ANALYSIS OF THE ACTIVE MANAGEMENT OF EXISTING AIR CLEARANCES TURBOCOMPRESSOR ENGINES

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The purpose of this article is active clearance control analysis (ACC) between rotor and casing of turbine in gas turbine engines (GT). The article deals with clearance creation in GT. Also, there are analyzed ACC requirements and problem of tip clearance sensing in turbine. Also, there are described clearance control general principles, focused on the most widely used active thermal system clearance control (ATS). Also, there are described clearance control developments.
K e y w o r d s: system, active clearance control, gas turbine engine, turbine efficiency

1 INTRODUCTION

Aviation GT operate with various gas temperatures. These temperatures change with thrust setting and outside air temperature (OAT). Considering various thermal expansion characteristics of turbine rotor and casing, tip clearances change during GT operation. Larger clearances decrease turbine efficiency, resulting in larger specific fuel consumption (SFC) and larger gas temperature. Lower turbine efficiency decreases total GT efficiency. Minimal tip clearance may cause blades rubbing into turbine casing.

2 ANALYSIS OF GAS TURBINE CLEARANCES CREATION

Turbine and compressor are subject to high mechanical load and thermal load (particularly turbine). Mechanical load effects on rotor through centrifugal force. Thermal load effects particularly on turbine rotor, but also on GT casing through thermal expansion. Both of these factors affect negatively GT operation during flight, because it increase and decrease radial and axial clearances. It is necessary to maintain minimal clearances, because of hydraulic losses minimize in GT.

Clearances between rotor and casing are affected by loads that may be divided into two categories:

- engine load (forces and moments caused by GT operation),
- aerial load (forces and moments caused by airplane flight).

There are presented engine and aerial loads types that affect radial and axial clearances:
Engine load is divided:

- centrifugal load,
- thermal load,
- thrust load.

Aerial load is divided:

- inertial load,
- aerodynamically load,
- gyroscopically load.

Engine load caused symmetrical and asymmetrical tip clearance changes (fig. 1 and 2). Aerial load caused asymmetrical tip clearance changes only.

Next will be described particularly tip clearance, by reason of its creation character.

2.1 Symmetrical changes of tip clearance

Symmetrical changes of tip clearance are caused by uniform engine load that effects on casing and rotor, therefore creates uniform radial displacement (fig. 1). The largest tip clearance changes are consequence of centrifugal and thermal loads.

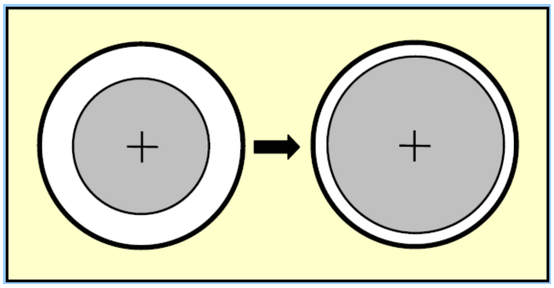

Fig. 1 Symmetrical changes of tip clearance

Centrifugal load causes symmetrical changes of tip clearance. Rotor expands and contracts during acceleration and deceleration. Thermal load causes symmetrical and asymmetrical changes of tip clearance. Symmetrical changes are consequence of rotor and casing thermal expansion. Asymmetrical changes are caused by non-uniform cooling of these GT parts. There are high dimensional displacements of these parts in GT with large turbine casing diameters (>915 mm). It is caused by high temperatures (>1371 ºC) and high rotor speeds (>10 000 rpm).

2.2 Asymmetrical changes of tip clearance

Asymmetrical changes of tip clearance are caused by non-uniform engine load (thermal, thrust) and aerial load (inertial, aerodynamically).
Asymmetrical changes of tip clearance rise generally on GT casing. Non-uniform load causes non-uniform casing deformation (fig. 2).

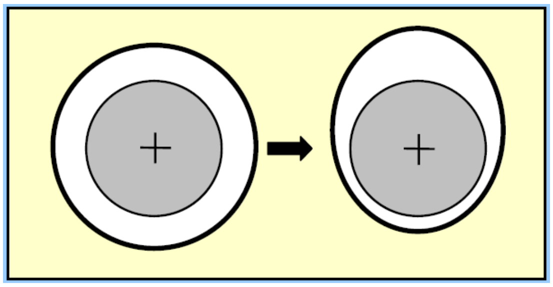

Fig. 2 Asymmetrical changes of tip clearance

2.2.1 Aerodynamically load

Considering that airplane GT are mounted above their axis (fig. 3a), aerodynamically load reactions create moment. This moment causes casing bending in view of rotor. Aerodynamically load of engine inlet creates shearing forces and bending moments. These forces and moments effect on fan casing and it transmit into main solid GT structure (fig. 3b). Aerodynamically load is biggest after take-off rotation movement. That time, angle of inlet air is biggest. Generally, this load makes itself felt during take-off, so that it reduces tip clearance on sixth hour of GT.

2.2.2 Thrust load

In addition, thrust load contributes for casing distortion during take-off, so that it creates bending moment effecting from below GT. This moment increases tip clearance in upper part of GT and decreases tip clearance in bottom part of GT (fig. 3c). This factor is known as „backbone bending“ of GT. Opposite situation happens at thrust reversing. Then bending moment effects from above, so that it decreases tip clearance in upper part of GT and increases tip clearance in bottom part of GT.

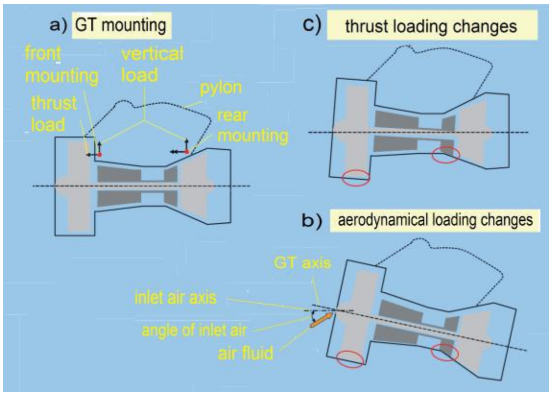

Fig. 3 a) GT mounting; b) Tip clearance change caused by aerodynamically load; c) Tip clearance change caused by thrust load

2.2.3 Inertial load

Inertial maneuver load, combined with aerodynamically load and high thrust load, also contributes for reduction of tip clearance.

Bearing clearances do not have larger impact on tip clearance changes. Manufacturing clearances contribute a little for tip clearance changes. Both of these clearances add to tip clearance less than 0,25 mm.

Large axial displacement rises in high pressure turbine (HPT) by rotor thermal load effect. This displacement does not contribute for tip clearance changes of HPT. Increase of tip clearance by axial displacement effect is much greater in markedly conic parts of GT, such as low pressure turbine (LPT) [1, 2].

3 ACTIVE CLEARANCE CONTROL SYSTEM REQUIREMENTS

By reason of privation prevention, it is necessary to ensure thermal expansion control of turbine casing. It is achieved by compressor discharge pressure air system. This system ensures variable cooling effect in a very thermally stressed turbine parts. This system is known as “active clearance control” (ACC). Tip clearance change of HPT during flight phases is shown at fig. 4. Solid line shows tip clearance with ACC and dashed line shows tip clearance without ACC.

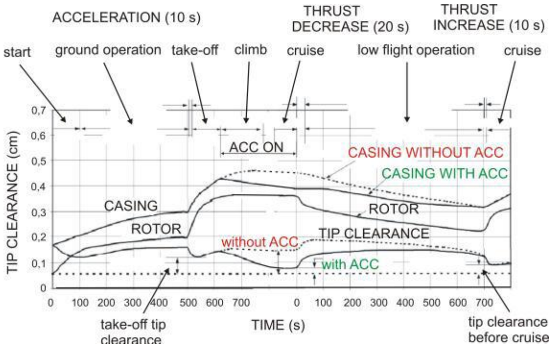

Fig. 4 Tip clearance change of HPT during flight phases

However a variety of current ACC systems have been designed only for HPT and LPT, some GT used ACC system of high pressure compressor (HPC) too.

Each clearance control type (for commercial or military GT), has to meet certain requirements. There are particularly requirements for operation conditions, operational capability (response rate, actuation and sensing accuracy and other), reliability, economy, manufacturability, maintenance, ecology and other.

3.1 Response rate requirements

There are large clearance changes during GT flight operation. High requirements must be set on actuating mechanisms of ACC system. Actuating mechanisms must be able to ensure tip clearance change at a rate of 0,025 $cm.s^{-1}$. Generally, thermal ACC systems maintain tip clearance ranging from 0,038 to 0,051 cm during cruise. Further, tip clearance is not decreased. It is for retention of safety reserve in case, that actuating mechanisms have longer response rate. This longer response rate rises due to thrust transients or cruise maneuvers. There are used ACC systems with fast response rate of actuating mechanisms on the present. These actuating mechanisms permit faster and more effective determination of HPT tip clearance.

3.2 Actuating accuracy requirements

There is very important actuating accuracy for airplane GT. Any ACC system must be designed thoroughly. Average pressure of two stage HPT cross section may be approximately 0,827 MPa. The pressure effecting on inner casing diameter 76 cm with thickness 5 cm is approximately 1,655 MPa. For casing produced from 16 segments (segments length is approximately 15 cm), any segment will be loaded of 6,4 kN force. With retention of required actuating accuracy (e. g. $\leq$0,013 cm), it must be used special structure designs.

3.3 Requirements for temperature and pressure of cooling air

Compressor discharge pressure air (CDP) has temperature from 649 to 704°C at HPT casing. HPT cooling is required for proper HPT casing operating, because stator vanes are exposed to temperatures approximately 1371ºC and more.

HPT casing cooling is shown on fig. 5.

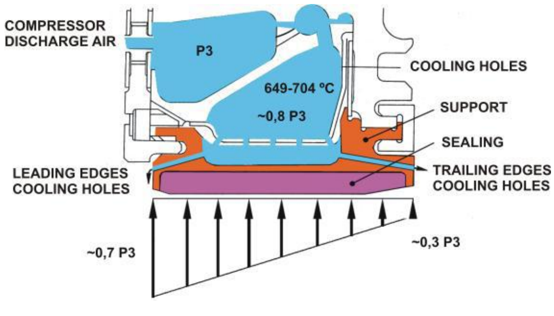

Fig. 5 Axial pressure layout in HPT casing

Pressure of HPT cooling air of large GT is approximately from 60 to 80% of CDP. For tip clearance area, this pressure changes from leading edge to trailing edge and reaches approximately from 70 to 30% of CDP. For proper fluid retention of turbine, cooling air on vanes leading edges must be larger as on vanes trailing edges. Radial pressure gradient creates loading effecting into center of rotor shaft axis. ACC system must be able to overcome this loading and resulting force moment that is generated by non-uniform layout of pressure in axial direction.

3.4 Material requirements

Alloys of various materials submitted large improvement, particularly in the field of material properties and life cycle. Even though these materials do not show properties, that could be permit usage inside the HPT without advanced cooling systems. High-temperature metal actuation based on thermal expansion, ensures very reliable, accurate and predicting system solution, but with slow response rate. Response rate time may be reduced with using special materials with various shape modifications. For all that may not be disrupted total structural integrity of system.

3.5 Safety requirements

Any system affecting GT operation must be designed as "fail-safe". Concerning ACC system, as it is not maintained adequate tip clearance during GT operation, so it rises a risk of GT parts damage. It may happen GT break down during flight, as worst-case. Therefore any system has to show these properties that eliminate emergency conditions.

ACC system "fail-safe" arrangements are these:

- redundancy (back-up) of system parts,
- tip clearance control in advance,
- GT-health (vibrations) monitoring.

3.6 Economic requirements

Unkept tip clearance can end in increased SFC and decreased GT service life. There is very important from structure aspect, that it would not be excess exhaust gas temperature (EGT – T_{4c}) during GT operation. EGT increase is main cause of GT shutdown. Federal Aviation Authority (FAA) certifies any airplane GT with determination of „EGT limit“. When GT reaches its "EGT limit", has to take expensive obligatory repair. These repair costs can reach 1 million dollars by large GT.

Wiseman approved, that with increase of HPT tip clearance of 0,025 mm, SFC increases approximately of 0,1% and EGT increases of 1ºC. That means, decrease of HPT tip clearance of 0,25 mm, results in a SFC decrease approximately of 1% and EGT decrease of 10ºC. Improvement of these parameters (SFC and EGT) should be lead to massive yearly costs savings on fuel and GT maintenance. Fig. 6 shows total fuel consumption (TFC) of national U. S. carriers finally 25 years. It shows assumption of average fuel consumption on next 23 years. Also, it shows assumption of cost savings, with fuel consumption decrease of 1%. Average fuel cost is under consideration from year 2001. Per year 2002 were reached cost savings 160 million dollars, by SFC decrease of 1%. It is needed to write, that since 1976, improvement of GT production technology decreased fuel consumption upwards of 50%.

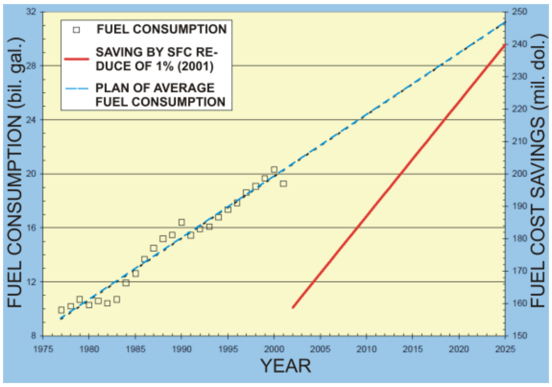

Fig. 6 History and schedule of fuel consumption and costs saving at reduction of SFC by 1%

New GT engines have determinate service life, i. e. number of life cycles (from 3000 to 10 000 life cycles – flight hours) by producer. EGT increase affects negatively turbine service life of GT. New GT engines or GT after general repair, are released into operation with minimal clearance. This clearance increases with time following cut of special layer. Author Kawecki published a publication, where he described advantages of clearance seal for GT with small and large bypass ratio. He discovered contribution in life cycle costs (LCC) for GT with various types of clearance control systems. Kawecki approved, that HPT clearance decrease results in quadruple LCC decrease of HPT and low pressure turbine (LPT) and LCC double decrease of high pressure compressor (HPC). Also, he discovered that contribution for civil airplanes is twice the size as for military airplanes.

3.7 Ecologic requirements

Decrease of fuel consumption results in decrease of total emissions of aerial GT engine. American „Rocky Mountain Institute“ calculated that Americans have flown 764 millions of flights per annum. Fuel consumed by civil airplanes doubled per last three decades. Increased fuel consumption signifies 13% of total emissions of carbon dioxide (CO_2) in transport sphere. Emissions of modern aerial GT engines consist of 71% CO_2, 28% water (H_2O) and 0,3% nitrogen dioxide (NO_2), included with trace amount of carbon monoxide (CO), sulfur dioxide (SO_2) and other. Air transport represents 2,5% of CO_2 world production, what is approximately 600 million tons of fuel. Increase of burning efficiency in GT combustion chambers decreases significantly emissions of aerial GT engine.

4 ANALYSIS OF PROBLEM OF TIP CLEARANCE SENSING IN GAS TURBINES

Tip clearance sensing is important for any ACC system. Sensors should be produced with sensing accuracy of 0,0025 cm. Sensor response requirements differ by sensor determination (clearance sensing, vibration sensing and other). Response should be for clearance sensors of 50 kHz. This response enables multiplex clearance sensing for any blade. Sensors should be endured in no-failure operation during long length of GT service life (over 20 000 flight hours). Sensors have to resist high temperatures and high vibrations, moisture, dirt and burning products. Also, sensors must be in position simple maintenance, calibration or regular replacement. There is large amount of examined technological methods in clearance sensing area. The most widely known methods are:

- x-ray methods,
- capacitive methods,
- inductive methods,
- optical methods,
- eddy currents methods,
- micro-wave methods,
- acoustical methods.

Researchers in tip clearance area examine sensors mounted on blade tips upwards of 30 years. These sensors enable accurate sensing of tip clearance and its time of arrival. Flotow described detailed description of clearance sensing technology by sensors mounted on blade tips. Also, he described fact, that signal from sensors may be used for blade vibration monitoring.

The largest problem of turbine tip clearance sensing is high temperatures and high vibrations. Present designers know that high turbine efficiency will be reached only at small tip clearances. On the present, listed methods are tested on various experiments. Even though it remains problem of high thermal and mechanical stress of turbine. This problem blocks reliable turbine operation during GT operation. It exist also reliable methods, that ensure reliable GT operation at high temperatures and vibrations, but these methods are science subject.

5 ANALYSIS OF BASIC PRINCIPLES OF ACTIV CLEARANCE CONTROL IN GAS TURBINES

Generally, it exist three main principles of clearance control system realization:

- two-position (“on/off”) control,
- model-based control,
- feed-back control.

5.1 Two-position (“on/off”) control

Two-position control is optimal only for one GT operating mode. This control type provides tip clearance reduction during cruise. Kawecki reported publication, where he compares transport airplanes to fighter airplanes in military area. He reported, that transport airplanes consume 89% of fuel and 93% of flight time at cruise. Fighter airplanes consume 69% of fuel and 75% of flight time at cruise. This show that during long flight time may be provided ACC system advantages. Even though, it stay undetermined tip clearance changes during others GT operating modes.

5.2 Model-based control

Model-based control provides to set tip clearance at more as one GT operating mode. Tip clearances take certain central positions depending on GT operating mode. Model-based control uses GT parameters. Sensors mounted on various GT parts, senses various parameters (e. g. rotor speeds, temperatures, pressures and other). Engine control unit following real parameters calculates required tip clearance and transmits signals into actuating unit. Actuating unit sets required positions of actuating mechanisms. It follows, that required tip clearance is function of actual GT operating conditions.

5.3 Feed-back control

Feed-back control in compare with model-based control uses continual tip clearance sensing and setting during flight. Feed-back is information about actual position of turbine casing actuating valve. This information is transmitted as electrical signal back to engine control unit. Engine control unit compares real valve position with required valve position. As it will be difference between these positions, engine control unit will perform control action. Control action is electrical signal transmitted to actuating unit. This control type requires high actuating accuracy of actuating mechanisms.

6 ANALYSIS OF ACTIVE THERMAL CLEARANCE CONTROL SYSTEM IN GAS TURBINES

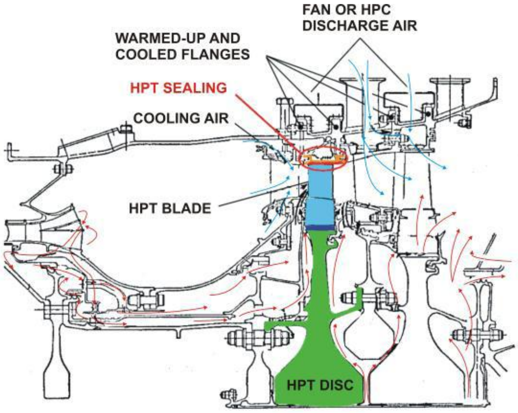

Fig. 7 Active thermal clearance control system

Since 1970, GT producers started to use thermal ACC systems. Thermal ACC systems are frequently used in turbines of current modern GT engines (fig. 7). Principled, it uses selective cooling of turbine parts during GT operation. This system uses fan and compressor discharge air. These systems are limited by slow thermal response. Long response time of these systems practically limits its usage at take-off, acceleration or deceleration. Therefore these systems are used only during cruise.

7 ANALYSIS OF ACTIVE CLEARANCE CONTROL OF GAS TURBINE CFM56 GT CFM56 HPT AND LPT ACC

HPT clearance control uses HPC discharge pressure air (from 5. and 9. stages) to HPT casing cooling. It ensures high HPT efficiency during cruise. Also, it minimizes EGT during maximal GT operating mode. System decreases risk of compressor stall at engine starting. HPT clearance control system is shown on fig. 8.

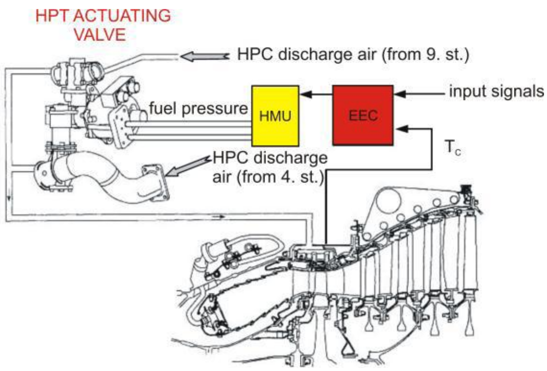

Fig. 8 HPT clearance control of CFM56

HPT clearance control system arrangement is shown on fig. 9 [6].

LPT clearance control system is very similar to HPT clearance control system. Therefore is not shown on figure. LPT clearance control uses fan discharge pressure air to LPT casing cooling. LPT clearance control system ensures high LPT efficiency during all GT operating modes. Also, system monitors EGT. LPT clearance control system arrangement is shown on fig. 10.

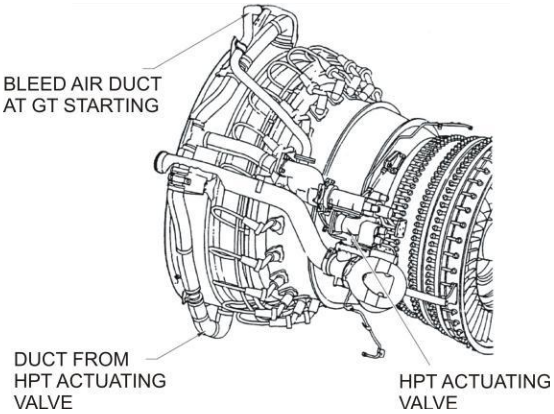

Fig. 9 HPT clearance control arrangement of CFM56

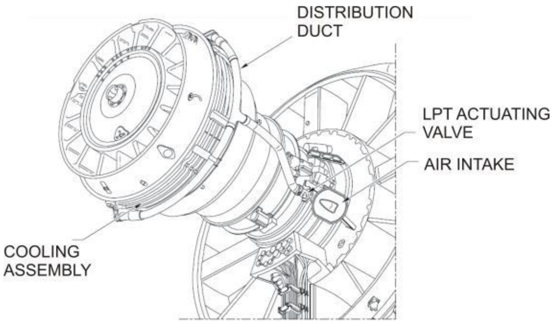

Fig. 10 LPT clearance control arrangement of CFM56

Proper ACC system operation is ensure by electronic engine control (EEC), that is a part of full authority digital engine control system (FADEC). EEC calculates and transmits required positions of turbines actuating valves. Required valve positions are transmitted into hydromechanical unit (HMU) as electrical signals. HMU sets required fuel pressure that continues into HPT and LPT actuating valves. Fuel pressure effects on valve pistons. Dual sensors LVDT (RVDT) mounted on valve pistons transmit information about real valve position back to EEC. EEC compares real valve position to required valve position and determines possible control action [4].

8 CLEARANCE CONTROL DEVELOPMENTS IN GAS TURBINES

Sensors, actuating mechanisms and materials used in ACC systems, submitted large development. Currently, it is effort to use advanced actuating mechanisms and intelligent materials.

Current designers allow for two main tip clearance control possibilities into the future:

- rub-avoidance system,
- regenerative system.

The first possibility is based on rub avoidance of turbine parts (fig. 11). It uses feedback or model-based control to maintenance of adequate tip clearance during all GT operating modes. Rub-avoidance system uses sealing that determine tip clearance during GT service life [3].

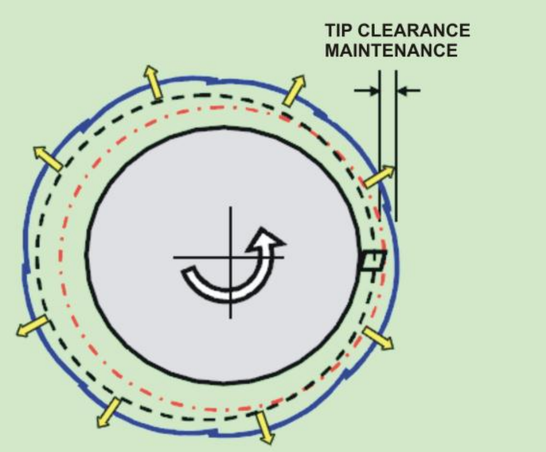

Fig. 11 Rub-avoidance ACC system

The second possibility is regenerative (fig. 12). To restore of worn sealing is used passive or active system. Regenerative systems are used in current ACC systems. Also, designers allow for them into the future.

Fig. 12 Regenerative ACC system

Fig. 13 shows GT service life extension by both previous possibilities, in compare with current ACC systems. Authors [1] believe that each from these possibilities may to extend GT service life over 1000 cycles.

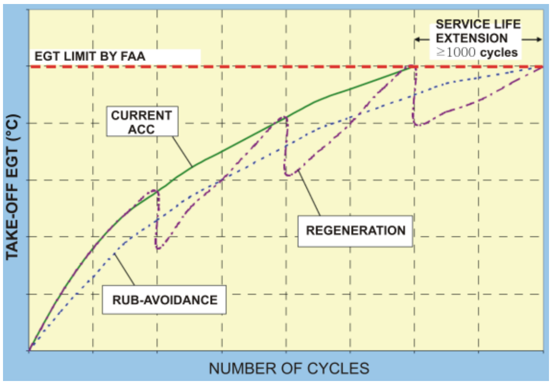

Fig. 13 Effect of rub-avoidance and regeneration ACC systems on take-off EGT [1, 2]

5 CONCLUSIONS

High GT efficiency may be achieved by clearance reduction. Improve of sealing between GT rotors and casing results in amount of advantages, e. g. efficiency increase, SFC decrease, and decrease of compressor stall risk, extended flying range, cargo increase, extended GT service life and other. Designer has to make provision for various requirements that are often opposite. Result of his work is compromise.

There is large accent on possible system failure at new GT development. Designer has two possibilities to increase GT reliability and airplane safety. Either he designs complex control system with redundancy (back-up) or simplifies total GT structure, but to the prejudice of complex system advantages [5].

Implementation of complex control system results in GT efficiency increase, but it rises simultaneously total GT complexity. GT complexity increases probability of system failure. Therefore complex system has to be redundant. Also, total airplane weight rises. Large weight decreases flying range and increases fuel consumption. Development and operating costs of airplane with this complex system also rise. Designer has to consider advantages and disadvantages of this system by GT requirements.

At first sight, simplify of GT structure results in more advantages. Total system stays relatively simple, what is positive concerning larger reliability. It is not needed any back-up system and total airplane weight stays low. That means, airplane is able extended flying range. But this designer possibility has one very large disadvantage. This disadvantage consists in impossibility to achieve maximal GT efficiency during various operating modes and operating conditions. This is reason for often withdrawal from this possibility, even though assumption of complex system disadvantages. This is particularly about GT engines of airliners flying on large distances.

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