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DEVELOPMENT OF A PERFORMANCE PREDICTION METHOD FOR TURBOSHAFT OVERHAULED POWER SECTIONS.

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DEVELOPMENT OF A PERFORMANCE PREDICTION METHOD FOR TURBOSHAFT OVERHAULED POWER SECTIONS.

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SUMMARY.

A statistical application has been developed to predict the probabilities that a turboshaft aeroengine achieves prescribed performance specifications. The application is based on a statistical model that relates different relevant assembly variables to the performances parameters, and on a simulation procedure, that estimates the influence of the uncontrollable variables on the performances.

This method has been developed and tested on the overhaul of the PT6-T6 power sections repaired and overhauled by Alfa Romeo Avio.

The parameters of the statistical models are estimated upon several observations, collected on tests performed over the period of three years. Each observation is composed by various mounting parameters, the performances at acceptance test and a group of variables that takes account of the status (new or used) of the various components and of the modification standard of the engine.

The overhaul process during the first period suffered of an high rejection rate that reached the 25.%; this high rejection rate was essentially due to high NG and sometimes to high EGT or combination of high EGT and high NG.

So in order to reduce this high rejection rate has been developed a procedure that can give the configuration of the engines at final acceptance test that maximize the probability to pass this test.

During the first period of application of this procedure the rejection rate has been decreased to the value of about 13%. Efforts to optimize this procedure are undergoing to reach the target of reduce the rejection rate to value less than 10%.

1. INTRODUCTION.

One of the main effort for reducing the helicopter operating cost is oriented trough the reduction of the maintenance cost that impact for about ¼ of the helicopter operating cost in particular about the 30.% of this cost is due to the engine maintenance cost (ref.1).

As one of the italian company involved in the helicopter engine reparation and overhaul the Alfa Romeo Avio is conducting a total quality plan for reducing the cost of the overhaul of helicopter power sections.

A statistical application has been developed to predict the probabilities that a turboshaft aeroengine achieves prescribed performance specifications. The parameters of the statistical models are estimated upon several observations, collected on tests performed over the period of three years.

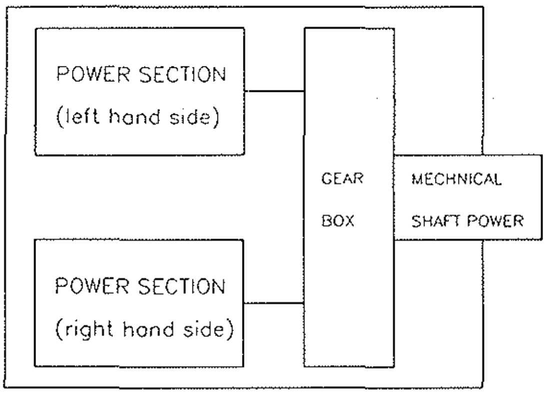
This model coupled with the engineering model that simulate the engine by the means of a simulation code allows the development of a methodology for the prediction of the performances overhauled turboshaft power sections.

The overhaul process of this engine requires to define with attention the sizing areas (class) of the turbine gas generator and power turbine nozzle guide vanes (NGV), since the power section (PS) performances are strictly dependent on the class matching. The experience gained from the assembly and relative testing of more than two hundreds KITs of power sections done by ARA during last ten years show different behavior respect to overhauled power sections for which the matching in NGV capacity is different from the completely new one.

In this paper is described the development of this methodology through the experimental application of the procedure on the power sections of the PT6-T6 turboshafts overhauled by the Alfa Romeo Avio.

2. THE OBJECT OF THE STUDY.

The PT6-T6 engine on which the methodology has been developed has two power sections (PS), parallel and independent each other, connected to a common gear-box, by which the global power is transmitted to the utility, like figure 1 shows.

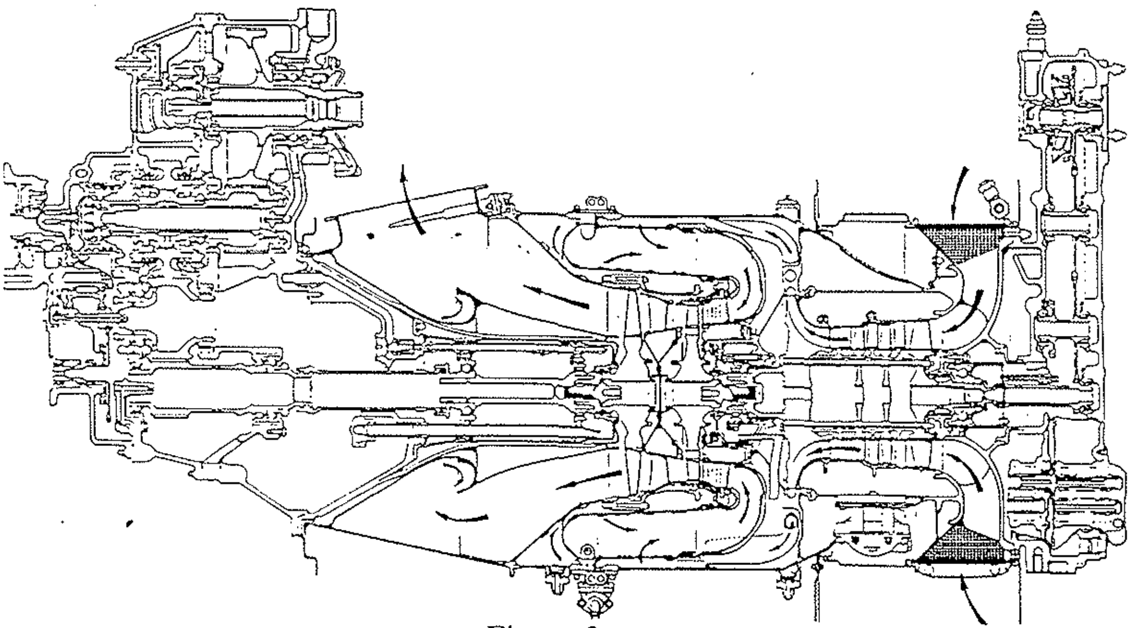


- Figure 1. -

The engine overhaul is relative to each module, i.e. the single power section (PS) and the gear-box.

The PS has two mechanically independent rotating groups, the gas generator (GG) and the other called power section (PW). The GG section has a compressor (3 stages axial and 1 centrifugal), a reverse annular combustor and a single axial turbine stage. The GG axial turbine gives the power to the compressor by a rotating shaft. The PW section has one axial turbine stage, that gives its power through a rotating shaft to the gear-box.

The following figure 2 shows the cross-section of the PS.



- Figure 2. -

Alfa Romeo Avio was involved first in assembling more than two hundreds KITs of engines for helicopters used by Italian Army, Navy, Air Force and several civil services then in repairing and overhauling those engines.

3. PROBLEM STATEMENT.

The engine overhaul must be done typically after 2000 flight operating hours.

The engine is completely disassembled, and each item is inspected to verify its integrity status and degree of functionality, in order to be declared OK for to reassemble. That means a series of inspective controls, repairing process applications if they are possible and convenient, or substitutions of items in presence of significant damage or for components at the end of useful life.

At the end of this phase of the overhaul process, a list of all items of the engine to be assembled together is defined: they are in the majority items coming from the same engine, but eventually some parts could be replaced by new or used (i.e.coming from different engines).

This operation of rebuilding the engine could affect the performances.

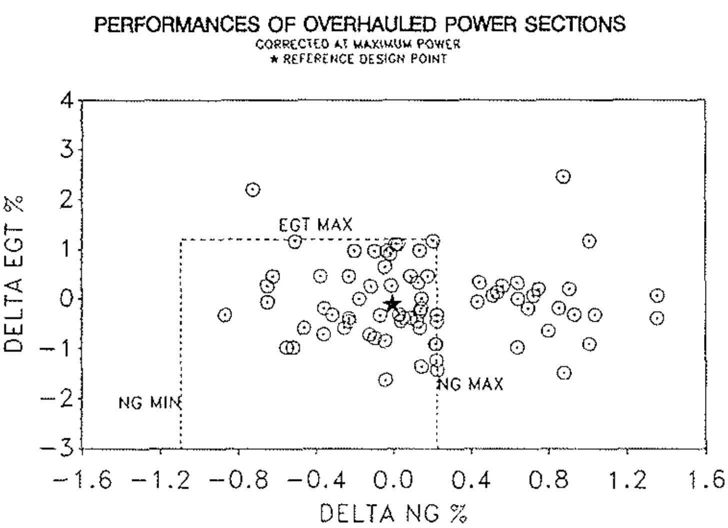
In fact simply disassembling and reassembling a turbine there will be a random shift in the performance of the engine due to small changes in the internal geometric tolerances in the flow path of the component (ref.2). Similarly the compressor can change its efficiency because of even small variation between the design and the production compressor, in particular used blading can adversely affect the performances of the compressor (ref.3). This results in a rematch of the turbine with the compressor which shows up shifts in the component and overall engine performance.

The sum of this effects can affect the engine performance up to the order of the 1% on the various engine parameters.

For the engine object of this study the process requires to define with attention the sizing areas (class) of the turbines.

The experience gained from the assembly and relative testing of more than two hundreds KITs of engines done by ARA during last ten years show different behavior respect to overhauled engines for which the matching in NGV capacity is different from the completely new one.

The main problem experienced was the high number of engine overhauled that does not satisfy the acceptance test.



- Figure 3. -

In fact the as shown if fig.3 when the overhaul process started more than 40 % of the total engines tested were rejected for "low performance"; as the experience on the overhauled power section increased the rejection percentage decreased to about 25.%.

The rejections at final acceptance test were essentially due to high NG, sometimes at high EGT or combination of high EGT and high NG. This high rejection rate was essentially due to the fact that the experience done for the overhauled engines was different respect to completely new one, for which much less were the rejection motivated by "low performances".

This problem increased the cost of the overhaul process for the Company.

This penalty in the past has been considered acceptable because of the initial phase of the overhaul process.

The main difficult was due the effectiveness of the decisions regarding the overhauled engines assembly, in order to get the required target performances.

It seems that the behavior of the overhauled engines, having used components assembled together with new ones, very often is different respect to a completely new engine, and the amount of such difference is hard to quantify, due to the deteriorated aerodynamic performances of the compressor and turbine static and rotating blade-rows, caused by the erosion effects suffered during the operative life.

Due to its small size the engine has a greater sensitivity to clearance, dirt and FOD than larger engines (cfr 4).

The performances of this engine with all used components shows significant changes respect to the one with all new components this is due to typical wear and erosion experienced through the engine overhaul life.

4. ENGINE PERFORMANCE ANALYSIS.

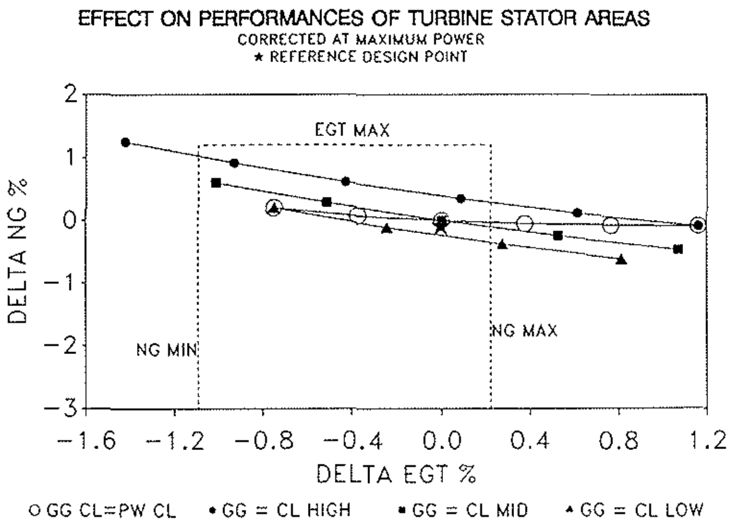
The engine cycle analysis has been performed to acquire a first knowledge of the problem; the cycle analysis has been done by the means of a simulation code.

The code developed by Alfa Romeo Avio is based on the state vector technique and the matching of the components and uses the component characteristics map.

The matching of components is based on the assumption that the mass flow rate exiting from a component must be processed by the following component.

Moreover there is not a torque imbalance on the shaft linking the compressor and the turbine.

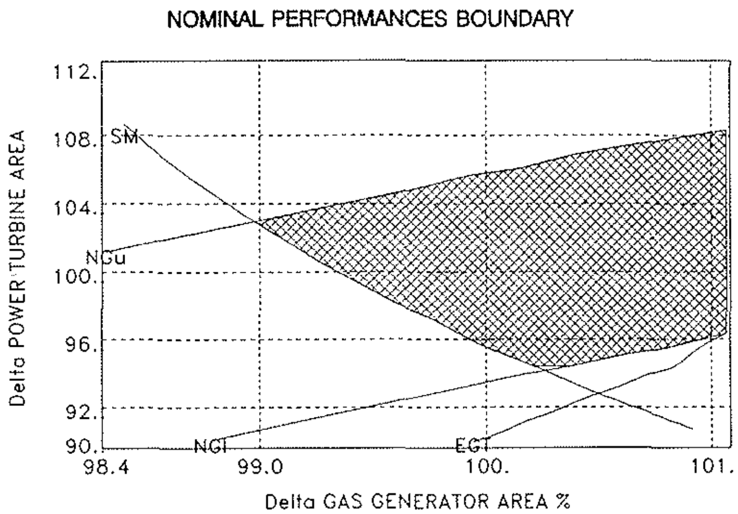
The code has been calibrated upon the mean values of performance parameters obtained at the acceptance test.



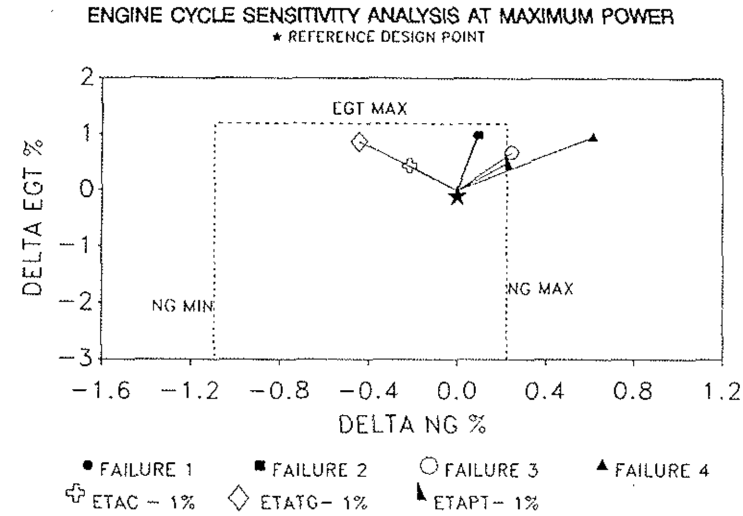
- Figure 4. -

Since, as shown in fig.4, the engine performances are strictly dependent on the class matching with this code has been possible to evaluate the effect of the turbine stators areas on the performances.

Running the simulation code has been possible to find the limits upon the possible matching of turbine capacity in terms of surge margin (SM), maximum exhaust gas temperature (EGT), maximum specific fuel consumption (SFC), maximum and minimum NG (NGu and NGl respectively); those limits for the baseline engine are shown in figure 5, where with the shading is shown the area in which the engine respects the acceptance limits.



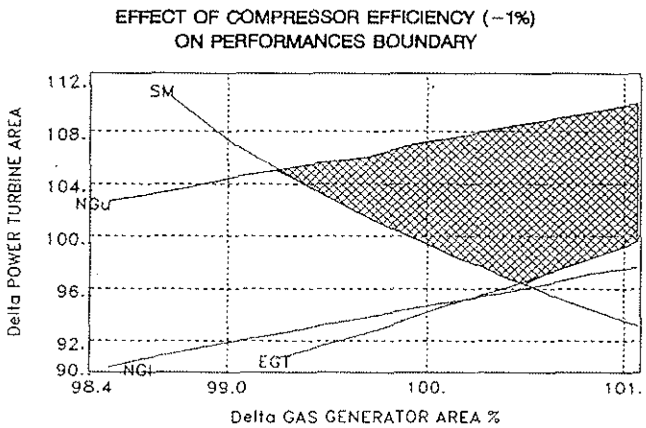
- Figure 5. -



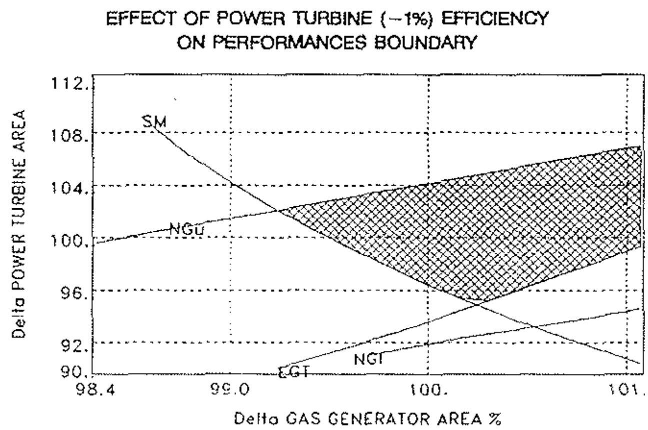
\- Figure 6. -

With the simulation code has been possible to evaluate either the effects of the air-system on the cycle or the sensitivity of the cycle to the variation of flow passages (i.e. variation of mass flow used for the cooling of turbine and disks).

The effect on EGT and NG are collected in fig.6 where are reported the effects of various efficiency and the effect of some failures of the air system; with failure 1 is indicated a bleed valve leakage; with failure 2 is indicated a cooling flow leakage; with failure 3 is indicated a bleed overboard at compressor exit; with failure 4 is indicated a by pass of turbine; with ETAC is indicated a deterioration of 1% in compressor efficiency similarly ETATG is a deterioration in gas generator turbine efficiency while ETAPT is a deterioration in power turbine efficiency.



\- Figure 7. -



\- Figure 8. -

In fact running the simulation code with deteriorated components (i.e. components with scaled down efficiency) is possible to see how the limits NGu, NGl, EGT and SM showed in fig.5 can change as those showed in figg 7 and 8 where are simulated the effects of the gas generator group and power group efficiencies. From this figures is possible to see how the performance of the engine can change for the effect of deteriorated components even if is still possible to adopt them for the engine rebuild.

5. THE DEVELOPMENT OF THE STATISTICAL MODEL.

The first step in the creation of a statistical model was the collection of the data of the configuration of the engine and the performance at acceptance test.

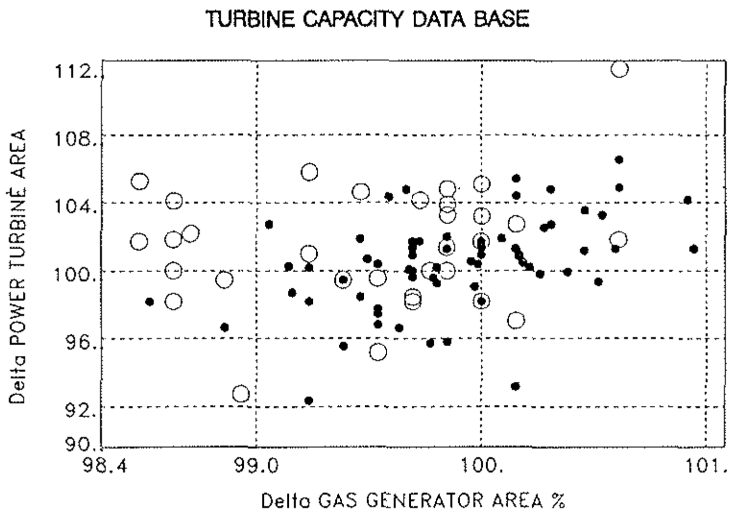
The data base has been splitted into two subsets: the first subset contains all the informations on the engines at their first test; the second contains the information about the engines at their following acceptance test.

The mounting data collected are essentially the turbine stator capacity, the radial clearance between rotating and static parts, some axial clearance between rotating and static parts, the engine serial number the date of testing, the performance data and the indication of the operator.

The observations collected were classified into groups depending on the status (new or used) of the various components and on modification standards of the engine so was possible to evaluate the influence of the assembly of new or used components on the performances of the power sections.

Then using descriptive analysis was possible to determine which were the mounting parameter that can affect strongly the performances.

A typical representation of the data collected is shown in fig.9 where with the empty symbol are reported the engines that were rejected at the final acceptance test and with the dark symbols the engines that passed the test.



- Figure 9. -

After this analysis was possible to identify which were the clearances and the qualitative variables that can affect the performances. The variables that seems to have a greater impact on the performances are: the power turbine stator capacity, the gas generator turbine stator, the radial tip clearance of power turbine rotor, the axial clearance between the gas generator stator and the turbine rotor, some critical clearance of the air-system and finally the status (new or used) of the hot end components; other variables such as the status of compressor parts or clearances relative to the cold part of the engine shows no effects on the performance.

On this basis was possible to perform a regression analysis of the variables used for the acceptance of the engine that must respect at the maximum rating some limits:

Corrected rotating speed of GG,	NG between NG,min and NG,max value
Corrected exhaust gas temperature,	EGT less than EGT,max
Corrected specific fuel consumption,	SFC less than SFC,max

Than was possible to develop a procedure, based on a series of statistical models aimed at alleviating decision making, regarding the possible overhaul actions. Thus, the statistical models relate the critical performance measures (NG and EGT) with those variables found to have significant impact on them. These variables are classified as:

C - quantitative variables, relative to the areas of the turbine stators, defined at the pre-assembly phase (C_{GG}, C_{PW}),

X - quantitative variables, measuring some clearances with values set at the pre-assembly phase, and limited to prescribed tolerance ranges (X_1, X_2),

Y - quantitative variables, measuring some clearances, whose values are defined at the final assembly phase, and are limited to prescribed tolerance ranges (Y_1, Y_2),

Q - qualitative variables, relative to the status (new/used) of critical sub-components (Q1,Q2,Q3,Q4).

The variables listed above were selected upon 2 criteria:

- engineeristic knowledge of all the variables having potentially strong influence on the performance measures,

- and a statistical criterion for selecting a subset of these variables, that, given the sampled data, exhibit significant effects on NG and EGT, and yield most precise and least biased prediction.

Due to relatively small number of initial observations, at the beginning of the study only linear models were considered. As more data became available, also some non-linear models were applied and analyzed.

Out of the 4 classes of predictor variables, described above, those denoted by Y_1 and Y_2 were treated as noise, since their values could not be controlled during the pre-assembly phase. In order to assess their impact on prediction of performances, their values were randomly generated over the prescribed tolerance ranges.

Thus, the procedure developed consists of the following steps:

0. Setting some global parameters (e.g. number of runs R).
1. Setting the values to the variables C, X and Q (lists or ranges).
2. Generating random Y variables.
3. Evaluating the predictions of NG and EGT, at each combination of values of predictor variables.
4. Estimating the expected probabilities of both performance measures falling within the specification limits, and mean predicted NG and EGT, for each combination of variables C, X and Q, and R runs.

An example of the table created by this procedure is shown in Table 1. Each entry in the Table, corresponding to a single setting of C, Y and Q variables reports the predicted probabilities of success (both performances within limits) p, and prediction interval limits, p_l and p_u, showing the precision of this estimate. The width of the prediction interval (p_l,p_u) depends on how precisely can NG and EGT be predicted, for given values of C, X and Q, and on how far from the specification limits these predictions are.

C_{GG} =MID Q0=0000

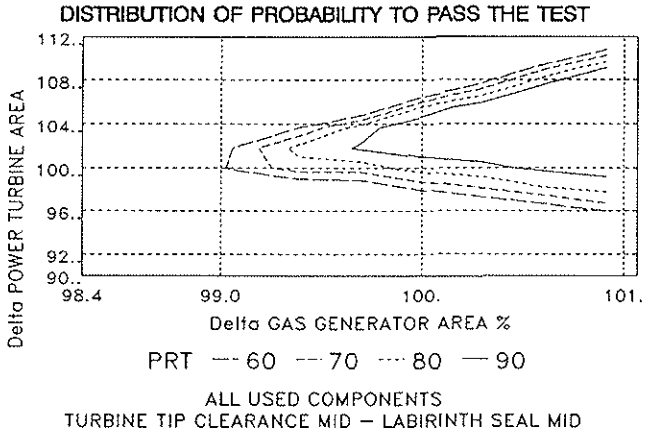
	RADIAL TIP CLEARANCE											
	LOW						HIGH					
	LABYRINTH SEAL						LABYRINTH SEAL					
	MID			HIGH			MID			HIGH		
C_{PW}	(	PRT	)	(	PRT	)	(	PRT	)	(	PRT	)
LOW	76	93	99	26	59	87	0	0	1	0	13	36
MID	99	100	100	17	36	56	40	64	84	0	3	14
HIGH	96	100	100	0	0	0	42	76	97	0	0	0

A success is defined as an outcome when both predicted performance measures fall within the prescribed specification limits i.e. a target area identified in the plane NG/EGT by the following limits:

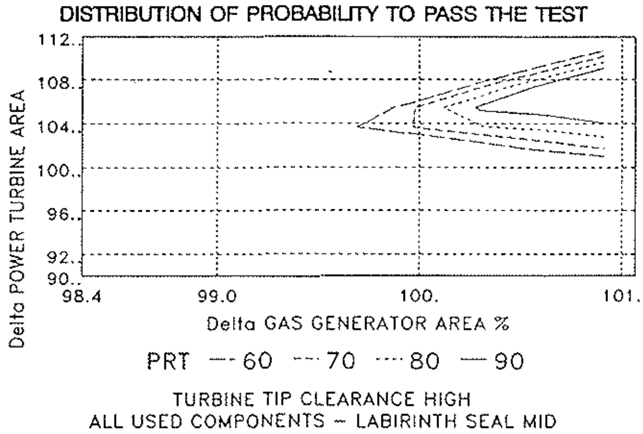
$$NG_{min\ target} = NG_{min} + \Delta NG$$
$$NG_{max\ target} = NG_{max} - \Delta NG$$
$$EGT_{max\ target} = EGT_{max} - \Delta EGT$$

where ΔNG and ΔEGT are used for the first period to take into account as conservative rule for possible differences between the reality and the statistical model adopted and NG_{min},NG_{max} and EGT_{max} are the limits for the acceptance test of the engine; as the application of this procedure will go on should be possible to be more confident on the results and this Δ could be reduced.

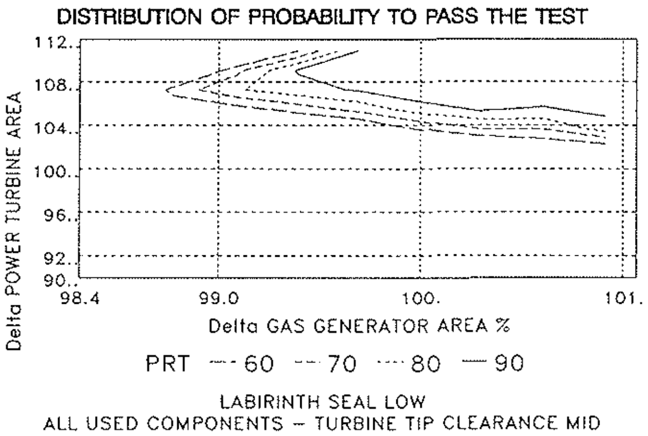
In the figures from 10 to 13 are displayed four typical distribution of probability to pass the acceptance test for four different typical configuration; in fig 10 is displayed the distribution for a engine with all used components and clearances at their mid value; in fig 11 is possible to see the negative impact of a turbine tip clearance high; in fig 12 is possible to see how the area in which is possible that the engine pass the acceptance test is increased for effect of the labyrinth seal at its lowest value and finally in figure 13 is possible to see the impact of a new gas generator stator with clearances at their mid value.



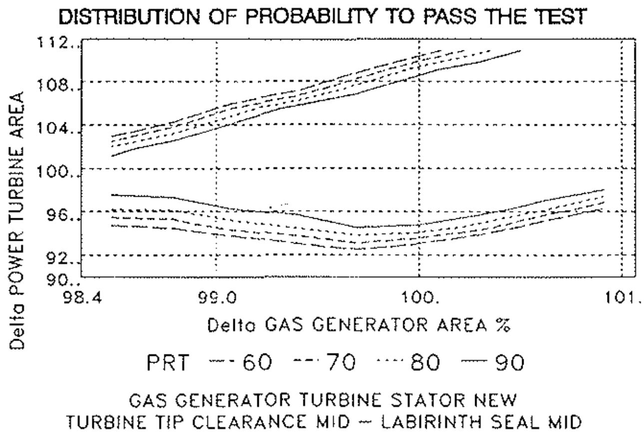
- Figure 10. -



- Figure 11. -



- Figure 12. -



- Figure 13. -

On this basis is possible to see how the "optimum" matching of the turbine stators can change with the configuration in terms of new or used components and in terms of clearances low or high.

6. RESULTS OF FIRST APPLICATIONS.

This procedure is being tested on field. The indication taken from this procedure are put into the decision process for the overhauled engines.

The procedure has been utilized in the following way: once the status of components and some clearances have been defined during the initial phase of the mounting running the procedure is possible to find which is the combination in terms of turbine stator capacities and clearances that can maximize the probability that the engine pass the acceptance test.

The output of the simulation are given in terms of turbine stator capacities and in terms of a reduced range of tolerances of the power turbine rotor tip clearance and power turbine seal.

As the statistical model can be utilized with good confidence for combination of qualitative variables already present in the data base and in a range of data that is just a little wider than the data in the data base because of possible non linearities the information of this procedure, when it was applied far from the data of the data set (i.e. the results have been extrapolated), have been integrated with the results of the engineering model (in this case the only output possible is given in terms of turbine stator capacities).

This procedure based on the analysis of the power sections overhauled by the Alfa Romeo Avio has been applied also at reparation engines for which the acceptance limits are less critical.

In the first period of application the rejection rate for the overhauled engines is decreased from about 25.% to about 15.% while the rejection rate for reparation engines is about 18.%.

Efforts to improve the levels of prediction of the procedure are undergoing in order to reach the target value of the 10.% rejection rate.

7. CONCLUSIONS.

The first period of application of this procedure gives good indication about the reduction of the rejection rate of the engine at acceptance test, this already good results can be improved as process will go on first creating a better engine model increasing the data base on which the statistical model is based in order to give evidences of other variables or eventual non linearities and second improving the level of simulation of the engineering model and finally with a greater integration between the two methodologies.

Finally if the methodology will show good results will be possible to extend this approach to other engines of the same family (i.e. PT6-T3 and PT6-T3B) overhauled by Alfa Romeo Avio.

8. ACKNOWLEDGMENTS.

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