Reducing the Turbo Lag of a Fixed Geometry Turbocharger

Ali Assi[1], Bassel Chokor[1], Mohamad Hammoud[1,2], Ali Hallal[1], Ali AL Shaer[1], and Bakri Abdulhay[1]

[1]SDM Research Group, Mechanical Department, School of Engineering
Lebanese International University, Beirut, Lebanon

Abstract

The use of turbochargers is becoming increasingly popular in automotive applications and an essential method to compensate the lost energy in an engine. The main function of the turbocharger is to benefit from the exhaust of the engine, by the application of a turbine attached to a compressor via a shaft, into providing more air, thus more oxygen, to the engine in order to enhance the combustion process of the fuel into generating a more effective torque. However, the mass moment of inertia of the turbine, being made of high density material, poses a response-lag (called Turbo-lag), which is a time-delay for the turbine to reach the needed rotational speed to achieve a boost. The aim of this paper is to find material that can replace the nickel based Inconel or titanium alloy in the making of the turbine in order to reduce the Turbo lag, and still maintain the temperature resistance, pressure tolerance, and a factor of safety to resist failure. The main domain of this research is the composite materials field, which is becoming the essence of the new industrial and technological designs. Four materials were studied; Zirconium Oxide, Silicon Nitride, Silicon Carbide, and Boron Carbide. Silicon Nitride was the suitable material to the application of the turbine wheel in a turbocharger due to its mechanical properties and its high heat resistance.

Keywords: *Turbocharger, Heat Resistance, Mechanical Properties, Composites material.*

1. Introduction

Increasing the power output of the internal combustion engine through additive methods was a primary concern in the automotive industry. For this purpose, increasing the pressure of the air-fuel mixture at the inlet of the engine seemed the most operable way to achieve it. This method was applied by the designing the concept of supercharging, which is providing the combustion process with air pressurized more than the atmospheric pressure by the use of a compressor connected at the inlet manifold of the engine, thus yielding more horsepower while preserving the same given combustion engine. There are three ways of supercharging depending on the way the compressor is driven; they are as follows:

- Independently driven compressors: The compressor is run by an independent auxiliary engine that could be run electrically to operate the compressor [1].
- Engine Driven Compressor: The compressor is connected directly by the fly wheel of the engine. A fraction of the engine’s total power output would be consumed by the compressor for supercharging, and that isn’t preferable since it increases the fuel consumption. For example, if a supercharger which will technically increase the horsepower of the car an extra 150 hp is used, but its compressor consumes 50 hp to operate, the result would be an increase of 100 hp for the engine only. This method was later called solely “supercharging” to differentiate between it and the next method [1].
- Turbocharging: This method proved to be a success since it is driven solely by the exhaust gases acquired by the combustion, hence not requiring any additional power to operate it.

Turbochargers went under many developments since they were invented. The main goal of a turbocharger is to compress air entering the engine but using mechanical energy, in order not to consume any of the power output of the engine. In normally-aspirated engines, the pressure of the air going into the cylinders is equal to the atmospheric pressure; air enters directly to the intake manifold from the atmosphere. When a turbocharger is introduced, air is interrupted with the compressor before entering the intake manifold in order to be compressed. The operation starts when burnt gases exit the cylinders through the exhaust, then they enter the turbocharger on the turbine wheel side. The gases hit the turbine wheel in axial direction making it rotate, therefore running the compressor. The compressor is made of a centrifugal wheel that encounters the air coming from the atmosphere, compresses it then it sends it to the intake manifold of the engine.

Turbochargers were classically made of a turbine wheel which is made of steel or highly heat-resistant nickel-base alloy (Inconel) [2] and in some cases, titanium. The turbine wheel is connected to a compressor which was in general made up of aluminum alloys, but later in 1990’s new materials like titanium alloys, magnesium alloys and stainless steel were introduced into the production of the compressor wheel [2, 3]

The rotor of a turbocharger as shown in Fig. 1 which is made up of the turbine wheel, the shaft and the compressor reaches very high speeds since it turns with a speed of 160,000 to 300,000 rpm. In a gasoline engine, the temperature of the exhaust gas reaches up to 1050°C, so the turbine wheel must be made of materials that can withstand such high temperature, and that was why turbochargers turbine wheels were made up of metal alloys. The classical turbochargers were simple and were made with this rotor system without extra modifications. But this system, however, was functional only to a high-boost application, where the larger mass flow rate of the exhaust gases was sufficient to rotate the turbine in a tolerated time and produced the needed boost. However, at low-end torques (i.e. torques produced at low engine speed (rpm)), the turbine was simply too heavy and large compared to the given exhaust gases flow rate. Thus, it could not reach sufficient rotation needed so that the compressor could compress air enough to produce boost (extra engine power). This disadvantage raised the principle of turbo lag.

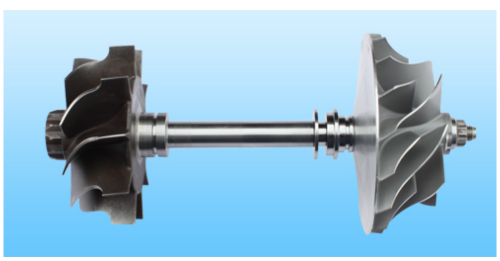

Fig. 1: Turbocharger rotor showing the compressor (right wheel) and turbine (left wheel) [4]

Turbochargers depend on a turbine wheel to operate which in turn depends on exhaust gases energy. But exhaust gases energy depends on the quantity of gas being expelled out of the cylinders which in turn depends on the speed of which the engine is operating. Consequently, scientists faced a problem at low engine rpms; the turbocharger couldn't give sufficient boost in power to the engine. Therefore, when the engine is accelerating, it needs to get to a threshold rpm for the turbocharger to give sufficient boost. The time between the beginning of acceleration when the driver presses on the gas pedal and the time when the turbocharger boosts the engine, is called turbo lag. Earlier scientists tried installing smaller turbochargers which would spool relatively quickly so they would give an engine a boost at low rpm's. However, the disadvantage was that it cannot boost an engine's power at high rpm because of its low capability [4].

To reduce turbo lag, scientists supposed different solutions such as reducing the rotational inertia of the turbine wheel, reducing bearing losses due to friction, using multiple turbochargers in parallel, or varying the geometry of the turbocharger [3]. All Those suggestions were introduced to classical turbochargers of fixed geometry [4]. Classically turbochargers were made with fixed geometry rotors as discussed earlier which consisted of a turbine that had a fixed geometry and nickel-base alloy material. To improve turbochargers productivity and reduce turbo lag, scientists maneuvered around the design of the turbocharger and invented three different designs as follows:

- Twin Turbo: It is called also bi-turbo, and it consists of two turbochargers, separated and working in parallel sequence. The two turbos are fed each with half of the exhaust gas, and one is small and operates at low rpms, while the second is relatively larger and starts when the engine reaches a specific minimum rpm. Therefore, the engine will receive boost a both low rpms and high rpms with both turbochargers installed [4].
- Twin Scroll: Also called divided turbochargers, consist of two exhaust gas inlets and two nozzles. The smaller nozzle has a sharper angle for quick response at low rpms, while the bigger nozzle is designed with a less sharp angle for high rpms. This allows the turbocharger give satisfactory performance at both low and high rpms, and reduces turbo lag [4].
- Variable Geometry: A turbocharger equipped with vanes that could adapt to the exerted pressure by the exhaust inlet, the vanes' angular position is variable and thus determines the angle of attack and affects the velocity vector of the exhaust gas flowing on turbine blades. The vanes angle decreases in order to open up, thus increasing the absolute pressure of the gases on the turbine wheel. Hence, the turbine wheel spools up easily at low rpms when the vanes are closed and high rpms when vanes open.

It is true that new designs were proposed to reduce turbo lag, but the fixed geometry turbocharger is still one of the most-widely used configurations and still has applications in the industry. Since new designs are relatively costly, in the present work, changing the material of the turbine wheel in a fixed geometry supercharger with newly-developed composite lightweight materials that endure same conditions is proposed. The lower density of composite materials compared to metals will reduce the rotational inertia of the turbine wheel significantly. Consequently, it will spool up quickly at low rpms and have enough size to give boost also at high speeds.

The paper is organized as follows: In section 2 four kinds of composite materials are proposed and their properties are compared with Inconel which is abundantly used in the manufacturing of turbochargers' turbines. In section 3, a thermodynamic analysis is conducted in order to derive the time response equation of a turbocharger's turbine wheel, also an experiment was performed to calculate the moment of inertia of a rotor made of Inconel 713C and thus evaluating, by proportion, the inertia of rotors made of the different materials we proposed. Time response attained with each material is then calculated for further comparison, and the most applicable material to be used instead of Inconel is chosen. Finally, concluding remarks are stated in section 4 as a summing up of the study.

2. Composite materials examination

Classically, the turbine blades of the turbocharger were made of Inconel 713C [3], but the drawback of this material is the high density it has. The main characteristics that made Inconel suitable for turbocharging applications are its high strength to withstand the conditions that the turbine blades endure. In order to reduce turbo lag, a new lighter material having similar (or better) characteristics of Inconel 713c will be selected. Inconel has the following thermal and mechanical properties as shown in Table 1:

Table 1: Mechanical and thermal properties of Inconel 713C [2]

Density	g/cm^3	7.91
Melting Range	°C	1260-1288
Tensile Strength	MPa @ 980°C	472
Tensile Strength	MPa @ R.T	758

Where R.T means Room Temperature.
The required material is chosen based on the following criteria:

- Temperature tolerance: the exhaust gas temperature may reach up to 1050^{o}C [7] in gasoline engines, thus, for increasing factor of safety, the material must endure a temperature of at least 1400^{o}C before failure.
- Low density: Lower density yields lower mass of the turbine, which means a lesser mass moment of inertia that is proportional to the response-time of the turbine by the equation
- Hardness: The exhaust gas exerts a large traction force on the turbine wheel; the material chosen must endure it without failure or fracture, and thus have high hardness.
- Tensile strength: The material should endure the high pressure exerted by the exhaust has on the turbine wheel. The required tensile strength will be compared to that of Inconel 713C at room temperature and at temperatures that range between 900^{o}C and 1200^{o}C.

Four kinds of ceramic composites with the nickel based alloy Inconel 713C will be investigated to find out the best choice in comparison of properties and applicability. The proposed composites are Silicon Nitride, Silicon Carbide, Boron Carbide and Zirconium Oxide.

- Silicon Carbide is also known as carborundum and is a combination between silicon and carbon. Its chemical formula is SIC and is produced from Silicon Oxide SiO_2 found in plant material. It is applied in various electrical, cutting and mechanical uses. It is used in bulletproof vests and in car brake for its ability to withstand high temperatures and pressure [8]. It is proposed as a possible choice for turbine blades since it has the following properties as shown in Table 2:

Table 2: Mechanical and thermal properties of Silicon Carbide (SiC) [6]

Density	g/cm^3	3.21
Hardness	Knoop (kg/mm^2)	2800
Tensile Strength	MPa @ R.T	310
Use T in air (max)		1400

- Silicon Nitride have been used earlier in automotive industry and its chemical formula is Si_3N_4 which is a combination of silicon and nitrogen to form a relatively hard composite that withstand high temperatures and stress, as can be seen in through Table 3:

Table 3: Mechanical and thermal properties Silicon Nitride (Si_3N_4) [6]

Density	g/cm^3	3.31

Hardness	Knoop (kg/mm^2)	2200
Tensile Strength	MPa @ R.T	360-434
Tensile Strength	MPa @ 1200°C	372
Use T in air (max)	ºC	1500

- Boron Carbide has a chemical formula of B_4C and it is a composite made of boron with carbon to form a strong and hard material. It was discovered in the 19th century but it chemical formula was not known until the 1930s. Boron Carbide is one of the hardest materials there is, it just comes third to cubic boron nitride and diamond in hardness. Its properties are listed in details in Table 4:

Table 4: Mechanical and thermal properties of Boron Carbide (B_4C) [6]

Density	g/cm^3	2.51
Hardness	Knoop (kg/mm^2)	2900-3580
Tensile Strength	MPa @ 980°C	150
Use T in air (max)	ºC	500

- Zirconium Oxide, having a chemical formula ZnO_2 is made up of zinc and oxygen atoms. Zirconia also has high hardness and toughness, but comes shorter when compared to other materials because it cannot withstand high temperatures as specified Table 5:

Table 5: Mechanical and thermal properties Zirconium Oxide (ZnO_2) [6]

Density	g/cm^3	6.04
Hardness	Knoop (kg/mm^2)	1600
Tensile Strength	MPa @ R.T	248
Use T in air (max)	ºC	500

The thermal properties of the materials were judged based on a comparison with those of Inconel-713C, knowing that it has a maximum allowed temperature before failure of 1260ºC – 1288ºC. As for the mechanical properties, Boron Carbide possessed the highest hardness, following it Silicon Nitride and Silicon Carbide. However, hardness is an opposite characteristic to toughness; Inconel-713C possesses a higher tensile strength than all the proposed material, and boron carbide has the least 155MPa at 980ºC. Among the proposed material, Silicon Nitride has the highest tensile strength but still less than the nickel-base alloy at room temperature. However, the tensile strength of Silicon Nitride is less affected by temperature than that of Inconel, due to its higher heat resistivity. At a temperature of 980^{o}C, the tensile strength of Inconel was 471.6 MPa, which indicates a large drop with increasing temperature, while Silicon Nitride had a tensile strength of 372 MPa at 1200ºC indicating a simple decrease over the increasing temperature. To further examine the properties difference between Silicon Nitride, Boron Carbide and Inconel 713C we calculated the specific tensile strength as shown in Fig. 2 of each of those materials at high temperatures and it is clearly found that Silicon Nitride beats both of them easily with a high specific tensile Strength of 112.39. Knowing that Inconel 713C fails at 1260ºC while Silicon Nitride still has a high tensile strength at this temperature, we can conclude that Silicon Nitride is more suitable for the turbine wheel, which experiences a sudden increase of temperature when protruded by the exhaust gas.

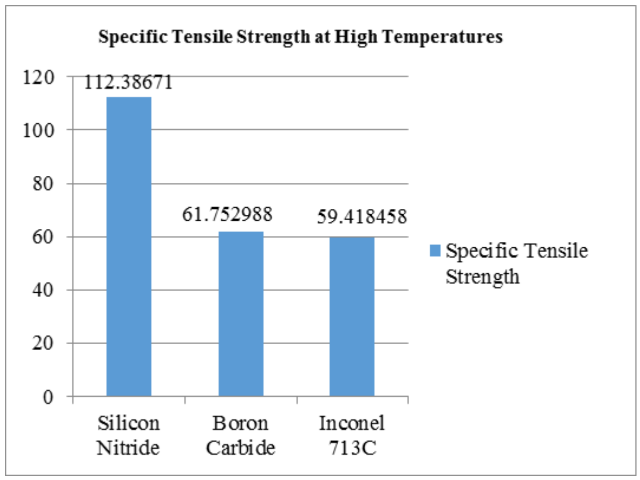

Fig. 2: Specific Tensile Strength of some Composite materials at high temperature.

Based on the study done before, we conclude for each material the following:

- Zirconium Oxide: This material has a high density of 6.04 g/cm^3 with respect to other materials, and though it has acceptable mechanical properties of compressive strength (2500 MPa) and hardness (1600 kg/mm^2), its maximum applied temperature before failure is 500^{o}C, which is very low considering that the exhaust temperature can reach up to 1050ºC. Its tensile strength is 248 MPa, which is inapplicable as a turbocharger turbine wheel. Zirconium Oxide is thus eliminated from the proposed materials.
- Silicon Carbide: This material has a low density of 3.21 g/cm^3, and a high hardness of 2800 Knoop

(kg/mm^2) and good compressive strength (1725-2500 MPa @ Room Temperature (R.T)). It also has a maximum applied temperature of 1400ºC, which presents a factor of safety of 1.33. Its tensile strength is 310 MPa at room temperature. Thus, Silicon Carbide is a candidate material, but has a high risk of failure regarding tensile stress.

- Boron Carbide: This material has the least density among the proposed materials, weighing at 2.51 g/cm^3. It is also has the third highest hardness (2900-3580 Knoop) following diamonds and Boron Nitride. But its low maximum use temperature of 500 ºC which is because it begins to oxidize and low tensile strength of 155 MPa at high temperatures, which is far less than Inconel, make it not fit for the use in turbochargers. Thus, Boron Carbide cannot be applied as a turbine wheel for a turbocharger.
- Silicon Nitride: This material has a low density of 3.31 g/cm^3, and a good hardness of 2200 Knoop and good compressive strength (687-2760 MPa @ room temperature). It also endures an applied temperature of 1500ºC, which presents a factor of safety of 1.42. It has a tensile strength that ranges up to 434 MPa at room temperature and high heat resistance that allows it to maintain a tensile strength of 372 MPa at 1200^{o}C and specific tensile strength of 112.39, which as elaborated previously proves a better applicability than Inconel.

In conclusion, Silicon Nitride is the most qualified material regarding its properties and its ability to withstand the temperature and pressure of the exhaust gas at the turbine wheel.

3. Qualitative Study and Results

Some essential thermodynamic characteristics of gases are needed to understand the turbocharging process. It is safe to assume while analyzing turbochargers that the charge air and exhaust gas are compressible ideal gases. Due to the expansion of the exhaust gases out of the engine in the turbine, turbine power that depends on the mass flow rate of the exhaust gas through the turbine and the isentropic enthalpy drop in the turbine is generated. The effective turbine power is given by [5]:

$$Pt = \eta_T . \dot{m} . |\Delta h_{st}| \quad (1)$$

The isentropic enthalpy drop in the turbine stage is calculated using thermodynamic equation:

$$\Delta h_{st} = C_p . T_i . \left[1 - \left(\frac{P_e}{P_i} \right)^{\left(\frac{k-1}{k} \right)} \right] \quad (2)$$

Where k is the isentropic exponent of the gas exhaust:

$$K = \frac{c_p}{c_v} = 1.32$$

Thus, the equation of power of the turbine is:

$$P_t = \eta_T . \dot{m} C_p . T_i . \left[1 - \left(\frac{P_e}{P_i} \right)^{\left(\frac{k-1}{k} \right)} \right] \quad (3)$$

Where η_T is the isentropic efficiency of the turbine. It normally ranges between 65% and 70%. $\dot{m}$ is the mass flow rate at the inlet of the turbine, C_p is the specific heat capacity of the exhaust gas, Ti is the temperature of the exhaust gas at the inlet of the turbine, and $\left(\frac{P_e}{P_i} \right)$ is the expansion pressure ratio of a turbine.

Similarly, using the thermodynamics analysis on the compressor, an equation of the compressor power as a function of mass flow rate, inlet conditions and compression ratio can be obtained:

$$P_C = \frac{\dot{m} C_p . T_i}{\eta_C} . \left[\left(\frac{P_e}{P_i} \right)^{\left(\frac{k-1}{k} \right)} - 1 \right] \quad (4)$$

To determine the parameters needed for this equation, a compressor efficiency map is used, where the efficiency of the compressor and the rotor speed are determined as a function of mass flow rate and compression ratio. An example on the calculation of compressor power is shown below, as well as the compressor map. One way to calculate the mass flow rate in the turbocharging process is to use the specifications of the engine along the density of the compressed air at the intake manifold.

For a naturally aspirated four-cylinder, four stroke gasoline engine, having: V_d = 2.316 cm^3, bore = 96 mm, stroke = 80 mm and a volumetric efficiency of 0.84, this engine is turbocharged. At an engine speed of N = 90 rps, compression ratio equal to 1.5, the mass flow rate as a function of volumetric efficiency, density of compressed air-fuel mixture, engine speed and displaced volume of the engine can be calculated using the following equation:

$$\dot{m} = \frac{E_v . \rho_i . V_d . N}{2} \tag{5}$$

Assuming air to be an ideal gas, the density can be calculated by the ideal gas equation where the pressure is 1.5 times the atmospheric pressure, thus the mass flow rate is $\dot{m} = 0.14$ kg/s .

Tracing the compressor map shown in Fig. 3, we can estimate the compressor efficiency and the rotor speed at the given conditions of mass flow rate and compression ratio:

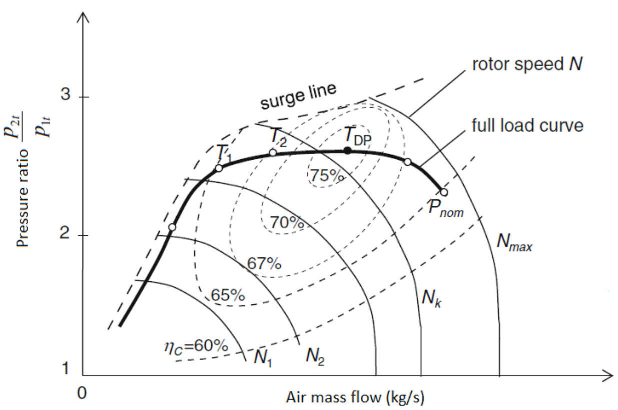

Fig. 3: Compressor performance map of a turbocharger [5]

Compressor efficiency = 0.65, Rotor speed N = 1660 rps. For the determined parameters, the power of the compressor can now be determined: P_c = 8.2 KW. Since the turbine and the compressor are joined by a shaft, the power of the compressor Pc results from the power of the turbine and the mechanical bearing efficiency η_m, thus:

$$P_C = \eta_C P_t = \eta_C . \eta_T . \dot{m} . C_p . T_i . \left[1 - \left(\frac{P_e}{P_i} \right)^{\left(\frac{k-1}{k} \right)} \right] \tag{6}$$

The time-response τ_{90} is defined by the minimum time required to reach the boost threshold of 90% of the maximum engine torque T_{max}. The time-response is mainly dependent on the effective turbine power and the polar mass moment of inertia of the rotor system. Using the dynamics equation, the angular acceleration α of the rotor system is calculated by:

$$\eta_C P_t - P_C = I_P . \alpha . W \tag{7}$$

Where I_P is the polar mass moment of inertia of the rotor system and Ω is the angular velocity of the rotor system. The rotor speed N_{TC} is calculated using the equation: $N_{TC} = \Omega / 2\pi$

Integrating the angular acceleration with respect to time, and then substituting the equations to eliminate the angular acceleration, we obtain the equation of the time response

$$\tau_{90} = \frac{4\pi^2 I_P N_{90}^2}{\eta_m P_t - P_C} \tag{8}$$

Where P_t is the effective turbine power, P_C is the effective compressor power, and η_m is the mechanical efficiency of the bearing system.

For a better transient response of the turbocharger, the time response τ_{90} must be reduced. For the reduction of the time response, the usage of other lighter material, that can also endure the conditions in the exhaust system, is proposed in two cases; the first one for the Inconel-713C turbine and the second one for the proposed material. For a given value of the rotor speed N_{90}, by taking $(N_{90})_1 = (N_{90})_2$, an equation can be set up to calculate the turbo lag. The effective power of the turbine P_t and the compressor P_C depend on the efficiency, the mass flow rate, the inlet gas temperature, and the expansion/compression ratios, i.e. it has no direct relation to the angular acceleration and to the polar mass moment of inertia of the used material. In the present application, the geometry of the compressor is conserved, and since the main aim is to reach the same rotor speed, the compression ratio is also conserved. In other words, the power of the turbine and the power of the compressor can be taken as constant with the material variation, $(P_C)_1 = (P_C)_2$ and $(P_t)_1 = (P_t)_2$

Setting up the ratio between $(\tau_{90})_1$ and $(\tau_{90})_2$, the following ratio is obtained:

$$\frac{(\tau_{90})_1}{(\tau_{90})_2} = \frac{I_{P1}}{I_{P2}} \quad (9)$$

Turbochargers rotor geometry is very complicated and could not be calculated using a given equation. To measure the frequency, we suspended the rotor using a mild steel wire from a fixed support as shown in Fig. 4, then the moment of inertia is calculated using the following frequency equation:

$$f = \frac{1}{2\pi}\sqrt{\frac{GI}{Jl}} \quad (10)$$

Where *f* is the frequency in *Hz*, *G* is the modulus of rigidity of mild steel calculated using:

$$G = \frac{E}{2(1+\upsilon)} \quad (11)$$

Where *E* and υ are the modulus of elasticity and Poisson's ratio of mild steel, respectively. *L* is the length of the wire used to do the experiment, and *J* is the second moment of inertia of the wire which is calculated using the following equation:

$$J = \frac{\pi d^4}{32} \quad (12)$$

Where *d* is the diameter of the wire.

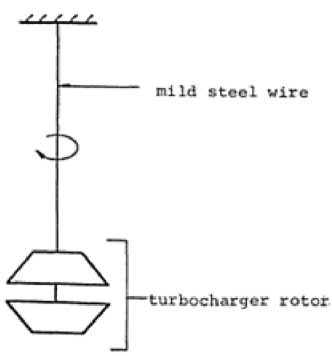

Fig. 4: Setup diagram of the experiment

The procedure of the experiment as shown in Fig. 5 followed the steps below:

a. Rotate the rotor with a given angle
b. Wait till the end of two oscillations
c. Record the time
d. Divide by two to get the time the rotor takes to do one period
e. Calculate the frequency by getting the reciprocal of the period: *f = 1/T*

Fig. 5: Experimental setup to measure the inertia of the turbocharger rotor

Table 6 shows the collected data from the experiment:

Table 6: Collected data for the inertia calculation experiment

Diameter of wire	m	0.001
Length of wire	m	0.4
Modulus of Elasticity of mild	GPa	210
Poisson's ratio of mild steel		0.303
Time of two oscillations	s	2.11

After calculating the frequency, we will apply the following equation to calculate the inertia:

$$I = \frac{GJ}{4\pi^2 f^2 l} \quad (13)$$

The inertia calculated by this experiment will be of the given rotor we used, which had a turbine wheel made of Inconel. Now to calculate the inertia of rotors made of turbine wheel with different materials, we will use the law of proportionality since the new rotors will have the same geometry of the rotor we used in the experiment. The inertia of the rotor is proportional to the density of the turbine wheel and to the diameter. We can calculate the inertia of any new rotor with different turbine wheel's material using the following equation:

$$I_2 = \frac{\rho_2 . I_1}{\rho_1} \quad (14)$$

Where I_1 is the inertia of rotor made of Inconel 713C, I_2 is the inertia of rotor made of new material, ρ_1 is the density of Inconel 713C and ρ_2 is the density of new material. The calculated results of the experiment are shown in Table 7.

Table 7: Results of inertia calculation experiment

Parameter	unit	Value
G	GPa	80.5833
T	s	1.055
F	Hz	0.9479
J	m^4	9.81748×10^{-14}
I	kg. m^2	5.5757×10^{-4}

Now with the inertia of a rotor made of Inconel is calculated, we can calculate the inertia of the rotors which will be made of the new materials we proposed. The inertias are as following:

Table 8: Calculations of the rotors inertia made of composite materials

Proposed Material	Density (g/cm^3)	Inconel rotor inertia ($kg.m^2$)	Inertia of the rotor ($kg.m^2$)
Silicon Carbide (S_iC)	3.21	5.5757×10^{-4}	2.2624×10^{-4}
Silicon Nitride (Si_3N_4)	3.31	5.5757×10^{-4}	2.3329×10^{-4}
Boron Carbide (B_4C)	2.51	5.5757×10^{-4}	1.76906×10^{-4}

Equation 9 achieves analytically the desired reduction in the time response of the turbocharger by being the ratio of the polar mass moment of inertia of the rotor composed of the Inconel-713C to that composed of the new material. Note that this time response corresponds to a given rotor speed and power, i.e, the basic variable in the equation is the angular acceleration.

The three tested materials are Silicon Carbide, Silicon Nitride, and Boron Carbide. Table 9 illustrates the time response ratios of those materials, each when applying its inertia relative to the inertia of Inconel 713C rotor:

Table 9: Time response ratio for various materials compared to Inconel

Proposed Material	Time response ratio with respect to Inconel 713C
Silicon Carbide (SiC)	2.4645
Silicon Nitride (Si3N4)	2.39
Boron Carbide (B4C)	3.1518

This means that, for example, taking the ratio of Boron Carbide, the time response of a Boron Carbide turbine is almost a one-third of that of a normal Inconel-713C turbine.

Based on the above results, the best applicable material corresponding to a density study is Boron Carbide, having a response-time ratio of 3.1513 with respect to Inconel-713C. However, Boron Carbide, in its industrial compound form, and due to its very high hardness, has a low tensile strength and low max use temperature, so using it in a turbine wheel of a turbocharger would result in failure. The response-time ratio of Silicon Carbide and Silicon Nitride is very close (almost 0.067). Knowing that the usage of Silicon Nitride has been increasing lately in the automotive applications and under high-temperature stresses [4]; from bearings and spark plugs and control valves to engine rotor parts, and achieving very pleasant results concerning efficiency and safety. However, the use of Silicon Carbide in automotive industry is relatively new; Toyota Car Company launched a Hybrid HV car with its semiconductors made of Silicon Carbide to enhance fuel consumption. But since the toughness and tensile strength of the Silicon Nitride is higher than that of the Silicon Carbide, it is safer to use Silicon Nitride in the construction of the turbocharger turbine wheel.

Eliminating previously the Zirconium Oxide compound and Boron Carbide, and now setting aside Silicon Carbide for the mentioned reasons, our proposed material for constructing the turbine wheel of the turbocharger instead of the Inconel-713C is Silicon Nitride Si_3N_4, whose application can reduce the time-response for the boost threshold up-to 41.84% of its current value. It also has a very good tensile strength at high temperatures and can withstand higher temperature applications than Inconel 713C.

4. Conclusions

The present research aimed at introducing a method to reduce the turbo-lag in the turbocharging application, which is the time needed for the turbocharger rotor to reach a threshold speed that can provide the engine the needed boost. The proposed solution was to reconstruct the turbine wheel, which has the biggest contribution to the weight of the whole rotor due to its construction from heavy material, using alternative lower-density material. However, the new material has to endure the pressure and temperature of the exhaust gas entering through the intake housing of the turbocharger. For that purpose, four materials were studied; Zirconium Oxide, Silicon Nitride, Silicon Carbide, and Boron Carbide. Out of those four materials, Boron Carbide, a composite ceramic gaining new popularity in the industrial application showed the best results regarding the moment of inertia and hardness. However, it had low tensile strength and low max use temperature of 500 ºC and could not be applied to turbochargers. Zirconium Oxide was eliminated due to its low temperature endurance. Silicon Nitride and Silicon Carbide showed good results regarding the dynamic functioning of the turbine wheel. Silicon nitride was selected due to its better tensile strength. Silicon Nitride is also highly heat resistant composite ceramic, and the comparison of its tensile properties with Inconel 713C showed that it is slightly affected by the high increases in temperature, where it showed good results at 1200^{o}C, while the strength of Inconel dropped considerably at almost 900^{o}C and it fails at 1260^{o}C.

A thermodynamic study was performed on the turbocharger, and a response-time equation was introduced as well as an equation to calculate the effective power of the compressor. By aiming at reaching a given rotor speed and a given compression ratio and mass flow rate, and by considering the polar mass moment of inertia to be in direct proportion to the density of the material and the 5^{th} exponent of the diameter of the turbine wheel, a ratio between the response-time of the turbocharger composed of Inconel-713C and that composed of our proposed material was calculated. Silicon Nitride, the final adopted material, gave a response-time of 41.84% of that of the Inconel-713C turbocharger.

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