Performance Analysis of an Aircraft Gas Turbine Engine using Particle Swarm Optimization

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Abstract

A turbo fan engine performance analysis and the optimization using particle swarm optimization(PSO) algorithm have been conducted to investigate the effects of major performance design parameters of an aircraft gas turbine engine. The FJ44-2C turbofan engine, which is widely used in the small business jet, CJ2 has been selected as the basic model. The design parameters consists of the bypass ratio, burner exit temperature, HP compressor ratio, fan inlet mass flow, and nozzle cooling air ratio. The sensitivity analysis of the parameters has been evaluated and the optimization of the parameters has been performed to achieve high net thrust or low specific fuel consumption.

Key words: Gas Turbine Engine, Turbo Fan Engine, Particle Swarm Optimization, Net Thrust, Specific Fuel Consumption

1. Introduction

The design of aircraft engines is complex as they contain tens of thousands of components. It begins with parametric cycle analysis, which includes the determination of compressors' compression ratios, combustor exit temperature, bypass ratio and so on. It is important to determine the optimization of these parameters which meets customer's requirements like maximization of thrust or minimization of specific fuel consumption in the early phase of engine development. This is because the cost of solving a problem related to the engine design increases exponentially if discovered in the production stage. Many different criteria have been used to evaluate the performance of aircraft engines. For example, Homaifar et al. (1994) used thrust per unit mass flow rate and overall efficiency as the performance measurements and Mach number, compressor pressure ratio, fan pressure ratio, and bypass ratio as key parameters for system optimization

of turbofan engine. Asako et al. (2002) employed thrust specific fuel consumption (TSFC) as the performance measurement and high pressure turbine (HPT) efficiency as a key parameter about aircraft engine conceptual design applying multidisciplinary design optimization (MDO). And Atashkari et al. (2005) used TSFC, specific thrust, propulsive efficiency, and thermal efficiency as the engine's performance indicators with regard to thermodynamic Pareto optimization of turbojet engines and considered both two-objective of four indicators and 4-objective optimization processes; this is because they bring an optimized value of an objective or cost function, and single-objective optimization problems have constraint functions on the design variables, and they are considered as constrained optimization problems [1-3].

Concerning optimization algorithm, PSO algorithm is one of the genetic methods used to evaluate birds or insects living in a group and having low intelligence. In the group, each particle has a low intelligence and a simple role, but the

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synergy of the group's performance is excellent through the common rule and exchanging information. And in the case of low intelligence modeling, computation quantities are significantly reduced as compared with other techniques. The PSO algorithm has the advantages of an ordinary genetic computation's random search performance and search & converge optimum solution in each revolution stage [4, 5]. For these reasons, the PSO algorithm has been applied to various optimization studies. For example, Seyed et al. (2012) utilized the PSO algorithm for optimizing thermo-economic analysis of combine gas turbine power plant. And Sadeghierad et al. (2010) performed design of high-speed micro turbine generator which has high rotor speed and high frequency of the stator winding current by using the PSO algorithm for optimizing the efficiency of machine. Weiping et al. (2013) carried out the forecasting of steam turbine heat rate which is important in assuring the economic, efficient, and safe operation by applying PSO algorithm in order to optimize the regularization parameter r and the kernel parameter σ^2 [6-8].

In this research, net thrust and specific fuel consumption (SFC) of gas turbine performance are chosen for the performance indicators. The maximum thrust is related to survivability for a combat mission and the minimizing specific fuel consumption makes more endurance time for a surveillance mission. The turbofan engine performance has optimized values of net thrust and specific fuel consumption when performance parameters such as the bypass ratio, burner exit temperature, high pressure compressor ratio, nozzle cooling air ratio, and fan inlet mass flow are successfully selected. The Gasturb 10 and the PSO algorithm have been employed for this study.

2. Theoretical Method

2.1. Performance Analysis

A Performance Analysis of the basic turbofan engine has been undertaken by using the Gasturb 10 program. The Basic engine configuration for an analysis model is the FJ44-2C of the small business jet Citation CJ2, developed by Williams International Co. Performance parameters for turbofan engine optimization, illustrates the net thrust and specific fuel consumption.

Figure 1 shows the schematics of FJ44-2C turbofan engine modeling.

In this study, the airstream entering the turbofan engine will flow through the fan and the engine core separately. Cycle analysis is then applied to both the bypass stream and engine core stream separately as listed next. The performance analysis process follows the classical method described in the reference written by Mattingly [9, 10].

We consider only the uninstalled thrust F , which depends on the engine alone and hence is independent of the nacelle. Expressed in terms of mass flow rate through fan air stream $\dot{m}_f$, the flight Mach number M_0 , sound speed a_0 , velocity V , temperature T , pressure P , and specific heat ratio γ_c , the uninstalled thrust of bypass stream per unit fan air mass flow rate is given by

$$\frac{F_f}{\dot{m}_f} = \frac{a_0}{g_c} \left(\frac{V_{16}}{a_0} - M_0 + \frac{T_{16}/T_0}{V_{16}/a_0} \frac{1 - P_0/P_{16}}{\gamma_c} \right) \quad (1)$$

where the number in subscripts represents the location indicated in Fig. 1.

Fig. 1. Engine Schematics for FJ44-2C Cycle Analysis

The engine core stream cycle analysis is similar to the bypass stream except that it includes energy addition/subtraction across all components in the engine. The uninstalled thrust of the engine core stream per unit core airflow rate is given by

$$\frac{F_c}{\dot{m}_c} = \frac{a_0}{g_c} \left[(1+f) \frac{V_{16}}{a_0} - M_0 + (1+f) \frac{R_c}{R_c} \frac{T_8/T_0}{V_8/a_0} \frac{1-P_0/P_8}{\gamma_c} \right] \quad (2)$$

where f is mass flux ratio of fuel to the air through the engine core.

Combining the thrust equations for the fan stream and the engine core stream, the total thrust equation can be demonstrated as follows:

$$\begin{aligned} \frac{F}{\dot{m}} = & \frac{1}{1+\alpha} \frac{a_0}{g_c} \left[(1+f) \frac{V_8}{a_0} - M_0 + (1+f) \frac{R_c}{R_c} \frac{T_8/T_0}{V_8/a_0} \frac{1-P_0/P_8}{\gamma_c} \right] \\ & + \frac{\alpha}{1+\alpha} \frac{a_0}{g_c} \left(\frac{V_{16}}{a_0} - M_0 + \frac{T_{16}/T_0}{V_{16}/a_0} \frac{1-P_0/P_{16}}{\gamma_c} \right) \end{aligned} \quad (3)$$

The fuel air ratio and specific fuel consumption, S are demonstrated as follows:

$$f = \frac{\tau_\lambda - \tau_\gamma \tau_c}{\eta_b h_{PR} / (C_{pc} T_0) - \tau_\lambda} \quad (4)$$

$$S = \frac{f}{(1+\alpha)F/\dot{m}} \quad (5)$$

2.2. Optimization

The PSO employed in this study requires basic mathematical operators, and is computationally inexpensive in terms of both memory requirements and speed, whereas genetic algorithm and simulated annealing techniques take much time to calculate and require a lot of computation resources. Also, if there are sufficient data, PSO can converge the optimization points without a formula of objective functions. PSO usually consists of velocity and position updating formulations which are illustrated as follows:

$$v_{ij}(t) = \omega(t)v_{ij}(t-1) + c_1 r_{1j} [p_{ij}(t) - x_{ij}(t)] + c_2 r_{2j} [p_{gij}(t) - x_{ij}(t)] \quad (6)$$

$$x_i(t+1) = x_i(t) + v_i(t) \quad (7)$$

$\omega(t)$ in Eq 6 means that the inertia weight and both c_1 and c_2 are acceleration constants. r_1 and r_2 can get arbitrary values from 0 to 1. The second term of Eq 6 is a cognitive term and updates partial optimization positions with the experiences of particles themselves. The third is a social

Table 1. FJ44-2C engine basic performance analysis inputs

Parameters	Unit	Value
Altitude	m	0
Mach Number		0
Intake Pressure Ratio		1
Inner Fan Pressure Ratio		1.3
Outer Fan Pressure Ratio		1.5497
IP Comp. Pressure Ratio		1.6140
HP Comp. Pressure Ratio		6.1001
Design Bypass Ratio		3.35
Burner Exit Temperature	K	1,378.7
Burner Design Efficiency		0.9994
Fuel Heating Value	MJ/kg	43.124
Overboard Bleed	kg/s	0
Power Offtake	kW	0
Burner Pressure Ratio		0.9499
Inlet Corr.Flow W2Rstd	kg/s	33.9863
Nominal LP Spool Speed		18000
Isentr.Inner LPC Efficiency		0.86
Isentr.Outer LPC Efficiency		0.87
Nominal HP Spool Speed		40,000
Isentr.HPC Efficiency		0.79
Isentr.HPT Efficiency		0.86
Isentr.LPT Efficiency		0.88

term and is related to global optimization values. Eq 7 shows the position after a second of t , which we can get simply by adding $v_i(t)$.

3. Performance Analysis

3.1. On-design performance data

In accordance with public release, the take-off thrust of the FJ44-2C engine is the same as the maximum continuous thrust of 10.69 kN which is selected as the target value for the performance design as the take-off thrust in this study.

The initial inputs for the analysis are illustrated in Table 1, and Table 2 represents the performance result. The results obtained by employing the performance efficiencies of HPC, LPC, HPT, and LPT listed in Table 1 are very similar to the public released performance [11], which verifies the adaptabilities for a basic performance analysis.

where

LPC : Low Pressure Compressor

IP Compressor : Intermediate Compressor

FHV : Fuel Heating Value (MJ/kg)

FN : Net Thrust (kN)

TSFC : Thrust Specific Fuel Consumption (g/(kg*s))

WF : Fuel Flow (kg/s)

BPR : Bypass Ratio

A8 : Nozzle Area (m²)

CD : Nozzle Discharge Coefficient

WBLD : Bleed Flow (kg/s)

3.2. Design performance data evaluation

In order to conduct properly a performance analysis after analyzing an on-design data of F44-2C turbofan engine, a sub-system performance diagram is necessary for forecasting the sub-system efficiencies in the off-design condition. The ordinary sub-system diagram stacking method multiplies the relevant scaling factors, which are calculated to the design points of new engine, to the original total sub-system data. This method could be quite accurate if the new engines are similar to the reference engines. In this study, the scaling method supplied by the Gasturb model is applied to stacking a similar sub-system performance diagram [11, 12].

$$f_{Mass} = \frac{(W\sqrt{\theta_R} / \delta)_{dp}}{(W\sqrt{\theta_R} / \delta)_{R,map} \times f_{W,RNI}} \quad (8)$$

$$f_{Eff} = \frac{\eta_{dp}}{\eta_{R,map} \times f_{\eta,RNI}} \quad (9)$$

$$f_{P_3/P_2} = \frac{(P_3/P_2)_{dp} - 1}{(P_3/P_2)_{R,map} - 1} \quad (10)$$

$$f_{Speed} = \frac{1}{N_{R,map}} \quad (11)$$

where

$W\sqrt{\theta_R} / \delta$: Corrected Mass Flow

P_3/P_2 : Pressure Ratio

Table 2. FJ44-2C Design Point Analysis

Station	W	T	P	WRstd	FN	=	10.69
amb		288.15	101.325		TSFC	=	14.0314
02	7.813	288.15	101.325	7.813	P02/P1	=	1.00000
12	26.173	288.15	101.325	26.173	P12/P1	=	1.00000
2	33.986	288.15	101.325	33.986	WF	=	0.1499
13	26.173	332.21	157.023	18.135	s NOX	=	0.3735
21	7.813	314.20	131.723	6.276	Core Eff	=	0.3408
24	7.813	370.05	212.995	4.212	Prop Eff	=	0.0000
25	7.813	370.05	212.995	4.212	BPR	=	3.3500
3	7.735	675.95	1299.293	0.924	P2/P1	=	1.0000
31	7.500	675.95	1299.293		P3/P2	=	12.82
4	7.650	1378.70	1234.198	1.374	P5/P2	=	1.5872
41	7.807	1365.71	1234.198	1.395	P16/P13	=	0.97500
43	7.807	1100.85	417.284		P16/P6	=	1.00740
44	7.885	1096.90	417.284		P16/P2	=	1.51096
45	7.885	1096.90	404.765	3.851	P6/P5	=	0.94500
49	7.885	901.98	160.818		A8	=	0.04251
5	7.963	899.08	160.818	8.862	A18	=	0.08035
8	7.963	899.08	151.973	9.378	XM8	=	0.79776
18	26.173	332.22	153.098	18.600	XM18	=	0.79118
					CD8	=	0.96631
					CD18	=	1.00000
					PWX	=	0.00000
					V18/V8_id	=	0.61124
					WBLD/W21	=	0.00000
					WBLD/W25	=	0.00000
					Loading %	=	100.00
					e444 th	=	0.85597
					WHcl/W25	=	0.01000
					WLcl/W25	=	0.01000
					ZWBld	=	0.00000
Bleed Air:	PBld =	213.00	TBld =	370.1			
hum [%]	war0	FHV	Fuel				
0.0	0.00000	43.124	Generic				

- η : Efficiency
- N : Spool Speed
- f_{Mass} : Corrected Mass Flow Scaling Factor
- f_{Eff} : Efficiency Scaling Factor
- f_{P_3/P_2} : Pressure Ratio Scaling Factor
- f_{Speed} : Corrected Speed Scaling Factor
- $f_{W, RNI}$: Corrected Mass Flow Reynolds Number Effect
- $f_{\eta, RNI}$: Efficiency Reynolds Number Effect
- R, map : Reference Map
- dp : Design Point

Table 3 compares the off-design analysis results with the basic performance analysis data for net thrust and specific fuel consumption, which shows a maximum difference of 5.88% for ground and flight altitudes and flight Mach

numbers.

3.3. Performance Analysis

A performance analysis of parameters is conducted for finding major parameters, which are the bypass ratio, burner exit temperature, HP compressor ratio, fan inlet mass flow, and nozzle cooling air ratio with respect to the basic model of FJ44-2C, having effects on the net thrust and specific fuel consumption. X-axis means the net thrust and y-axis stands for the specific fuel consumption in Fig. 2 through Fig. 5.

Figure 2 shows the case of variations of the bypass ratio from 2.0 to 4.0 with 0.2 intervals and the HP compressor ratio from 4.0 to 8.0 with 0.4 intervals. Increments of the bypass

Table 3. Evaluation of performance data of FJ44-2C

Altitude(m)	Speed(M)	Net Thrust Difference (%)	SFC Difference (%)
0	0	0	0
0	0.2	-0.10	0.11
0	0.4	-0.52	0.38
0	0.6	0.14	-0.11
3,000	0	1.60	1.42
3,000	0.2	0.97	1.95
3,000	0.4	-0.11	2.68
3,000	0.6	-0.50	2.53
6,000	0	3.42	2.91
6,000	0.2	2.67	3.51
6,000	0.4	1.36	4.32
6,000	0.6	0.55	4.27
9,000	0	5.88	3.08
9,000	0.2	5.21	3.65
9,000	0.4	4.15	4.47
9,000	0.6	3.56	4.69

Fig. 2. Specific fuel consumption and net thrust to the bypass ratio vs. HP compressor Ratio

Fig. 3. Specific fuel consumption and net thrust to burner exit temperature Vs. HP compressor ratio

ratio with respect to the constant HP compressor ratio make positive linear lines in the direction of both the specific fuel consumption and the net thrust lower, and increments of the HP compressor ratio with respect to the constant bypass ratio that looks like parabolic shapes with the maximum net thrust.

Figure 3 shows the case of variations of the burner exit temperature from 1,200 K to 1,400 K with 20 intervals and the HP compressor ratio from 4.0 to 8.0 with 0.4 intervals, and increments of the burner exit temperature with respect to the constant HP compressor ratio that looks like bowl shapes with the minimum specific fuel consumption and increments of the HP compressor ratio with respect to the constant burner exit temperature initially make parabolic shapes and change to linear lines.

Figure 4 shows the case of variations of the inlet corrected mass flow from 32.0(kg/s) to 36.0(kg/s) with 0.4 intervals and the HP compressor ratio from 4.0 to 8.0 with 0.4 intervals. Increments of the inlet corrected mass flow with respect to the constant HP compressor ratio do not have an effect on the specific fuel consumption and influence only the net thrust, and increments of the HP compressor ratio with respect to the constant inlet corrected mass flow make the similar parabolic shapes with the maximum net thrust.

Figure 5 shows the case of variations of the Nozzle Guide Vane (NGV) cooling air ratio from 0.01 to 0.03 with 0.002 intervals and the HP compressor ratio from 4.0 to 8.0 with 0.4 intervals. Increments of the NGV cooling air ratio with respect to the constant HP compressor ratio make linear lines changing directions, and increments of the inlet corrected mass flow with respect to the constant HP compressor ratio make the parabolic shapes with the maximum net thrust.

Fig. 4. Specific fuel consumption and net thrust to inlet corrected flow vs. HP compressor ratio

3.4. Sensitivity Analysis

A performance optimization is conducted for maximizing the net thrust and minimizing the specific fuel consumption. The critical parameters for optimal design are bypass ratio, burner exit temperature, HP compressor compression ratio, fan inlet mass flow, and the nozzle cooling air ratio etc. When optimizing a turbofan engine performance, one must consider all potential sensitivities of the parameters. The bypass ratio (BPR), burner exit temperature (BET) and HP compressor ratio, and output parameters are set as the major input parameters since the net thrust and specific fuel consumption are not so sensitive to nozzle cooling air ratio. In this study, the OAT (One-at-a-once) Method where one parameter is changing while the other parameters are fixed, is used for sensitivity analysis [13].

Figure 6 shows the One-at-a-once (OAT) analysis results. The gradient rate of change in net thrust is the sequence of bypass ratio, burner exit temperature, HP compressor ratio as of -0.0004312, 0.00147, and -0.0000660 respectively. The burner exit temperature is the most dominant parameter of the three parameters in the rate of change of the net thrust, and the net thrust increases when the bypass ratio and HP compressor ratio decrease. The gradient rate of change in specific fuel consumption is the sequence of bypass ratio, burner exit temperature, HP compressor ratio as of -0.000154, 0.0003012, and -0.0000831, respectively. The bypass ratio is the most dominant parameter of these three in the rate of change of the specific fuel consumption, and the sensitivity of the HP compressor ratio is much less than that of the others. Also, the specific fuel consumption increases when the burner exit temperature increases.

Fig. 5. Specific fuel consumption and net thrust to NGV cooling air ratio vs. HP compressor ratio

Fig. 6. Sensitivity analysis for bypass ratio, burner exit temperature, and HP compressor ratio

4. Optimization

4.1. Net thrust optimization

The design parameters can be derived for maximizing net

thrust without reference to specific fuel consumption.

Figure 7 through Fig. 10 show the optimized PSO results with respect to the net thrust. Each case calculates 20 times of generations with 20 population size. The axis of

Fig. 7. Net thrust optimization process for bypass ratio vs. HP compressor ratio (case1)

Fig. 9. Net thrust optimization process for NGV cooling air ratio vs. HP compressor ratio (case3)

Fig. 8. Net thrust optimization process for burner exit temperature vs. HP compressor ratio (case2)

Fig. 10. Net thrust optimization process for fan inlet mass flow vs. HP compressor ratio (case4)

x means the HP compressor ratio, and the axis of y in Fig. 7 expresses the bypass ratio. Owing to consisting of the results of the optimum net thrust in 21 by 21 matrices, the scopes of the axis of x and y cover 0 thru 21. PSO figures consist of 9 regions. The processes to search the optimum solutions are shown in order from the left-hand sides to the right and from the top to the bottom. The 9 figures show 1st, 3rd, 6th, 9th, 11th, 13th, 15th, 17th, and 19th calculation, respectively. The axis of y in Fig. 8 through 10 means the burner exit temperature, the NGV cooling air ratio, and the fan inlet mass flow. Also, Table 4 through Table 7 show the typical values of the optimization of each case. Case 1 represents the optimum solution between bypass ratio from 2.0 to 4.0 and HP compressor ratio from 4.0 to 8.0. In the same manner, case 2 does optimum solution between burner exit temperature from 1200 to 1400K and HP compressor ratio from 4.0 to 8.0. Case 3 does optimum solution between fan inlet cooling air ratio from 32 to 36 and HP compressor ratio from 4.0 to 8.0. Case 4 does optimum solution between NGV cooling air ratio from 0.01

Table 4. Optimum condition of case 1

Parameters	Value
HP Compress ratio	4.6
Bypass ratio	2
Net thrust(kN)	12.9592

Table 5. Optimum condition of case 2

Parameters	Value
HP Compress ratio	4.8
Burner Exit Temperature(K)	1400
Net thrust(kN)	10.9693

Table 6. Optimum condition of case 3

Parameters	Value
HP Compress ratio	4.6
NGV Cooling Air Ratio	0.01
Net thrust(kN)	10.8416

Table 7. Optimum condition of case 4

Parameters	Value
HP Compress ratio	4.6
Fan Inlet Mass Flow(kg/s)	36
Net thrust(kN)	11.4155

to 0.03 and HP compressor ratio from 4.0 to 8.0. Among 4 different cases, we found the net thrust can be increased to a maximum of 21.2% compared with FJ44-2C basic value 10.69kN by the bypass ratio and the HP compressor ratio optimized,

4.2. Specific fuel consumption optimization

The design parameter can be derived for minimizing specific fuel consumption without reference to net thrust.

Figure 11 through Fig. 14 show the optimized PSO results with respect to the specific fuel consumption. Each case calculates 20 times of generations with 20 population size same as the net thrust optimization. The axis of x in Fig. 11 through Fig. 14 means the high pressure compressor ratio, and the axis of y in Fig. 11 expresses the bypass ratio. PSO figures consist of 9 regions. From the left-hand sides to the right and from the top to the

Fig. 11. SFC optimization process for bypass ratio and HP compressor ratio(case 5)

Fig. 12. SFC optimization process for burner exit temperature and HP compressor ratio(case 6)

bottom, they show the processes to search the optimum solutions. The axis of y in Fig. 12 through 14 means the burner exit temperature, the NGV cooling air ratio, and the fan inlet mass flow. Also, Table 8 through Table 11 show the optimized conditions of each case. Case 5 explains the optimum solution between bypass ratio from 2.0 to 4.0 and HP compressor ratio from 4.0 to 8.0. In the same manner, case 6 does optimum solution between burner exit temperature from 1200 to 1400K and HP compressor ratio from 4.0 to 8.0. Case 7 does optimum solution between fan inlet cooling air ratio from 32 to 36 and HP compressor ratio from 4.0 to 8.0. Case 8 does optimum solution between NGV cooling air ratio from 0.01 to 0.03 and HP compressor ratio from 4.0 to 8.0. In case of the bypass ratio and the HP compressor ratio optimized among 4 cases, the specific fuel consumption can be reduced to a maximum of 11.0% compared with FJ44-2C basic value 14.03 g/(kN*s).

Fig. 13. SFC optimization process for NGV cooling air ratio and HP compressor ratio (case 7)

Fig. 14. SFC optimization process for fan inlet mass flow and HP compressor ratio (case 8)

5. Conclusion

Engine performance analysis and optimization have been conducted to investigate the effect of performance design parameters on net thrust and specific fuel consumption. Gasturb 10 and particle swarm optimization (PSO) algorithm have been applied to performance analysis and the optimization of the FJ44-2C turbofan engine.

The on-design data addressed in this study provide the engine performance favorably fit to the performance data deck of Gasturb 10. Sensitivity analysis results show that burner exit temperature is the dominant parameter in the rate of change of the net thrust, and bypass ratio is the dominant one in the rate of change of the specific fuel consumption.

The PSO algorithm effectively provides the optimized objectives within 20 times of generations with 20 population size. The maximum net thrust can be increased up to 21.2% or the specific fuel consumption can be reduced up to 11.0%

Table 8. Optimum condition of case 5

Parameters	Value
HP Compressor ratio	8.0
Bypass ratio	4
SFC (g/(kN*s))	12.4887

Table 9. Optimum condition of case 6

Parameters	Value
HP Compressor ratio	8.0
Burner Exit Temperature(K)	1,310
SFC (g/(kN*s))	12.9556

Table 10. Optimum condition of case 7

Parameters	Value
HP Compressor ratio	7.2
NGV Cooling Air Ratio	0.018
SFC (g/(kN*s))	13.5641

Table 11. Optimum condition of case 8

Parameters	Value
HP Compressor ratio	8
Fan Inlet Mass Flow(kg/s)	35.8
SFC (g/(kN*s))	13.2838

by the optimized air bypass ratio and HP compression ratio.

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