International Journal of Emerging trends in Engineering and Development
Issue 2, Vol.4 (May 2012) ISSN 2249-6149

Design-Point Performance Simulation and Adaptation of a Gas Turbine Engine

Abubakar Mohammed[1*], Akinola A. Adeniyi[2], Abdulkadir B. Hassan[1], Abubakar K. Mohammed[3]

[1]Department of Mechanical Engineering, Federal University of Technology Minna, Nigeria
[2]Department of Mechanical Engineering, University of Ilorin, Ilorin, Nigeria
[3]Geregu Thermal Plant, Ajaokuta, Kogi State, Nigeria

Abstract

A design point simulation and adaptation of anindustrial GE LM2500+ gas turbine engine is presented. The design point is chosen when the engine runs steadily at operating point and close to the nominal design condition at 29MW power output. The targeted performance parameters are the fuel flow rate (FF), the compressor exit total pressure (P3), the compressor turbine total exit temperature (T8) and the total exit temperature from the compressor (T3). The values obtained from simulation using PYTHIA for the targeted performance parameters are 2.57%, -0.5%, -0.52% and 1.11% for gas path pressure deviations at thecompressor turbine, pressure deviations at the compressor, temperature deviations at thecompressor turbine, and temperature deviations at the compressor respectively. The average percentage deviation of the design valuesis over 1%. To achieve a better result, adaptation was carried out and the values obtained from simulation of the adapted values were -0.000035%, 0%, -0.00009%, and 0%. These values match reasonably with the targeted overall percentage deviation of 1%.

Keywords: Design-point; Performance; Simulation; Adaptation; PYTHIA; Gas Turbine.

***Corresponding Author:** Abubakar Mohammed

1. Introduction

In the early days, design model engineers manually adjust model parameters, ran the model, and then plotthe predicted and measured parameters. Iteration was done until the matching was satisfactory. It was then left for the engineers experience and judgement to select what model parameters to adjust in order to secure satisfactory matching. A high percentage in matching error has been attributed to this manual turning, making it a major limitation to the procedure.This error was minimised by the adoption of semi-automated Newton Raphson algorithm [1]. The technique principally involves varying the model's independent parameters like gas path pressures and temperatures,until all the measured predicted residuals are tuned towards zero. The principle was based on the inversion of a given Jacobean matrix to find a converged solution. The major limitation is that the number of both dependent and independent parameters must be equal. This in many cases greatly limits matching accuracy.The Newton Raphson method did not yield an optimal estimate of model parameters for a given measurement set. To curb the above mentioned limitation, Roth et al. [2, 3] introduced a non-linear algorithm technique based on probabilistic matching. It provided the initial model a reasonable approximation of the real engine. In fact, this method is the first major attempt at design point adaptation. The basic assumptions made were that the initial estimates for the unknown model parameters are close to their true values and a smooth and continuous mapping exists between model parameters and measured outputs. The model is then linearized about a nominal parameter. Several developments of this method were carried out [4-7] and eventually led to the development of a computer code, PYTHIA [8, 9].

This paper presents the design point simulation and adaptation of a GE LM2500+ gas turbine engine using the PYTHIA code.

1.1 Engine Specifications

The gas turbine used is an industrial GE LM2500+ gas turbine engine installed at the Isle of Man, UK by Manx Electricity Authority (MEA). It has two LM 2500+ engines, each producing 29 MW at the dry mode. It drives a combined cycle power plant with two once-through steam generators and a steam turbine producing 20-25 MW [10].It has an additional stage zero blisk on the high pressure compressor (HPC), a new stage and variable guide vane. It also has a higher power output rated at about 25-29 MW at ISO condition with specific fuel consumption of 235 g/kWh. An accessory gear box located on the axial compressor frame takes the HP shaft power. The compressor is made up of 17 stage axial compressor with a fully annular Combustor with externally mounted nozzle which is bolted to the compressor and wrapping around the turbine stages. Fuel injection is done through atomising nozzles located at the rear of the combustor chamber. The power turbine has 6 stages, which drive the load operated over a cubic curve for mechanical drive.The engine and its configuration at sea level are shown in Figure 1 and Table 1.

Table 1. ISO performance of GE LM200+[11]

Description	Value
Length (m)	6.7
Width (m)	2.57
Height (m)	2.04
Weight (kg)	1500
Overall pressure ratio	22:1
Exhaust temperature (^{o}C)	516
Mass flow rate (kg/s)	89
Number of compressor stages	17
Number of LP turbine stages	6
Power output (MW)	28.5
Power turbine speed (rpm)	3600
Specific fuel consumption (g/kWh)	235
Thermal efficiency (%)	39

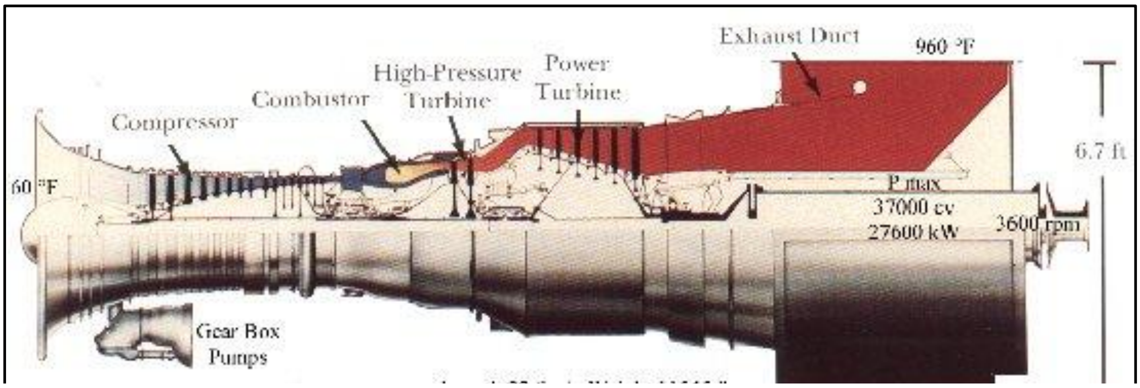


Figure 1. LM 2500+ with main performance and parameter specifications [11]

2. PYTHIA

2.1 Description of Pythia Model

The program used for the simulation is Pythia.The program offers a simple interface as a text file.The code words link the text file to the FORTRAN source code developed from the TURBO MATCH [12].APythia engine model is an amalgamation of component bricks with each component expressed by two or three station vectors (when Mixes and splitters are used). The station vectors project the entrance and the exit condition. Bricks usually correspond to particular components like the compressor (COMPRE), nozzle (NOZCON), which allows arithmetical operations (ARITHY) and access to resultant calculation. Details of this bricks and their functions are shown in Table 2 below. Pythia uses maps to represent compressor or turbines. Each map is calculated with non-dimensional parameters so as to vary easily with a corresponding variation in ambient condition. A set of brick data gives thermodynamic information to solve thermodynamic cycle equations. A parameter is then chosen as the ‘handle’ of the engine, so as to be able to simulate for different operating conditions. If a handle is chosen, other set of parameters which could serve as the handle are held as variables [13].

The configuration of the engine consists of bricks as shown in Figure 2. A single compressor brick represents the compressor. The cooling flow for the compressor turbine and power turbine are taken from the exit of the compressor,number 15 and number 16 respectively (Figure 2).

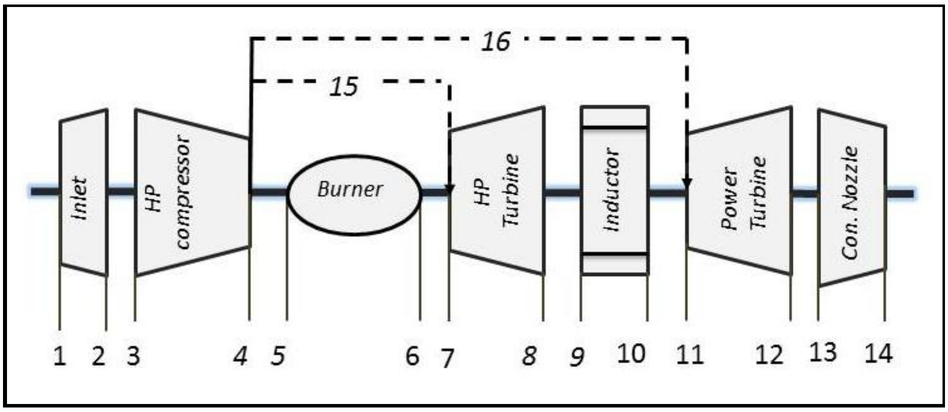


Figure 2. Schematic of Pythia model

Table 2. Engine model brick set

Station Number	Brick Name	Interpretation
1-2	INTAKE	Intake of engine
3-4	COMPRE	17 stage axial HPCompressor
4-15-7	PREMAS	Splits total flow into by pass and core mass flow to cool Compressor turbine
4-16-11	PREMAS	Takes percentage air from compressor exit to cool power turbine
5-6	BURNER	Combustion chamber
7-8	TURBIN	High pressure turbine
11-12	PTURBIN	6 stage power turbine
13-14	NOZCON	Core flow hot convergent nozzle

2.2 PYTHIA Composition

The compositions of Pythia consist of Bricks, Station vectors, Brick data (BD) and Engine vectors (EV). The Bricksare pre-programmed units, which represent engine configurations. They correspond to components like the INTAKE, COMPRE (compressor), BURNER (combustor) and NOZCON (convergent nozzle). Details of Pythia bricks names are shown in Table 2. The Station vectors (SV) are used as interface in linking bricks to represent a complete engine configuration.As most bricks calculate the thermodynamic process occurring within the bricks, assumptions are made that they operate based on inlet gas state to generate the outlet gas state. These gas states are collectively known as SV. A station vector item is represented by SV (I, J) where I is the station number 1-50 and J is station number1-8. The Brick data and Engine vector are coupled to its input and output as shown in Figure 3. In general brick needs other data to serve as input like efficiency, Pressure loss, etc.that does not form part of the SV.They differ for each brick and they are collectively known as brick data and forming a continuous set BD (K) for whole assembly of bricks. The bricks that generate outputs are different from station vectors. They are known as engine vector results EV (K). The value of K ranges from the number 1-800 [12].

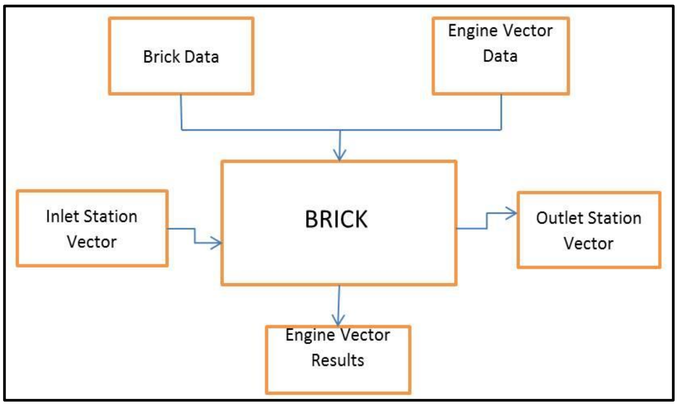


Figure 3. Pythia Engine brick details [12]

2.3 PYTHIACapabilities

Pythiaincorporates various processes of the diagnostics capabilities. These capabilities includes: Design point performance adaptation,offdesign performance adaptation, measurements for both deteriorated and clean engines. With these capabilities, Pythia can select optimal measurements in order to isolate faults [14].

3. Simulation and Adaptation

3.1 Test Data

A set of measurement data was utilised for this study with reference to point with peak thermal efficiency from the MEA data selected. For efficient usage of measured data some key factors were weighed, such as differences in the operating condition of the engine and the existing design point condition. Measurement bias and noise, coupled with the likelihood of engine running at non ISA conditions were also considered. Therefore, the measurement selected for the engine design point adaptation wasbased on its rate of efficiency.

3.2 Design Point Simulation

The pre-conceptual stage in engine modelling is getting a satisfying design point (DP) prior to an off design simulation. The design point is chosen after readings from a set of measurements taken at the Manx Electrical Authority (MEA). When the engine ran steadily at operating point and close to the nominal design condition, the peak efficiency per unit time was obtained and taken as the optimal design point power output.Gas path diagnostics principally depends on the accuracy of a performance simulation models around a chosen design point. The accuracy of the predictions highly depends on given engine data and the empirical component details, like the component characteristic maps.To generate engine model, values of independent gas parameters like mass flow, component efficiencies and pressure losses were guessed based on the theory of components. The engine was built and modelled to operate at non ISA condition similar to the one operated at MEA station at the Isle of Man,where the ambient temperature at optimal power of 29MW was 279K.Assumptions were made due to lack of specific values for some given gas path parameters, suitable values were then chosen based on experience and intuition. Equally, default values provided by PYTHIA software were chosen for some of these parameters. The surge margin (Z) and the compressor speed were taken to be 1.0.

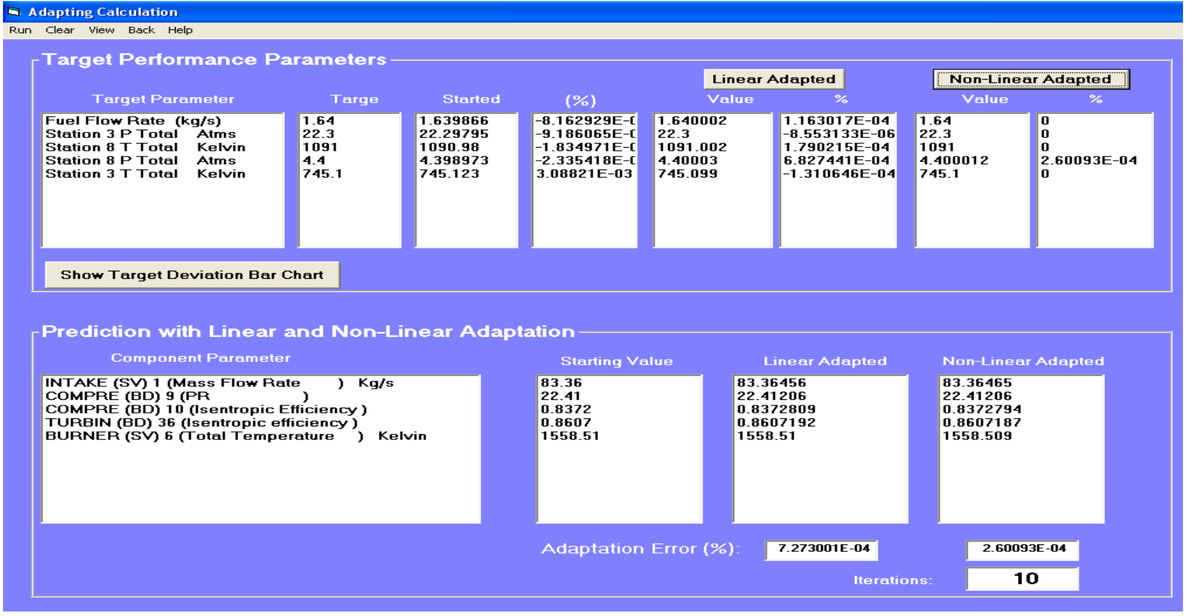
3.3 Design Point Adaptation

To produce an accurate engine model, one of the most crucial steps is to adapt a model to satisfy the design point performance of the engine. The target performance parameters were those obtained from the MEA data sheet at 29 MW, where the peak efficiency of components was obtained. The target performance parameters were the fuel flow rate, the compressor exit total pressure (P3), the compressor turbine total exit temperature (T8) and the total exit temperature from the compressor (T3) which supplied cooling flow for the compressor turbine and the power turbines. The design point adaptation or matching is done by the proper selection of a set of design point component parameters also known as the to-be-adapted component parameters. The to-be-adapted component parameters were the compressor pressure ratio (PR), the compressor isentropic efficiency (η_c), the compressor turbine isentropic efficiency (η_t), the turbine entry temperature (TET) and the air mass flow rate (m).

Factors like the functional relationship between the target parameters and the to-be-adapted parameters were considered so as to obtain proper adaptation results and good convergence. After the selection of the to-be-adapted component parameters, subsequent iterations of mass flow rates, component efficiencies, duct losses was done based information from widely available ranges on the theory of the components and from the GE site. The basic assumption made was that the ambient temperature and the compressor pressure ratios were assumed to be equal to those of the MEA readings at the non ISA condition.

4. Results

Figure 4, 5 and 6 show the simulated result from the PYTHIA software, the percentage deviation before and after adaptation respectively.



Target Performance Parameters

				Linear Adapted		Non-Linear Adapted	
Target Parameter	Targe	Started	(%)	Value	%	Value	%
Fuel Flow Rate (kg/s)	1.64	1.639866	-8.162929E-	1.640002	1.163017E-04	1.64	0
Station 3 P Total Atms	22.3	22.29795	-9.186065E-	22.3	-8.553133E-06	22.3	0
Station 8 T Total Kelvin	1091	1090.98	-1.834971E-	1091.002	1.790215E-04	1091	0
Station 8 P Total Atms	4.4	4.398973	-2.335418E-	4.40003	6.827441E-04	4.400012	2.60093E-04
Station 3 T Total Kelvin	745.1	745.123	3.08821E-03	745.099	-1.310646E-04	745.1	0

Prediction with Linear and Non-Linear Adaptation

Component Parameter	Starting Value	Linear Adapted	Non-Linear Adapted
INTAKE (SV) 1 (Mass Flow Rate) Kg/s	83.36	83.36456	83.36465
COMPRE (BD) 9 (PR)	22.41	22.41206	22.41206
COMPRE (BD) 10 (Isentropic Efficiency)	0.8372	0.8372809	0.8372794
TURBIN (BD) 36 (Isentropic efficiency)	0.8607	0.8607192	0.8607187
BURNER (SV) 6 (Total Temperature) Kelvin	1558.51	1558.51	1558.509

Adaptation Error (%): 7.273001E-04 2.60093E-04

Iterations: 10

Figure 4. Adaptation result in PYTHIA

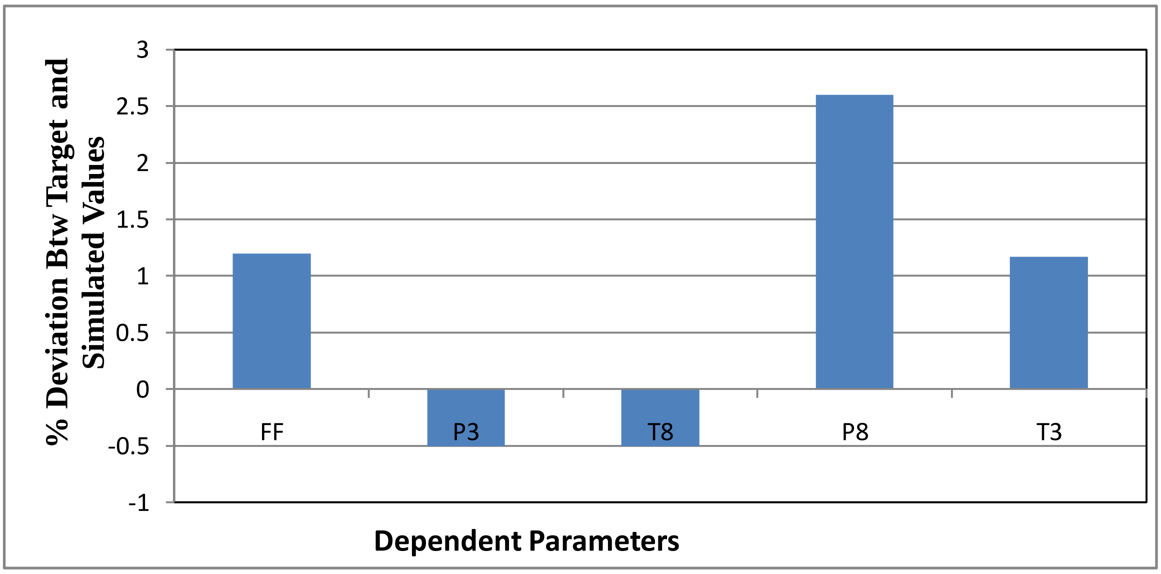


Figure 5.Percentage deviation of parameters before adaptation

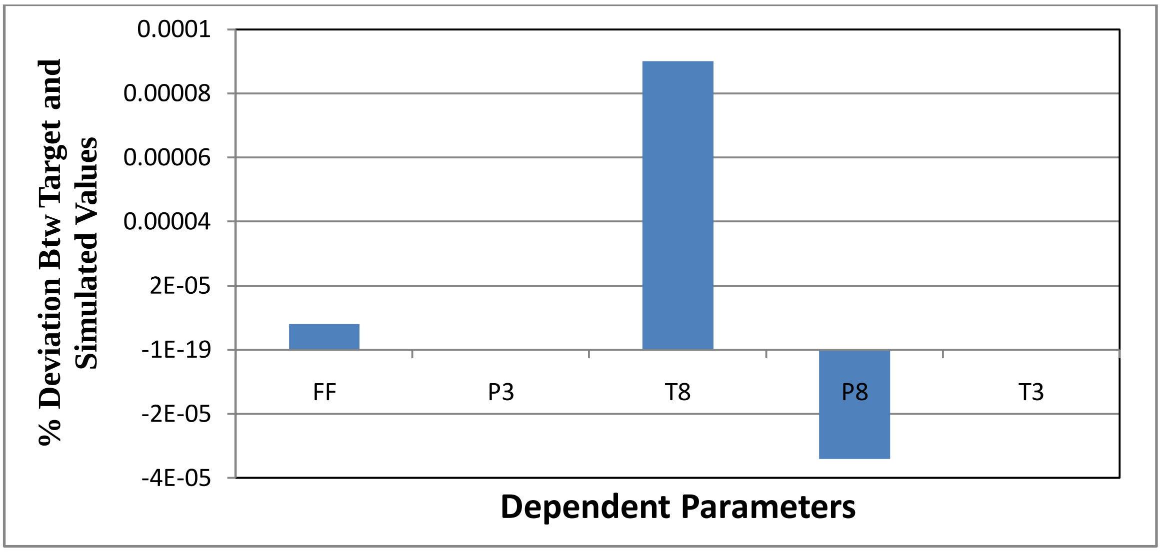


Figure 6. Percentage deviation of parameters after adaptation

5. Discussions

The design point was taking as the point where gas path pressure deviations at the turbine and the compressor were 2.57% (P8) and -0.5% (P3) respectively. The gas path temperature deviations were -0.52% (T8) and 1.11% (T3) for the turbine and compressor respectively as shown in figure 5. These values show that the overall predictions percentage deviation range was greater than ± 1%, which was pre-projected for the design point. After the first simulations, an error percentage greater than ± 1% was obtained, which is greater than the pre-projected target. The values of the to-be-adapted parameters supplied by the pythia software were fed back into the system. Running a second simulation with new values supplied by PYTHIA, a very small value was obtained for the relative percentage error and the RMS. With the overall percentage deviation less than the ± 1% projected as shown in figure 6.After adaptation, the gas path pressure deviations at the compressor turbine and the compressor were -0.000035% (P8) and 0% (P3) respectively. The gas path temperature deviations were -0.00009% (T8) and 0% (T3) for the turbine and compressor respectively as shown in figure 6. The adapted engine model matched the target performance.Though values were not 100% accurate, most probably due to variations in the component characteristic maps between the map used by MEA and those supplied by Pythia.

6. Conclusion

A design point simulation and adaptation of GE LM2500+ gas turbine engine installed at the Isle of Man, UK was successfully carried out. The design point was chosen when the engine ran steadily at operating point and close to the nominal design condition.The peak efficiency per unit time was obtained and taken as the optimal design point power output as 29MW. The values obtained from simulation using PYTHIA for the targeted performance parameters are the points where gas path pressure deviations at the turbine and the compressor were 2.57% (P8) and -0.5% (P3) respectively. While the gas path temperature deviations were -0.52% (T8) and 1.11% (T3) for the turbine and compressor respectively.Due to high level of percentage deviation, adaptation was carried out. The gas path pressure deviations at the turbine and the compressor were -0.000035% (P8) and 0% (P3) respectively. And gas path temperature deviations were -0.00009% (T8) and 0% (T3) for the turbine and compressor respectively. These values match reasonably with the targeted overall percentage deviation of ± 1%.

Acknowledgement

The authors will like to thank the Petroleum Technology Development Fund (PTDF) for providing the research fund on behalf of the Federal Government of Nigeria. The suggestions and contributions from Dr Y.G. Li of Cranfield University, UK during the research work were highly appreciated.

Reference

[1] Roth, B. A., Mavris, D. N., and Doel, D. L., 2003, Estimation of Turbofan Engine Performance Model Accuracy and Confidence Bounds, 16th International Symposium on Air Breathing Engines, ISABE Paper No. 2003-1208.
[2] Roth BA, Doel DL, Cissell JJ. Probabilistic matching of turbofan engine performance models to test data. ASME GT2005-68201, ASME TURBO EXPO 2005, June 2005.
[3] Roth B, Doel D, Mavris D, Beeson D. High-accuracy matching of engine performance models to test data. ASME GT2003-38784, ASME TURBO EXPO 2004, June 2004.
[4] House P. Gas path analysis techniques applied to turboshaft engines, MSc thesis, Cranfield University, England, 1992.
[5] Urban, L. A. (1975), Parameter Selection for Multiple Fault Diagnostics of Gas turbine Engines, Journal of Engineering for Power, Vol. 4 (4): 225-230.
[6] Urban, L. A. Gas Turbine Engine Parameter Interrelationships, HSD UTC, Windsor Locks, Ct, 1st Edition, 1967.
[7] Urban, L. A. Gas path analysis applied to turbine engine condition monitoring, A1AA-72-1082, 1972.
[8] Escher, P. C. and Singh, R. (1995), An Object-Oriented Diagnostics Computer Program Suitable for Industrial Gas Turbines, Proceedings of the United 21st International Congress on Combustion Engines (CIMAC), Interlaken, Switzerland: 15-18.
[9] Escher P.C. Pythia: An objective-oriented gas turbine path analysis computer program for general applications, PhD Thesis, Cranfield University, UK, 1995.
[10] Jeffs, E., 2004, Isle of Man Plant Has Novel Design, Turbomachinery International Magazine, **45 (**3): 27–28.
[11] GE Leaflet GE Marine & Industrial Engines: LM2500+ Gas Turbine or http://www.gepower.com.
[12] V.A, Pacchidis (2008.), "TURBO MATCH SCHEME", MSc thermal power course note, Cranfield University, UK: 29-76.
[13] Y. G. Li, P. Pilidis, M. A. Newby. 2006. An Adaptation approach for gas turbine design-pointPerformance Simulation. Journal of Engineering for Gas Turbines and Power, Vol. 128: 789-795.
[14] Li, Y.G. and Singh, R., An Advanced Gas Turbine Gas Path Diagnostic System - PYTHIA, ISABE-2005-1284, the Seventeenth International Symposium on Air breathing Engines (17th ISABE), Munich, Germany. 2005