges intended to improve accuracy and frequency of parameter readouts. Only sufficient amount of information shall enable application of the phase imaging method to efficient monitoring of technical and emergency operating conditions of aircraft engines.

Keywords: *aircraft engine diagnostics, phase mapping of engine parameters*

1. Introduction

Analysis of sophisticated dynamic systems is one of the most important things that are necessary to design and examine automatic devices.

The choice of status coordinates is particularly convenient when these coordinates represent subsequent derivatives of the most important variable, e.g. the initial variable of the system.

Such coordinates are referred to as phase coordinates. In case of a system of the second rank there exist only two status coordinates (i.e. phase coordinates), whereas the space of states can be defined as a plane referred to as the phase plane.

Advantages of phase plane are chiefly pronounced when examination of equation systems or single non-linear differential equations is the point. The method is generally confined to equation systems of the second rank.

The method of phase plane usually describes a system as a whole. It means that it abstains from penetration inside the system structure and considers the system as an autonomous unity, i.e. without external excitations. However, it is not an obstacle to deal with the analyzed systems with consideration to some structural properties of them, e.g. open-loop or closed-loop systems as well as systems with external excitations.

Moreover, it is believed that the method of phase plane can be suitable for not only designing or analyzing various systems but it can also be applied as a valuable measuring method, suitable to identify various states of the system. It allows to measure and record physical parameters that correspond to phase coordinates of the system with unknown properties but the obtained empirical trajectories are useful for further analytic analyzes.

Mapping of the solution onto the plane with coordinates (x, $\frac{dx}{dt}$) makes it possible to draw up so called *phase trajectory*, whilst the set for the family of solutions (trajectories) for various initial conditions makes up so called *phase portrait* of the system. Each point of a phase plane corresponds to a specific status of the system. The phase portrait is the graphic method intended to depict dynamic properties attributable to objects of the first or second ranks, both linear and non-linear.

This analysis is devoted to the PZL-10W engine installed on board of the W-3 'Sokół' helicopter with its number 360903, or, more specifically, to the basic operation parameters of the engine recorded by the S2-3a recorder of flight parameters (on-board log). It is the engine that exercised spontaneous shutdown during a helicopter flight. The engine stall was the reason for emergency landing and premature termination of the task.

The analysis below was meant to the following purposes:

- determination of basic static and dynamic characteristic parameters for the driving unit,
- finding possible deviations in waveforms of recorded operation parameters for engines and the helicopter rotor and to check them against the effective technical specifications,
- finding out whether it is possible to monitor technical condition of the package joint between the transmission shaft and the PZL-10W aircraft engine based on the analysis of flight parameters already acquired with use of the on-board recorder.

The evaluation and analysis involved the following measuring signals:

- rotation speed (rpm) N_{tnl} and N_{tnp} of turbine compressors respectively for the left and right engines, expressed in [%] of the rated value;
- rotation speed (rpm) N_{pg} of gas turbines and the helicopter rotor, expressed in [%] of the rated value;
- torques M_l and M_p generated respectively by the left and right engines, expressed in [%] of the rated value;
- temperatures T_{4l} and T_{4p} of exhaust gas from the left and right engines, expressed in [^{o}C].

The examinations were carried out by means of the selective method on the basis of data for basic operational parameters acquired from the both driving units of the W-3 'Sokół' helicopter.

At first, the engineering and operational documentation for the driving units of the helicopter was studied with particular attention to constrains imposed by the manufacturers of the engines and the helicopter itself.

The analysis covered quality of information received from the S2-3a on-board recorder of flight parameters, in particular its resolution and recording frequency.

Then it was possible to plot waveforms for variation of the recorded parameters associated with operation of the helicopter engines and its rotor. The waveforms were used to determine the most important fragments suitable for detailed analysis of variations exercised by basic parameters and to check them against the Operation Manual for flights of the W-3 helicopter.

The selected operation parameters were used for phase imaging (development of phase portraits), which served as the basis to assess dynamic properties of the parameters variations.

The final component of the study consisted in discussion of the obtained results with presentation of conclusions.

2. Examination results

Examination results obtained from the completed analysis of information acquired from the S2-3a on-board recorder of flight parameters are presented in the further parts of this study.

The analysis of the engineering documentation revealed that constraints imposed by the manufacturer of the helicopter engines are pretty clearly defined and can be construed with no doubts. Moreover, they have been presented in a very convenient graphic form, just as they are seen by a pilot sitting in the helicopter cockpit.

However, there are substantial doubts with regard to quality of information provided from the S2-3a on-board recorder of flight parameters. It was found out that the inconsistency results from insufficient resolution of rotation speed (rpm) measured for the turbine compressor – for the range of low rpm values, the deviations may be as high as 10% of the actual value. It is the reason that readouts for the rpm of turbine compressors are little trustworthy and need a very carefully approach during the analysis of recorded results. Resolution of all the remaining parameters, i.e. temperature T_4 of exhaust gases and torques M_g is absolutely good enough.

Doubts are also associated with recording frequency for individual parameters. The frequency, after scale mapping with use of Thetys software, is only a record per second. Such a status quo disables detailed analysis of waveforms for individual operational parameters of the helicopter driving unit, in particular its short-term departures and dynamic characteristics.

The analysis started with plotting of waveforms for variations of the flight altitude and speed, which made it possible to determine nature of the helicopter mission.

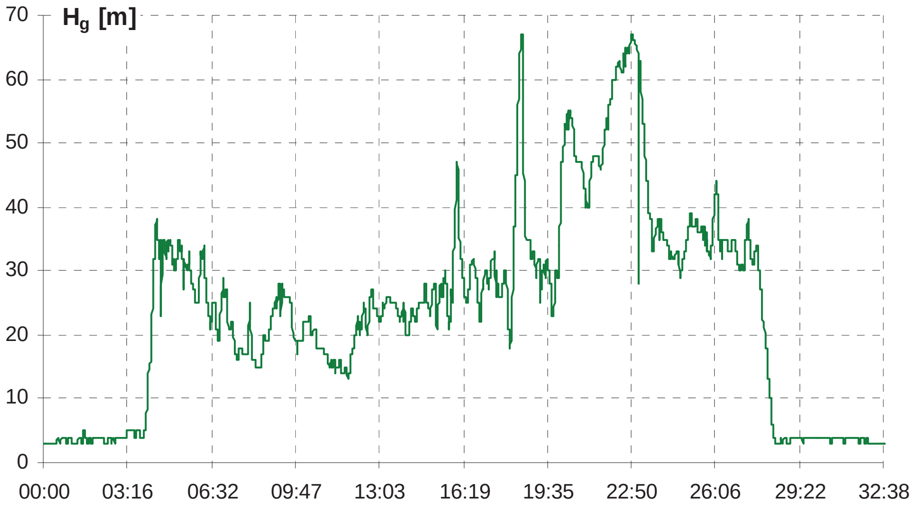

Fig. 1. Variations of the geometrical altitude for the flight

It was found out that the mission was carried out at relatively low altitude (from about 20 to 60 m) and altitude variations were of quite dynamic nature.

The waveform for variations of the helicopter speed looks in a different way as the speed until the moment of the left engine shutdown ranged from 150 to 165 km/h. Just after stall of the left engine the speed rapidly dropped by about 20 km/h.

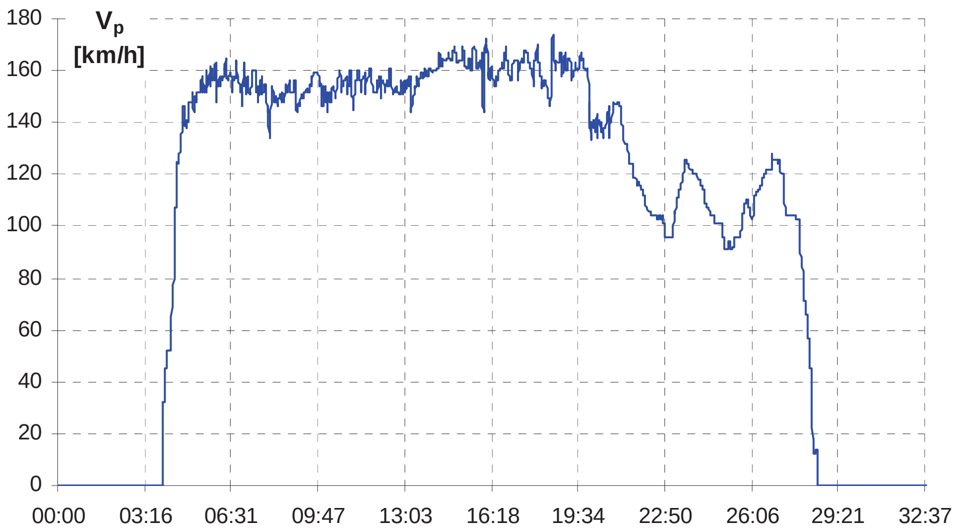

Fig. 2. Variations of the helicopter speed

The waveforms for variations of rotation speed values for turbine compressors of the both engines clearly show the moment when the left engine went off - Fig.3.

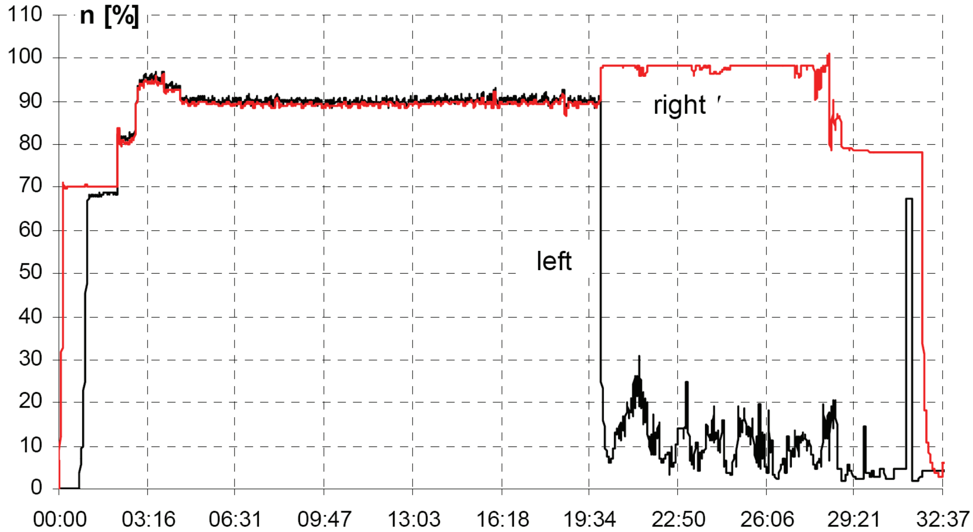

Fig. 3. Variations of the rpm values for turbine compressors of PZL-10W engines during the flight in question

Fig.3 shows that the right engine was started up as the first one. Operation of the both engines arouses no reservations until the moment of the spontaneous shutdown of the left engine. The engine stall took place at the 19th minute and 56th second from the beginning of the first (right) engine start-up. Rotation speed of the engine suddenly dropped to about 8% of the initial value and then oscillated about 10%. In the meantime, the automatic control of the right engine reacted properly and the right engine was switched over to the emergency operation mode.

Zoom-in for that part of the mission (Fig.4) made it possible to state that the remaining flight was performed with the rotation speed of the right turbine compressor ranging about 98% of the rated value. It is the limit value that differentiates the 30 OEI and 2.5 OEI ranges of power. However, due to the detected inaccuracies in rpm calibration of turbine compressor it is hard to say about possible moments of the threshold exceeding.

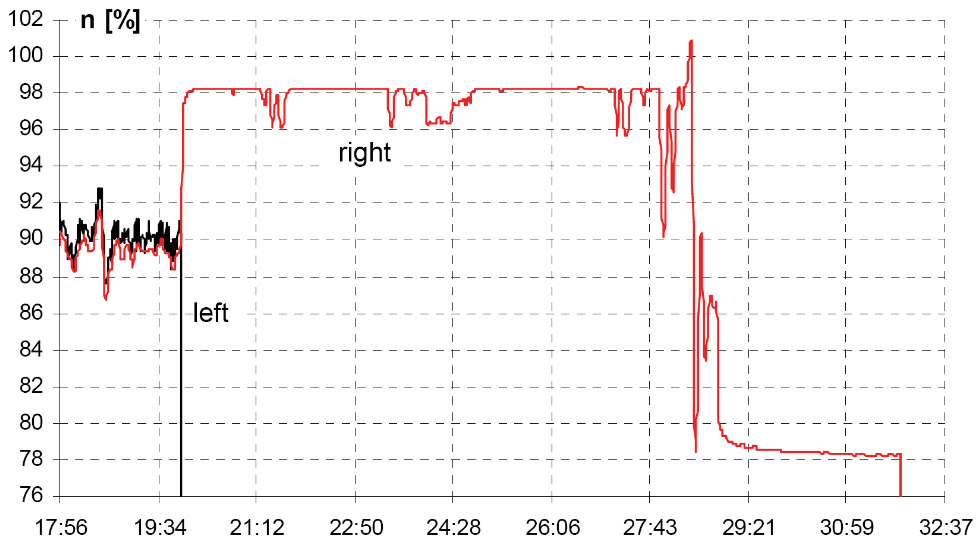

Fig. 4. Variations of the rpm values for turbine compressors of PZL-10W engines during the flight in question – the zoomed fragment of the waveform after shutdown of the left engine

The dynamic nature of the left engine shutdown can be inferred from the imaging obtained as the result from the analysis of the phase portrait for rpm variations of the turbine compressor for the left engine. The initial character of dynamic rpm variations is rather mild, even slightly less turbulent than the similar variations of the left engine – Fig.6. What's more, the left engine much faster reached the required rpm range (about 90%) than the right one. Due to the spontaneous shutdown of the left engine, its rpm drop from the range of about 90% was pretty dynamic, in particular during the initial phase of the engine stall.

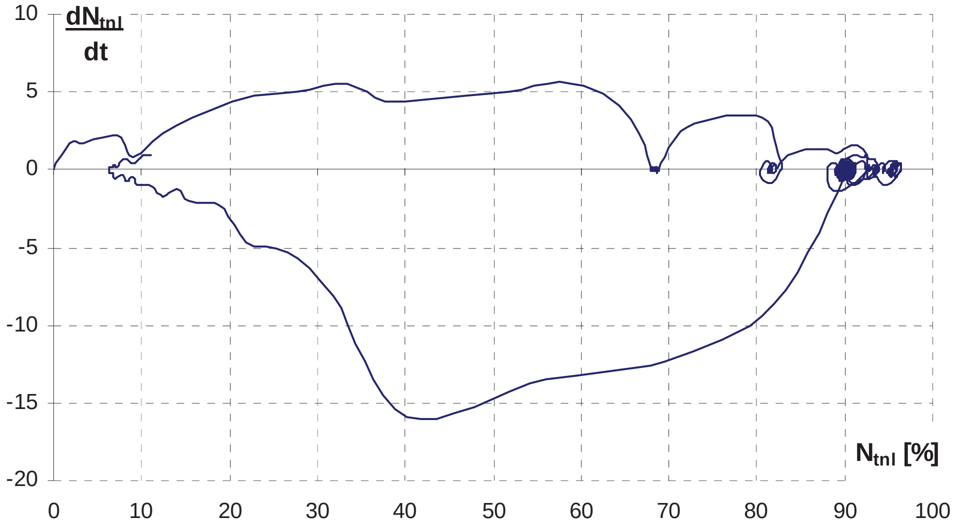

Fig. 5. Phase portrait for rpm increments of the turbine compressor for the left engine during the flight in question

One can also see that the nature of dynamic rpm variations during the final phase of the engine runout (i.e. for the range below 40%) after the left engine spontaneous shutdown and after manual shutdown of the right engine is quite similar. The slight discrepancies that can be seen of the graph results from different rpm range at the moment when the engine shutdown took place.

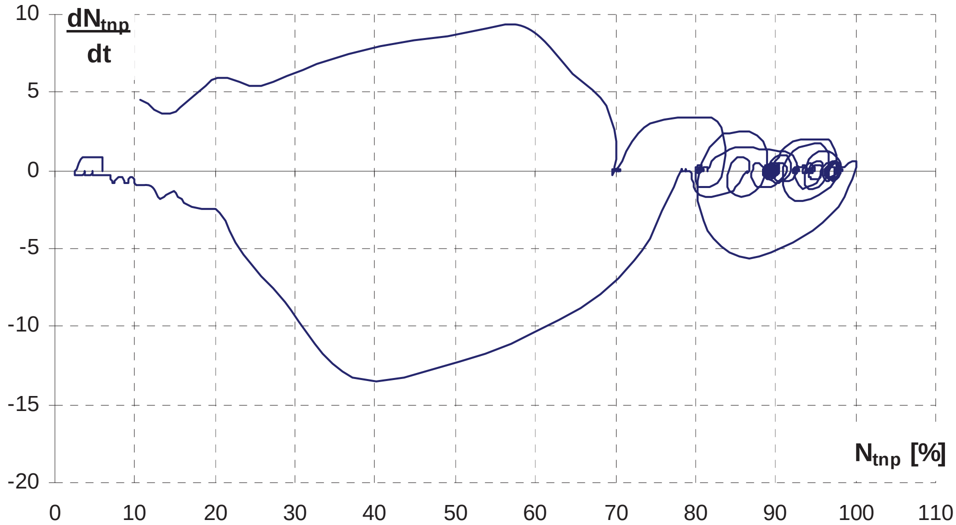

Fig. 6. Phase portrait for rpm increments of the turbine compressor for the right engine during the flight in question

On the contrary, rpm variations of driving turbines as well as the helicopter rotor (Fig.7) clearly show that the mission was practically carried out with the rotation speed of the turbine compressor ranging about 105%. Only after going the left engine off pretty stochastic variations of the rpm are visible, with a temporary increase, right before the end of the flight, to the value of about 115%. Operation Manual for the helicopter flights allows momentary increase of the rpm value up to about 112%. However, due to the errors in rpm calibration of turbine compressor and the recording frequency it is impossible to unambiguously judge that the threshold limits were exceeded at specific moments of time.

Fig. 7. Waveform for rpm variations of the helicopter rotor and the driving turbines for the both engines

When to analyze variations in temperature of exhaust gas that is discharged from engines during the flight in question (Fig.8), one has to state that no significant exceeding of permissible thresholds took place and waveforms for the temperature values are typical for that types of flights. The only one worth mentioning moment, when the permissible threshold was exceeded during the analyzed flight, took place not in air, but during the engine start-up on the ground. Such exceeding can be the result of the engine maladjustment over the considered rpm range. It is the fragment that needs a separate analysis.

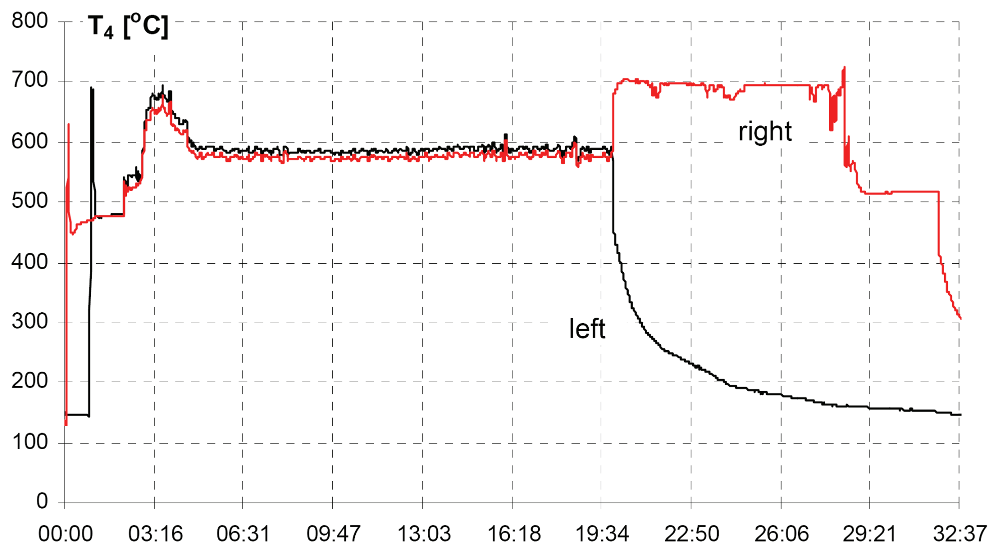

Fig. 8. Temperature variations of exhaust gases during the flight in question

On the other hand, the zoomed fragment of the foregoing waveform (to show behaviour of the exhaust gas temperature just before and after spontaneous shutdown of the left engine - (Fig.9) shows that right after the moment when the left engine went off the right engine was switched over to the emergency operation mode, which was associated with increase of the exhaust gas temperature up to about 700ºC.

When to analyze the already mentioned temporary increase of the exhaust gas temperature above the stated T_{4L} threshold that took place during the engine startup one can see that such exceeding occurred only for the left engine. The zoomed fragment of the waveform for temperature of exhaust gases vs. rpm of the turbine compressor during the engine startup indicates the moment when the exceeding took place - Fig.10. In addition, a quite abrupt drop of the rpm waveform is visible that makes up about 42-46% of the rated rotation speed. It serves as a proof that automatic protection for the engine was tripped with the attempt to decrease the temperature. Such an exceeding could not be detected during start-up of the right engine – Fig.11.

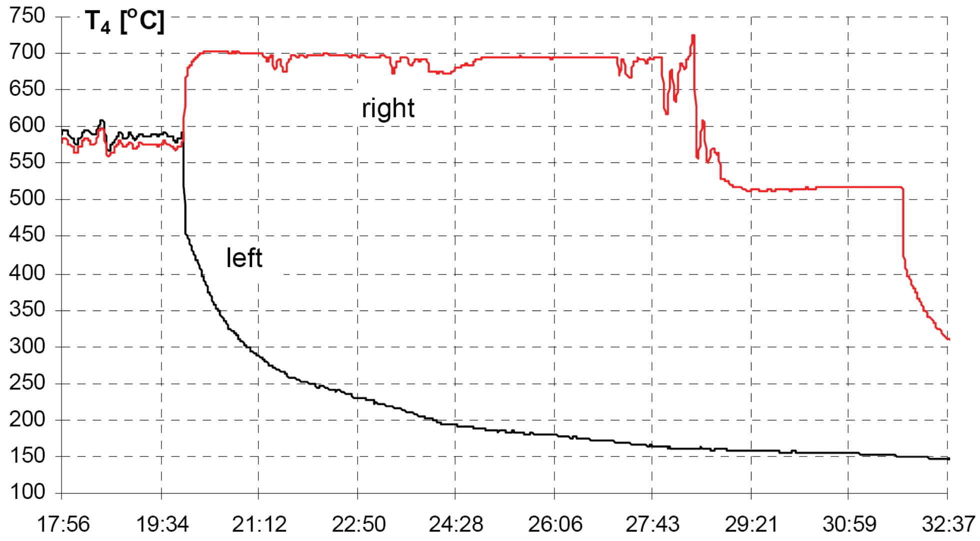

Fig. 9. Temperature variations of exhaust gases during the flight in question – the zoomed fragment of the waveform after shutdown of the left engine

Examination of dynamic behaviour exhibited by the temperature of exhaust gases for the both engines during their start-up made it possible to reveal slightly higher increments for the left engine (which caused the already mentioned temperature growth). It suggests maladjustment of the temperature parameter, which should be corrected for that engine - Fig.12 and Fig.13.

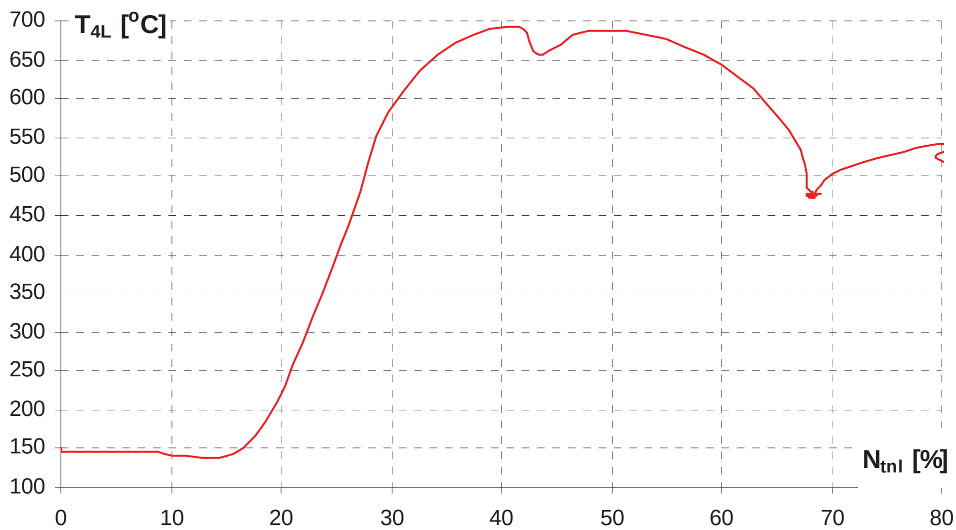

Fig. 10. Variations in temperature of exhaust gases during the left engine start-up vs. rpm of the turbine compressor of the left engine

Variations of waveforms for torque of the both engines during the analyzed flight are rather typical and disclose no exceeding of the permissible thresholds – Fig.14 and Fig.15.

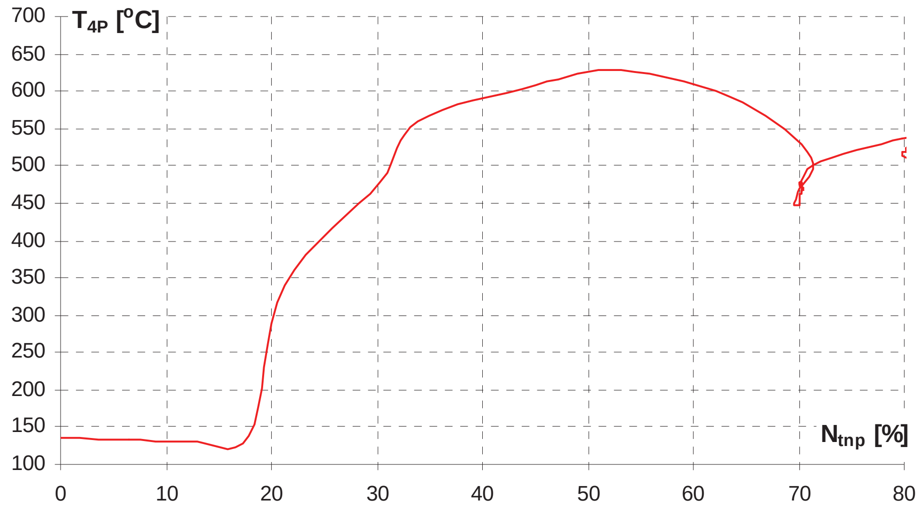

Fig. 11. Variations in temperature of exhaust gases during the left engine start-up vs. rpm of the turbine compressor of the right engine

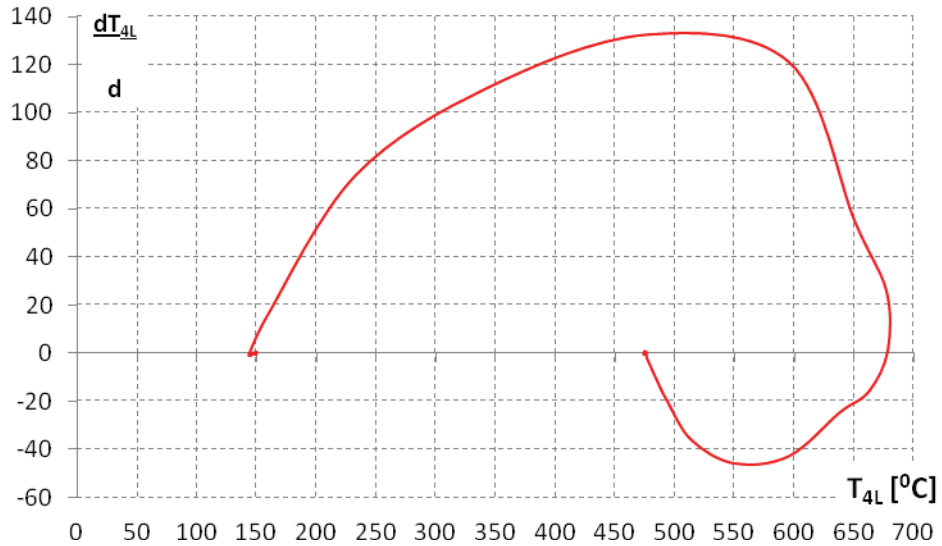

Fig. 12. Phase portrait for temperature increments of the exhaust gas during the left engine start-up

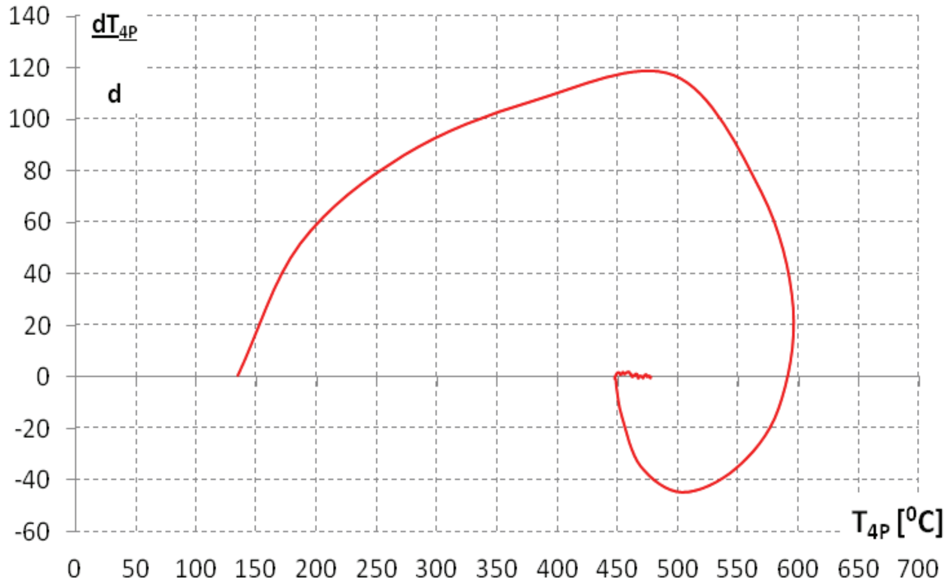

Fig. 13. Phase portrait for temperature increments of the exhaust gas during the right engine start-up

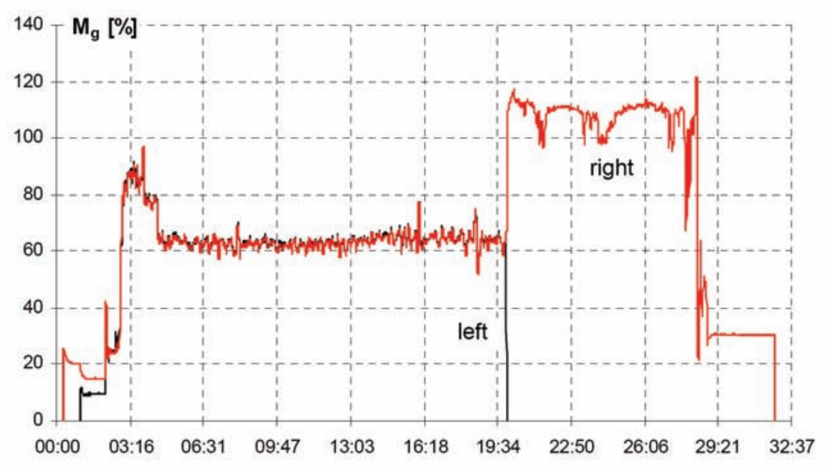

Fig. 14. Torque variations of the helicopter engines during the flight in question.

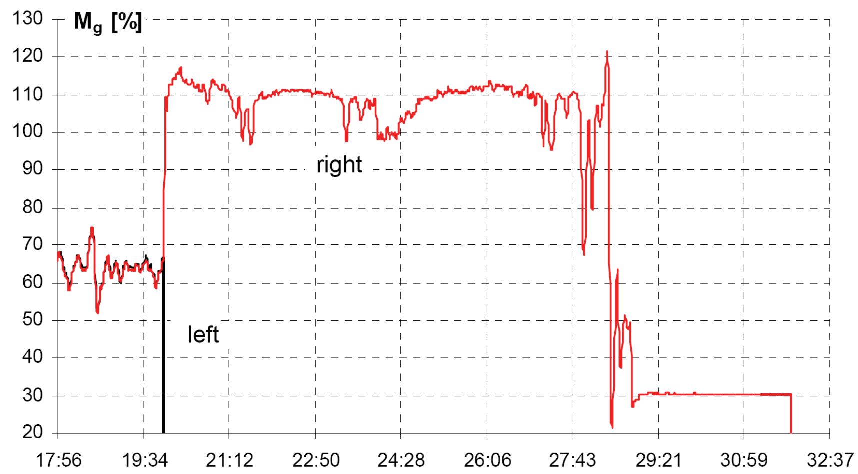

Fig. 15. Torque variations of the helicopter engines during the flight in question – the zoomed fragment of the waveform after shutdown of the left engine

The important relationship that conveys information about collaboration between rotating modules of the PZL-10W engine (i.e. the turbine compressor and the driving turbine) is the graph that presents variations of the turbine compressor rotation speed as a function of the corresponding rpm for the slow rotating turbine (the helicopter rotor). Such interdependence is shown in Fig.16. For the right engine, the waveform is rather typical and causes no reservations. On the other hand, waveforms for the left engine show very clearly when the spontaneous shutdown of the engine took place and provide the proof that rotation speed of the driving turbine oscillated between about 100% to 105% of the rated value.

3. Conclusions

- The completed analysis of operation parameters attributable to driving units of the W-3
- "Sokół" helicopter on the basis of information acquired from the on-board recorder revealed no substantial deviations from the Operation Manual. The only one factor that is in conflict with the Manual is the momentary growth of the exhaust gas temperature during start-up of the left engine, when the temperature reached 692ºC (according to the Operation Manual it must be always below 680ºC).
- Other insignificant discrepancies – the point is about information about rpm of turbine compressors and driving turbines – must not be considered as reliable due to revealed errors in calibration of these parameters.

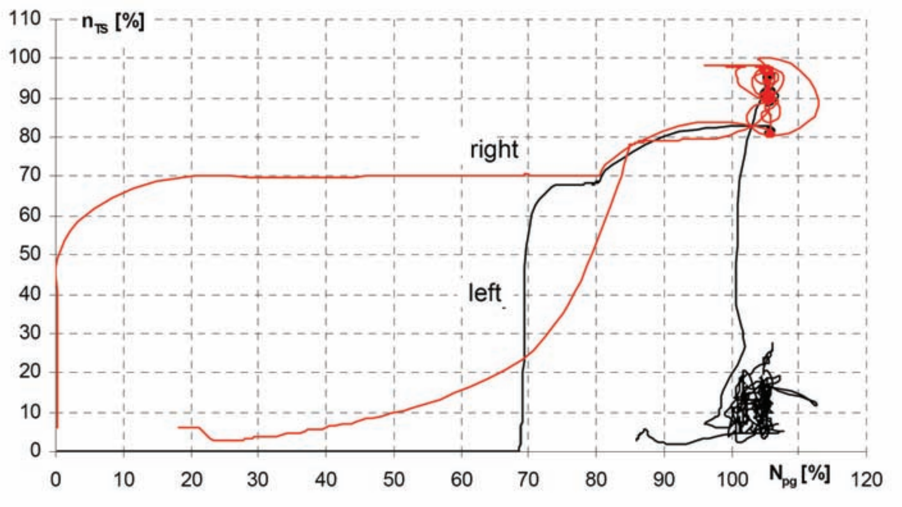

Fig. 16. Collaboration between turbine compressors and driving turbines for the both PZL-10W engines

- To make sure that no circumstances occurred that could suggest incorrect operation of the left engine before the flight in question it is advisable to analyze variations of basic operational parameters on the basis of data collected from several flights preceding the one when the engine went off.

Moreover, one has to conclude that it is infeasible to monitor technical condition of the package joint between the transmission shaft and the PZL-10W aircraft engine based on the analysis of flight parameters already acquired with use of the on-board recorder due to the limited range of recorded parameters and too low sampling frequency. It is advisable to install additional sensors and gauges intended to improve accuracy and frequency of parameter readouts. Only sufficient amount of information shall enable application of the phase imaging method to efficient monitoring of technical and emergency operating conditions of aircraft engines.

References

[1] Czempik, A., *Praktyczne wprowadzenie do opisu, analizy i symulacji dynamiki obiektów.* (manuscript). Accessible on the Internet: www.anna.czemplik.staff.iiar.pwr.wroc.pl/Studenci/Modele Ukladow/ModeleCw.pdf (*Practical introduction to description, analysis and simulation of dynamic behaviour of objects (manuscript).* Available from the website: www.anna.czemplik.staff.iiar.pwr.wroc.pl/Studenci/ModeleUkladow/ModeleCw.pdf

[2] Kowalski, M., Szczepanik R., Witoś M., Podskarbi S., *Condition – based maintenance of turbojet engines based on compressor blade vibration measuring method*. Pisa – Italy, 23.09-01.10.2000.

[3] Kowalski, M., Odwzorowanie fazowe prędkości obrotowej w procesie eksploatacji turbinowych silników odrzutowych. Logistyka nr 6/2009. (*Phase imaging of rotation speed during the operation of turbojet engines. Logistics, No. 6/2009*).

[4] Kowalski, M., Szczepanik, R., *Analiza pracy silnika lotniczego z pełnozakresowym, mikroprocesorowym układem typu FADEC i odwzorowanie fazowe.* Rozdział w publikacji książkowej ITWL pt.: Problemy badań i eksploatacji techniki lotniczej tom 7 pod redakcją J. Lewitowicza, S. Michalaka i R. Szczepanika. Warszawa 2010. (*Analysis of an avionic engine operation with use of a full-range circuit of FADEC type and application of the phase imaging method.* One chapter in the textbook published by Air Force Institute of Technology (ITWL) and titled *Issues associated with investigation and maintenance of avionic technical means,* Volume 7, Edited by Lewitowicz J., Michalak. S. and Szczepanik R., Warsaw, 2010.