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Faculty of Applied Science
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MSE426/726 – Introduction to Engineering Design Optimization –
- Final Project Report -

Optimization of the forced air induction on the Chrysler V6 engine

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Course Instructor:

Gary Wang

Author:

Dmitrii Gusev 301297008

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Abstract:

I am an electric vehicle enthusiast and I strongly believe in the gasoline-free future. At the same time, I really admire the golden era of American muscle cars when only the horsepower counts mattered. Some time ago I became the owner of the old Dodge Charger which I consider to be one of the best reincarnated muscle cars of the 2005-2010 generation. Unfortunately, it is clearly impossible to find a well-priced good condition V8 HEMI-powered car. Additionally, Lower Mainland's gas prices do not do a favor for high displacement cars. My Charger is equipped with standard Chrysler 3.5L V6 naturally aspirated engine with stock power rating of 250Hp and 250 lb-ft of torque (~340 N*m). While being a quite heavy car, this power is clearly not enough for this vehicle, thus I decided to proceed with forced air induction setup. This paper summarizes my discoveries in terms of mathematical optimization of the supercharged engine.

Optimization Problem Formulation:

Mechanical Forced Air Induction is a process when compressor (supercharger) or turbocharger is directly powered by the engine. As a general rule, a fixed gear ratio is sufficient for displacement compressors (e.g. Roots supercharger), while a variable gear ratio is necessary for most applications of turbo compressors [1].

In order to build a forced air induction, I acquired and rebuilt Eaton M90 Gen. 5 Roots supercharger previously used in General Motors L67/L32 3.8L V6 supercharged engine. This blower has displacement of 90 cubic inches (~1475 cc) per 1 rotation and contains two three-lobed rotational pistons arranged on two separate shafts as shown on the Figure #1. Main advantages of this supercharger design are simplicity and linear boost increase with respect to engine RPM. On the other hand, Roots supercharger does not provide internal air compression acting as an air pump between external environment and internal combustion chamber. While being mechanically driven air pump with no internal compression cycle, Roots supercharger allows to achieve instantaneous boost buildup, the wide range of power boost over the entire RPM map [1]. Additionally, Roots blower does not take additional measures on the “hot” exhaust side, thus it does not require intercooler when relatively low boosts are achieved (< ~12 PSI). However, Roots supercharger requires up to 10-20 HP to perform rotation provided by the host engine, thus reducing overall engine efficiency, compare to turbocharged setups that tend to increase overall engine efficiency as well as performance.

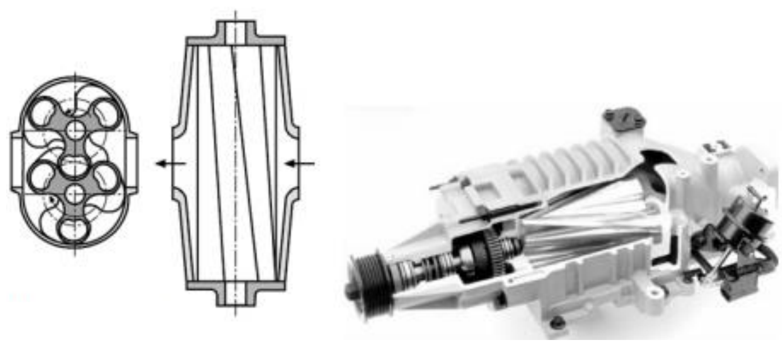

Figure #1: Eaton M62/M90 Gen. 5 General drawing [1]

Figure #2: Eaton M90 Gen. 5 placed on top of the Chrysler 3.5L V6 engine

Eaton M90 Gen. 5 Roots Supercharger specifications:

Displacement / 1 rotation:	90 cubic inches	1475 cc = 0.001475 m3
Max RPM:	12000	
Stock pulley size:	3.4 inch	86.4 mm

Chrysler 3.5L V6 Engine (production generation between 2005 and 2010) specifications:

Engine Displacement / 1 rotation:	215 cubic inches	3523 cc = 0.003523 m3
Max RPM:	7000	
Max Hp @ RPM:	250 Hp @ 6400 RPM	
Max Torque @ RPM:	250 lb-ft @ 3800 RPM	340 N*m @ 3800 RPM
Max boost @ stock engine block for safe daily operation:	8 PSI / 55 kPa / 0.5 atm	

Overall, these calculations take stock engine into consideration and do not account for all the necessary electrical and mechanical upgrades required to operate a forced air induction on this engine and the corresponding power increase prior supercharging upgrade. For example, engine requires certain parts to be replaced: new fuel system with increased gasoline volume flow rate, upgraded injectors (my choice was Mopar Stage 2/3 injectors used on Dodge SRT4 vehicles), upgraded air intake with lower operating temperature and higher volumetric flow rate. Additionally, the optimized engine performance is assumed at normal environmental conditions: 20 deg. C and 1 atm (1 atm = 14.7 psi = 101 kPa).

Mathematical optimization problem can be derived using the steps shown below. First, we are required to calculate Roots supercharger boost (either in kPa or in PSI) then it can be applied to calculate Pressure Ratio (PR) and airflow Density Ratio (DR). Second, we can derive boosted engine power based on the initial power rating and airflow pressure ratio [1].

$$Boost\ [kPa] = \left(\frac{Supercharger\ Displacement\ (SCD,\ m^3)}{0.5 * Engine\ Displacement\ (ED,\ m^3\ )}\right) * \left(\frac{Driving\ Pulley, mm}{Driven\ Pulley, mm}\right) * 101\ kPa - 101\ kPa$$

$$Pressure\ Ratio\ (PR) = \left(\frac{Boost\ (kPa) + 101\ kPa}{101\ kPa}\right) = \left(\frac{Supercharger\ Displacement\ (SCD,\ m^3)}{0.5 * Engine\ Displacement\ (ED,\ m^3\ )}\right) * \left(\frac{Driving\ Pulley, mm}{Driven\ Pulley, mm}\right)$$

$$Boosted\ Engine\ Power\ [kW] = \ Engine\ Power_{stock}\ [kW] * PR$$

Since Roots mechanically driver supercharger is used in this engine setup, it takes certain amount of engine power in order to generate boost and additional horsepower as a result, thus lowering the overall engine efficiency. Using Thermodynamics literature, we can obtain air compressor used power calculations [2].

$$Compressor\ Power\ [kW] = \ \dot{m}C_p(T_{outlet} - T_{inlet})$$

The equation above can be simplified using three main assumptions:

1. Eaton M90 does not restrict volumetric flow rate
2. Air is considered to be an ideal gas
3. Specific hear of air is assumed to at constant pressure and does not account for the engine increased temperature due to supercharging process. Constant pressure specific heat is used for this calculation

Using the assumptions above, we can further simplify this equation in according to the internal combustion engine thermosciences [3, 4].

$$\left(\frac{T_{inlet}}{T_{outlet}}\right) = \frac{101\ kPa}{Boost\ [kPa] + 101\ kPa}$$

$$Mass\ Flow\ Rate = \dot{m}\ [\frac{kg}{s}] = \frac{Volume\ Flow\ Rate\ (\dot{V}) * P_{atm}}{Universal\ Gas\ Constant\ (R) *\ T_{inlet}}$$

$$Volume\ Flow\ Rate = \dot{V}\ [\frac{m3}{s}] = \frac{Supercharger\ Displacement\ (SCD,\ \ m^3) * Supercharger\ RPM}{60}$$

Overall, Roots supercharger required power can be calculated as shown below:

$$Compressor\ Power\ [kW] = \frac{\frac{Supercharger\ Displacement\ (SCD,\ \ m^3) * Supercharger\ RPM}{60} * P_{atm}}{Universal\ Gas\ Constant\ (R) *\ T_{inlet}} C_p(T_{outlet} - T_{inlet})$$

$$T_{outlet} = \frac{(Boost\ [kPa] + 101\ kPa) *\ T_{inlet}}{101\ kPa}$$

Our goal is to use MATLAB fmincon() and ga() algorithms to perform minimization, thus our function for minimization will look like this:

$$\min \frac{1}{f(x)} = \max f(x)$$

where f(x) represents power difference between boosted engine power and power loss due to the rotation of the Roots blower.

$$f(x) = \ Boosted\ Engine\ Power\ [kW] - Supercharger\ Used\ Power\ [kW]$$

Using Boost [kPa] and Pressure Ratio formulas we can simplify equation:

$$f(x) = Stock\ Engine\ Power\ [kW] * \left(\frac{Boost\ (kPa) + 101\ kPa}{101\ kPa}\right) - \frac{Supercharger\ Displacement\ (SCD,\ m^3) * Supercharger\ RPM * P_{atm}}{60 * Universal\ Gas\ Constant\ (R) * T_{inlet}} C_p(T_{outlet} - T_{inlet})$$

We have set of predetermined fixed variables.

Engine displacement (m3):	0.003523
Stock Engine Power (Hp / kW):	250 / 186.4
Supercharger Displacement (m3):	0.001475
Universal Gas Constant (kPa*m3 / kg*K)	0.287
T inlet (C/K)	20 / 293
P atm (kPa)	101 kPa
Cp (kJ/kg*K), determined from the average internal combustion engine operating temperature and standard environment temperature. Average temperature is (20+90)/2 = 55C = 328K [2].	1.008

- ~90 deg. C is the standard working temperature for the liquid cooled engine that allows to prevent water buildup in the crankcase [3].

Because supercharger RPM is a result of the pulley ratio and engine RPM, we can simplify equation. Resulting equation to be optimized:

$$f(x) = 186.4 * \left(\frac{Boost\ (kPa) + 101\ kPa}{101\ kPa}\right) - 0.0000298 * Engine\ RPM * \left(\frac{Driving\ Pulley, mm}{Driven\ Pulley, mm}\right) * (T_{outlet} - 293)$$

Where (x) represents vector of five variables that will be changed during the mathematical optimization:

Driven Pulley (supercharger, mm)	D1
Driving Pulley (engine, mm)	D2
Engine RPM	RPM
Outlet Temperature from the supercharger (K)	Toutlet
Theoretical Boost (kPa)	B

Constraints:

Overall, I can split constraints into three groups: independent, dependent and non-linear. Independent constraints are chosen strictly between two values and the corresponding variable does not depend on other variables. Dependent constraints are set for variables that can be derived from the independent ones; however, they are required to compare model output with values obtained from the independent constraints. For example, outlet airflow temperature can be obtained from the optimized model, however it may not correlate with temperature value calculated based on the selected pulley ratio. Existence of "dependent" constraints allows us to prove how far optimized values are from the real-world problem and theoretically calculated values.

Independent constraints:

Pulley sizes can be obtained from the standard SAE pulley table. Driven pulley placed on the supercharger can vary between 2.0 inch and 3.8 inch. Driving pulley can vary between 5 inches and 9 inches in according to General Motors 3.8L V6 engine specifications.

$$50.8 \leq Driven\ Pulley\ Diameter\ [mm] \leq 96.5$$

$$127 \leq Driving\ Pulley\ Diameter\ [mm] \leq 228.6$$

Engine RPM is the next constraint. It is important to note that mathematically wise it makes sense to have zero engine RPM thus compressor will use zero power to run while generating boost. However, it does not correlate with physics of the internal combustion engine because when Engine RPM is zero, power and torque output is zero as well. Since maxed horsepower is the main goal, this code assumes RPM range between 6000 and 6600, as max stock engine power at certain RPM varies with production years and certain engine upgrades.

$$6000 \leq Engine\ RPM \leq 6600$$

Dependent constraints:

Temperature of the outlet airflow can be used between values of 304K (31 deg. C) which is theoretical temperature of the thermally insulated compressed air from the supercharger and 363K (90 deg. C) is the temperature of the engine. Otherwise, use of an intercooler will be required.

$$304 \leq T_{outlet}\ [K] \leq 363$$

Pressure constraint is related to the experimental observation obtained by the people who managed to perform supercharging of the Chrysler V6 engine. Stock aluminum engine block can safely work with the boost up to 8 PSI or 55 kPa. Lower boundary is 0 kPa which means zero engine supercharging:

$$0 \leq Boost\ [kPa] \leq 55$$

Non-linear constraints:

Supercharger RPM can be obtained from pulley drive ratio and engine RPM and must vary between 0 and 12000 RPM as specified by Eaton. Second equations show non-linear constrained applied within MATLAB code:

$$0 \leq Supercharger\ RPM \leq 12000$$

$$Engine\ RPM * \left(\frac{Driving\ Pulley, mm}{Driven\ Pulley, mm}\right) - 12000 \leq 0$$

Boost constraint based on pulley size.

$$0 \leq 84.54 * \left(\frac{Driving\ Pulley, mm}{Driven\ Pulley, mm}\right) - 101\ kPa \leq 55$$

$$84.54 * \left(\frac{Driving\ Pulley, mm}{Driven\ Pulley, mm}\right) - 156\ kPa \leq 0$$

MATLAB Optimization:

This section provides some general commentaries on the certain code sections. Full MATLAB code is attached to this report for reader's consideration.

Mathematical optimization requires user to setup initial guessed values for the fmincon() as well as set upper and lower boundaries for the fmincon() and ga().

Initial guess:

```
xInitial = [0.0762, 0.1778, 6000, 304, 20.6];
```

Upper and lower optimization boundaries are obtained directly from the previous page:

```
lower_boundary = [0.0508, 0.127, 6000, 304, 0];
upper_boundary = [0.0965, 0.2286, 6600, 363, 55];
```

Additionally, this model uses non-linear constraints because supercharger RPM and obtained boost value must be calculated using optimized belt drive ratio. Both fmincon() and ga() use non-linear constraints that must be <= 0, thus boost non-linear constraint becomes:

```
function [c ,ceq]= nonLinearBoostConstraint(x)
boostObtainedFromPulleyRatio = 84.54*x(2)/x(1); %absolute pressure boost
superchargerRPM = x(3)*(x(2)/x(1)); % belt drive ratio * engine RPM

c = [boostObtainedFromPulleyRatio - 156; superchargerRPM - 12000];

ceq =[];
end
```

Code also includes optimization options for both algorithms. Maximum population size for ga() and maximum number of evaluations for fmincon() was set to 1000.

```
optionsFMINCON = optimoptions('fmincon','Algorithm','interior-
point','Display','iter', 'MaxFunctionEvaluations', 1000);
optionsGA = optimoptions('ga', 'Display','iter', 'PopulationSize', 1000);
```

Optimization algorithm function call:

```
[x1,fval1] = fmincon(@boostedHorsePowerFunction, xInitial, A, b, [], [],
lower_boundary, upper_boundary, @nonLinearBoostConstraint, optionsFMINCON);


[x2,fval2] = ga(@boostedHorsePowerFunction, 5, A, b, [], [], lower_boundary,
upper_boundary, @nonLinearBoostConstraint, [], optionsGA);
```

Resulting equation set in MATLAB. This code minimizes 1 / maxed engine power rating, thus maximizing resulting engine power.

```
f = 1/(186.4*((x(5) + 101)/101)-0.0000298*x(3)*(x(2)/x(1))*(x(4) - 293));
```

Results and Conclusion:

Appendix section provides full list of iterations for both algorithms. This section provides analysis of the obtained results and final conclusions. As it was mentioned, two dependent variables (boost and outlet temperatures) are part of this code because they allow to see what the desired values are. However, higher boost results with higher outlet temperature what means that boost must be reduced, otherwise engine will require intercooling. My goal is to compare two algorithms against each other as well as understand why optimized and actual values of boost and temperature differ.

	FMINCON()	GA()
Driven Pulley (m)	0.0960	0.0965
Driving Pulley (m)	0.1276	0.0127
Engine RPM	6209	6000
Outlet Temperature (K/C)	304 / 31	304 / 31
Optimized Boost (kPa)	55	55
Max Engine Power (kW / hp)	285.2 / 382.5 hp	285.3 / 385.6 hp

It can be noticed that both algorithms obtain very similar results. It takes fmincon() 62 function iterations ga() needs 5 generations to optimize this mathematical model. Based on the data above and optimized RPM value, I consider fmincon() optimization to be closer in terms of real-life application because my 2008 3.5L V6 engine reaches its peak horsepower at 6400 RPM.

Once mathematical optimization is complete, code uses optimized independent variables to perform final calculations of the engine performance.

	Final values:
Driven Pulley Diameter (m) | fmincon optimized	0.0960
Driving Pulley Diameter (m) | fmincon optimized	0.1276
Engine RPM | fmincon optimized	6209
V-belt drive ratio | fmincon optimized	1.329
Supercharger Boost (kPa / psi) | fmincon optimized	55 / 8
Outlet Temperature (K) | fmincon optimized / real-world value @ 55 kPa	325 / 425
Supercharger Used Power (kW / hp)	39.2 / 52
Achieved Engine Power (kW / hp) | no supercharger cooling	248.7 / 333.5
Maxed Engine Power (kW / hp) | added supercharger cooling	285.2 / 382.5
Power loss due to air overheating (kW / hp)	36.5 / 48.9
Engine power boost	33-53 %

Based on the SAE and Eaton pulley charts, the best pulleys to use are: 3.7” (supercharger) and 5” (engine). V-belt length can be calculated accordingly.

It is important to mention that fmincon() uses maxed out boost value of 55 kPa (or 8 PSI) based on the assumption that temperature can be kept as close as possible to the desired 304K; however thermodynamic laws prove that it is clearly impossible and air temperature gradually rises up to 425K (151.85 deg. C) which is way above average internal combustion engine block temperature of 90C. Basically, it means that air overheating takes away up to 36.5 kW (or 48.9 hp) as well as results with engine overheating and potential internal damage. It is unsafe for public use to consider that car's internal thermostat will be capable of restoring engine's temperature and bringing those 48.9 hp back, however the safest and most reliable way is to install any kind of air cooler between supercharger and engine block.

Additionally, it can be noticed that Roots supercharger itself uses around 39.2 kW (or 52 hp) to operate, thus reducing overall engine performance and lowering engine efficiency. This tells us why most modern gas car manufacturers use turbocharged engines. Turbo exhaust-powered setup allows to prevent power loss due to mechanically driven compression cycle. Instead, it reuses wasted exhaust energy to perform air compression. Higher power gains can be obtained from smaller engines resulting with lowered fuel consumption.

Overall, engine power can be increased by 33 to 53% resulting with total horsepower between 333.5 and 382.5, which allows V6 supercharged engine to have V8 capabilities while total car weight is smaller by approximately 150 kgs.

References:

[1] Hiereth, H. and Prenninger, P., 2007. *Charging The Internal Combustion Engine*. Wien: Springer.

[2] Cengel, Y., 2010. *Introduction to thermodynamics and heat transfer.* 2nd ed. McGraw-Hill.

[3] Ferguson, C. and Kirkpatrick, A., 2015. *Internal Combustion Engines: Applied Thermosciences.* 3rd ed. Chichester: Wiley.

[4] Vizgalov, S., Chekushkin, G. and Volkov, M., 2015. *Investigation of three lobes roots blower with special ejector.* IOP Conference Series: Materials Science and Engineering, Vol. 90, p.12-18.

Appendix:

Main code:

```
%MECHANICALLY DRIVEN FORCED AIR INDUCTION OPTIMIZATION FOR THE GAS ENGINE |
%MSE426 | SPRING 2020
%CODE BY DMITRII GUSEV, ID: 301297008

clear all
clc

% INITIAL CONDITIONS
% DRIVEN PULLEY (meter), DRIVING PULLEY (meter), ENGINE RPM, TEMPERATURE OF
% THE OUTLET AIR (KELVIN) AND THEORETICAL BOOST (KPA)
xInitial = [0.0762, 0.1778, 6000, 304, 20.6]; %initial guess
lower_boundary = [0.0508, 0.127, 6000, 304, 0]; %lower boundary
upper_boundary = [0.0965, 0.2286, 6600, 363, 55]; %upper boundary

%mathematical model options for FMINCON() and GA()
A = [];
b = [];
optionsFMINCON = optimoptions('fmincon','Algorithm','interior-
point','Display','iter', 'MaxFunctionEvaluations', 1000);
optionsGA = optimoptions('ga', 'Display','iter', 'PopulationSize', 1000);

%fmincon optimization
[x1,fval1] = fmincon(@boostedHorsePowerFunction, xInitial, A, b, [], [],
lower_boundary, upper_boundary, @nonLinearBoostConstraint, optionsFMINCON);

x1;
maxedEnginePowerFMINCON = 1/fval1;

%ADDITIONAL CALCULATIONS FOR THE FINAL ENGINE GAINS
pulleyBasedBoostFMINCON = 84.54*(x1(2)/x1(1)) - 101;
temperatureAtOutletBasedOnPulleyRatioFMINCON = 293*(pulleyBasedBoostFMINCON +
101)/101;

boostFMINCON = x1(5);
temperatureAtOutletBasedOnFMINCON = 293*(boostFMINCON + 101)/101;

superchargerUsesKWFMINCON =
0.0000298*x1(3)*(x1(2)/x1(1))*(temperatureAtOutletBasedOnFMINCON - 293);
achievedEnginePowerKWFMINCON = 186.4*((x1(5) + 101)/101)-
0.0000298*x1(3)*(x1(2)/x1(1))*(temperatureAtOutletBasedOnFMINCON - 293);
achievedTorqueNMFMINCON = (30000/pi)*achievedEnginePowerKWFMINCON / x1(3);
superchargerRPMFMINCON = x1(3)*(x1(2)/x1(1));
powerLossDueToOverHeatingFMINCON =
(0.0000298*x1(3)*(x1(2)/x1(1))*(temperatureAtOutletBasedOnFMINCON - 293)) -
0.0000298*x1(3)*(x1(2)/x1(1))*(x1(4) - 293);

%genetic algorithm optimization
[x2,fval2] = ga(@boostedHorsePowerFunction, 5, A, b, [], [], lower_boundary,
upper_boundary, @nonLinearBoostConstraint, [], optionsGA);

x2;
```

```
maxedEnginePowerGA = 1/fval2;

%ADDITIONAL CALCULATIONS FOR THE FINAL ENGINE GAINS
pulleyBasedBoostGA = 84.54*(x2(2)/x2(1)) - 101;
temperatureAtOutletBasedOnPulleyRatioGA = 293*(pulleyBasedBoostGA + 101)/101;

boostGA = x2(5);
temperatureAtOutletBasedOnGA = 293*(boostGA + 101)/101;

superchargerUsesKWGA =
0.0000298*x2(3)*(x2(2)/x2(1))*(temperatureAtOutletBasedOnGA - 293);
achievedEnginePowerKWGA = 186.4*((x2(5) + 101)/101)-
0.0000298*x2(3)*(x2(2)/x2(1))*(temperatureAtOutletBasedOnGA - 293);
achievedTorqueNMGA = (30000/pi)*achievedEnginePowerKWGA / x2(3);
superchargerRPMGA = x2(3)*(x2(2)/x2(1));
powerLossDueToOverHeatingGA =
(0.0000298*x2(3)*(x2(2)/x2(1))*(temperatureAtOutletBasedOnGA - 293)) -
0.0000298*x2(3)*(x2(2)/x2(1))*(x2(4) - 293);
```

Function code:

```
function [f] = boostedHorsePowerFunction(x)
% Calculate objective f
f = 1/(186.4*((x(5) + 101)/101)-0.0000298*x(3)*(x(2)/x(1))*(x(4) - 293));
end
```

Non-linear constraints:

```
function [c ,ceq]= nonLinearBoostConstraint(x)
boostObtainedFromPulleyRatio = 84.54*x(2)/x(1); %absolute pressure boost
superchargerRPM = x(3)*(x(2)/x(1)); % belt drive ratio * engine RPM

c = [boostObtainedFromPulleyRatio - 156; superchargerRPM - 12000];

ceq =[];
end
```

Fmincon() run:

Iter	F-count	f(x)	Feasibility	First-order optimality	Norm of step
0	6	4.557570e-03	2.002e+03	1.364e-03	
1	12	4.557462e-03	1.987e+03	1.362e-03	2.410e-02
2	18	4.605284e-03	0.000e+00	2.297e-03	3.975e+02
3	24	4.605249e-03	0.000e+00	2.296e-03	9.491e-02
4	31	4.604541e-03	0.000e+00	2.286e-03	1.838e+00
5	38	4.601308e-03	0.000e+00	2.243e-03	6.749e+00
6	45	4.592261e-03	0.000e+00	2.122e-03	2.378e+01
7	59	4.590660e-03	0.000e+00	2.050e-03	3.181e-01

8	67	4.590376e-03	0.000e+00	2.045e-03	1.033e+00
9	83	4.589475e-03	0.000e+00	1.966e-03	3.252e-01
10	99	4.591047e-03	0.000e+00	1.904e-03	1.996e-01
11	105	4.590912e-03	0.000e+00	1.900e-03	6.187e-01
12	111	4.586036e-03	0.000e+00	1.809e-03	3.319e+01
13	135	4.586036e-03	0.000e+00	2.962e-04	2.596e-03
14	141	4.584908e-03	0.000e+00	2.852e-04	6.847e+00
15	148	4.580591e-03	0.000e+00	6.131e-04	2.577e+01
16	155	4.576902e-03	0.000e+00	1.422e-03	1.646e+01
17	162	4.577125e-03	0.000e+00	2.135e-03	1.530e+01
18	168	4.579001e-03	0.000e+00	1.736e-03	2.058e+01
19	174	4.579025e-03	0.000e+00	1.680e-03	1.689e-02
20	180	4.579060e-03	0.000e+00	1.671e-03	4.296e-01
21	186	4.578966e-03	0.000e+00	1.660e-03	2.777e-01
22	192	4.578274e-03	0.000e+00	1.646e-03	3.555e-01
23	198	4.574667e-03	0.000e+00	1.609e-03	3.140e+00
24	204	4.556963e-03	0.000e+00	1.453e-03	1.645e+01
25	210	4.478509e-03	0.000e+00	7.722e-04	7.566e+01
26	217	4.264932e-03	0.000e+00	5.199e-04	2.219e+02
27	223	4.334192e-03	0.000e+00	6.385e-04	1.093e+02
28	229	4.292893e-03	0.000e+00	5.627e-04	6.022e+01
29	236	4.290654e-03	0.000e+00	5.576e-04	2.599e+00
30	242	4.290219e-03	0.000e+00	5.560e-04	6.511e-02
31	248	4.288715e-03	0.000e+00	5.557e-04	7.077e-02
32	254	4.281319e-03	0.000e+00	5.595e-04	3.274e-01
33	260	4.245348e-03	0.000e+00	5.808e-04	1.594e+00
34	266	4.085989e-03	0.000e+00	6.718e-04	7.507e+00
35	272	3.613469e-03	0.000e+00	8.853e-04	2.802e+01
36	279	3.717673e-03	0.000e+00	8.867e-04	2.091e+01
37	285	3.631490e-03	0.000e+00	8.658e-04	4.114e+01
38	291	3.665892e-03	0.000e+00	8.820e-04	2.257e+01
39	297	3.665981e-03	0.000e+00	8.084e-04	4.159e+00
40	303	3.666009e-03	0.000e+00	7.905e-04	3.123e-01
41	309	3.666006e-03	0.000e+00	7.876e-04	1.495e-02

42	315	3.666005e-03	0.000e+00	7.873e-04	6.214e-03
43	321	3.666004e-03	0.000e+00	7.873e-04	6.771e-04
44	327	3.665998e-03	0.000e+00	7.872e-04	2.879e-03
45	333	3.665972e-03	0.000e+00	7.869e-04	1.539e-02
46	339	3.665840e-03	0.000e+00	7.855e-04	7.699e-02
47	345	3.665182e-03	0.000e+00	7.782e-04	3.833e-01
48	351	3.661966e-03	0.000e+00	7.425e-04	1.878e+00
49	357	3.647495e-03	0.000e+00	5.827e-04	8.540e+00
50	363	3.601283e-03	0.000e+00	4.517e-04	2.966e+01
51	369	3.572753e-03	0.000e+00	4.101e-05	5.159e+01
52	375	3.582626e-03	0.000e+00	5.648e-05	1.784e+01
53	382	3.582087e-03	0.000e+00	4.000e-05	8.191e-01
54	388	3.535150e-03	0.000e+00	2.277e-04	5.751e+00
55	395	3.526750e-03	0.000e+00	2.506e-04	1.069e+01
56	402	3.526296e-03	0.000e+00	3.638e-05	7.797e+00
57	409	3.526294e-03	0.000e+00	8.000e-06	1.403e+00
58	416	3.514539e-03	0.000e+00	8.554e-05	2.694e+01
59	432	3.513710e-03	0.000e+00	2.486e-06	7.368e-02
60	448	3.511998e-03	0.000e+00	2.234e-05	1.682e-01
61	460	3.509282e-03	0.000e+00	5.708e-06	3.042e-01
62	472	3.506464e-03	0.000e+00	1.610e-07	3.410e-01

ga() run:

Generation	f-count	Best f(x)	max constraint	Stall Generations
1	53000	0.00351088	0	0
2	105000	0.0035049	0	0
3	157000	0.00350488	0	0
4	209000	0.00350488	0	0
5	261000	0.00350488	0	0