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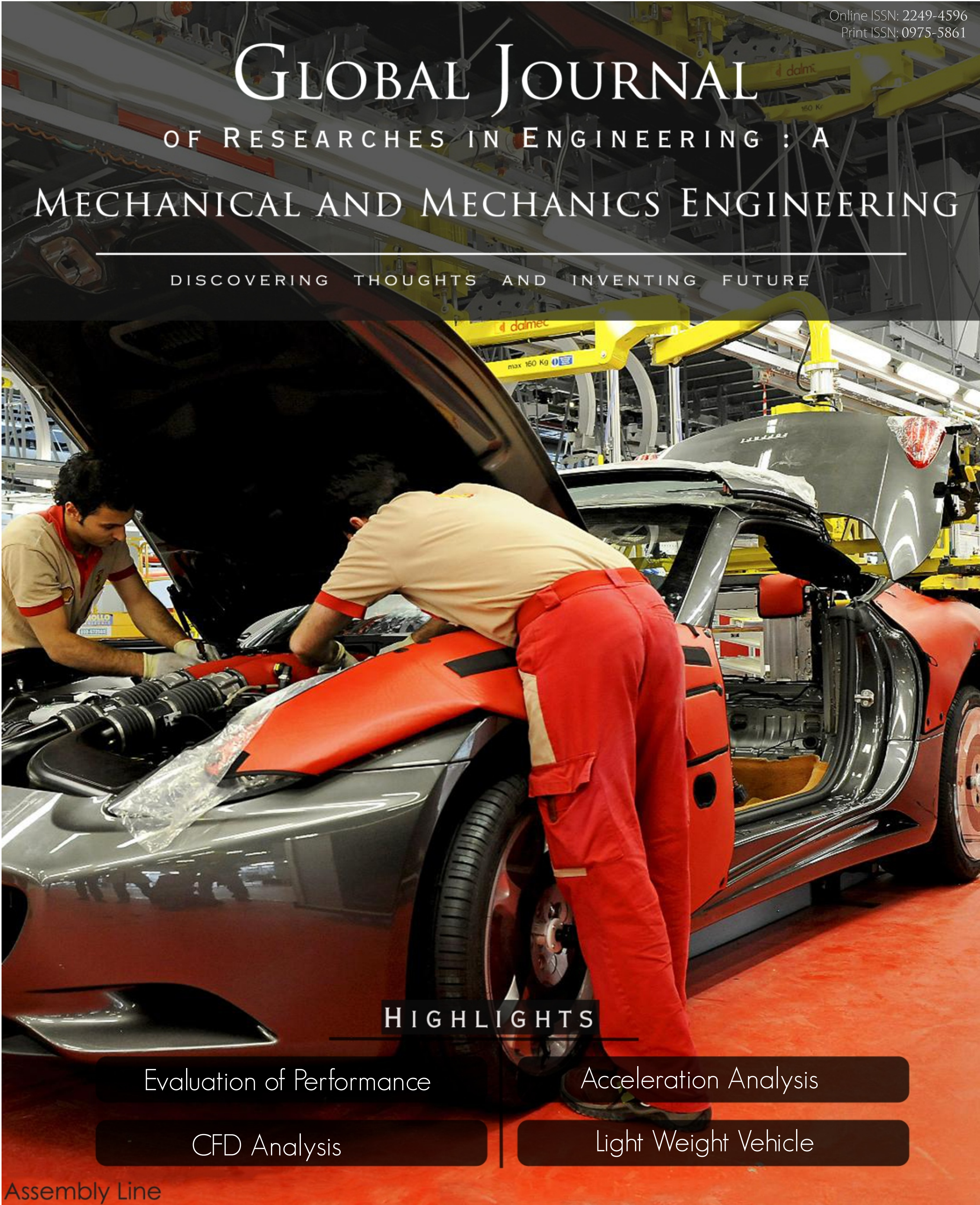

Highlights

Evaluation of Performance

Acceleration Analysis

CFD Analysis

Light Weight Vehicle

Assembly Line

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CFD Analysis of Solid Fuel Scramjet Combustors

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CFD Analysis of Solid Fuel Scramjet Combustors

Probhas Bose [α], K.M.Pandey [σ] & K.O.Reddy [ρ]

Abstract - The combustion of a solid fuel under supersonic cross flow conditions was investigated theoretically. A two-dimensional, axisymmetric, turbulent (k - ε), global one step reaction model was solved numerically. Numerical simulations of the combustor geometries presenting the situations with solid fuel regression were conducted using FLUENT software. The combustor inlet airflow had a Mach number of 2, total temperature of 1200 K and total pressure of 30 atm. The HTPB fuel and a global one step reaction mechanism were used. The results of non reacting computation reveal that the airflow velocity deceases in the majority zone of combustor with the solid fuel boundary regression. The results of reacting computation reveal that the supersonic zone in the divergent section of the case gets larger than non reaction case. Combustion takes place in the vicinity of solid fuel wall.

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I. Introduction

As flight Mach number is increased beyond the area of Mach 5, the hypersonic phenomena that begin to occur reduce significantly the performance of conventional ramjet engines with a subsonic flow combustion chamber. The demand for cost reduction and increased dependability of transporting payload to orbit has led to a constantly increasing interest in development of modern air breathing propulsion systems for hypersonic vehicles. Consequently, attention is being focused on the supersonic combustion ramjet (commonly known as scramjet). Ramjet engines operate at supersonic flight Mach numbers. In the conventional ramjet, the air flow is slowed down to subsonic flow velocities throughout the combustion chamber in order to achieve better flame stabilization and combustion efficiencies. However, for flight Mach numbers above 5, better performance (higher specific impulse) can be achieved if the combustor flow Mach number remains supersonic [1,2].The scramjet engine is usually powered by liquid fuels. For certain applications, however, one can see an advantage in employing solid fuels. The system design is greatly simplified, storage is very convenient, and a feeding system is not required. Hence, low cost propulsion system is enabled. However, unlike the case of liquid fuel combustion, the use of a solid fuel gives no direct control on fuel flow rate and injection velocity. The solid fuel undergoes degradation and gasification because of heat feedback from the hot gas flow, resulting in regression of the solid wall and establishment of diffusion flame within the boundary layer above the wall. Flame holding is achieved by the inlet step.

II. Literature Review

Scramjet (supersonic combustion ramjet) has proposed and is regarded as one of best propulsion systems for hypersonic flight. [1] Up to date scramjets with liquid fuel (e.g. kerosene) and gaseous fuel (e.g. hydrogen) have been studied widely. [2] In 2004 the liquid-hydrogen-fueled NASA X-43A scramjet flight vehicle performed two record breaking speed (Mach 7 and 10) self propelled flights, demonstrating the scramjet concept in actual flight conditions.[3, 4] At present there are still many research projects for hypersonic fight vehicle in America, including Hyfly, X-51A, FALCON and so on. [5] Reports related to solid fuel scramjet research, theoretical or experimental, are quite scarce in the open literature.

The use of solid fuels is widespread in conventional ramjet engines providing it with desirable characteristics: high energy density resulting in a more compact system, simplicity (no need of fuel tanks and feeding systems), safety, easy storage for long duration and finally, readiness upon demand. Consequently, the solid fueled scramjet engine should extend the operating limits of solid fuel oriented vehicles, such as missiles, boosters and sustainers and projectiles, into the hypersonic flight regime. [6] The direct-connect combustor tests and numerical simulations of combustor have been developed. In the direct-connect combustor tests, combustors have similar axisymmetric geometry sketched as Fig.1. The fuel grain contains three main sections. At the forward end air from the diffuser (or the air heater in the test system) enters at supersonic velocity and encounters a recess having a backward facing step at its head end and an oblique step at its rear. This arrangement causes some of the air to circulate near the walls, while in the center the flow remains supersonic. This section is essential for flame holding and it was found to enable self ignition of the fuel when the total temperature of the incoming air

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exceeds 1000K. The next part is a cylindrical section having a diameter smaller than the entrance chamber, in order to prevent the flow from accelerating too much. The final section of the fuel grain is a divergent cone, to prevent thermal chocking due to heat addition at supersonic velocities.[7]

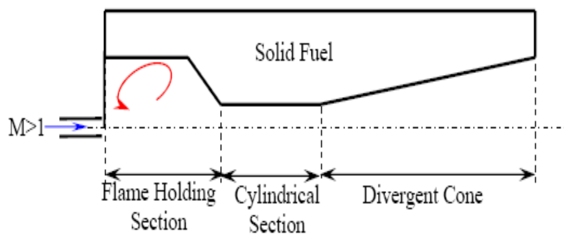

Fig. 1 : Solid fuel scramjet combustor geometry

Two type of solid fuels have been used in direct-connect combustor tests: Plexiglas (PMMA) and hydroxyl-terminated polybutadiene (HTPB). The advantage of using Plexiglas, despite its low energetic properties, is that due to its high mechanical strength there is no need for outer casing and its transparency enables observation of the flow and combustion phenomena within its axisymmetric bore.[6] Figure 1. Schematic geometry of the solid fuel scramjet combustor Gany et al from Israel Institute of Technology have conduced plentiful direct-connect combustor tests. Self-ignition and sustained combustion of PMMA with no external aid (such as reactive gas injection or a pilot flame) were demonstrated, flame holding limits were determined experimentally and temporal and spatial fuel regression rate data were obtained by video recording.[8] Direct-connect tests of Metallized and non metalized HTPB scramjet combustor have also been conducted. Aluminum powder was used as the metal fuel additive. Self ignition and stable combustion of both metalized and non metalized fuels has been achieved. Results show that the regression rate of metalized fuel is slightly higher. The addition of aluminum particles improved the specific thrust (thrust per air mass flow rate), while decreasing the specific impulse.[7] The objective of the present research is to determine the feasibility of numerical simulation by CFD software FLUENT and analyze the flow field of scramjet combustor, based on the combustor model and experimental data of Ref. 7.

Truck mounted multi barrel rocket launcher (MBRL) is an area weapons which is capable of launching free flight rockets (FFR) at the target from a distance of 30 – 40 km. In addition to conventional warheads, it also has the capability to deliver nuclear war head [8]. Brassey's Encyclopedia of Land Forces & Warfare [9] brought out that despite logistical penalties and the ease of detection, MBRLs are favoured by Western armies in place of heavy guns. FFR motors use solid propellants as it possess well defined, reproducible, and near constant rate of burning, non hygroscopicity, ability to be worked into grain of widely varying sizes, shapes and burning times. It has adequate mechanical and physical properties and have sufficient strength to prevent sagging at higher temperatures, or imbrittlement at low temperatures [10]. The major problems here as observed by MacLaren AJ et-al [11] is mid course thrust control as burning rate of propellant cannot be altered unlike its liquid counterpart; the other problem being low specific impulse. However, Fleeman EL [12] suggested three approaches for mid air control. These are use of pulsed and pintle motors and gel propellant. Guery JF et-al [13] brought out generation of high specific impulse and restart capabilities by liquid propellant. The specific impulses of solid propulsion systems are 20% and 80% lower than that of liquid and cryopropulsion systems, respectively. However, in this case the system is more complex and expensive states Gupta et-al [14]. Lipanov AM observed that once ignited, solid propellant usually burns smoothly at a predetermined rate on all the exposed surfaces of the grain [15]. For rocket launcher application the requirement is of constant thrust which is met by neutral burning surface.

Rossi et-al [16] established that in the class of solid fuels composite propellant is preferred. It presents the main advantage of low vulnerability and high specific impulse. Moreover, properties of composite propellant may be tailor made by changing the compositions and compound rate. It is composed of one binder (typically, Polybutadiene or glycidyle azide polymer), one oxidizer (typically NH_4ClO_4) and one fuel (Al, Zr or Mg). The metallic particles remain after combustion may cause damage to the nozzle if flight duration is considerable. However, in case of MBRL, small duration of burning and expelling of burning gases quickly does not provide adequate time to cause damage to the nozzle.

Nair UR [17] observed composite propellants have acquired greater significance because of advantage of wide range of mechanical properties and superior strain capability compared to conventional propellants in addition to higher delivered I_{sp}. For realizing smokeless exhaust Tarver CM et-al [18]explored RDX and HMX. It is observed that addition of combination of AP and nitramines improves the I_{sp} marginally. Tian Y et-al [19] and Florczak B [20] found superior performance level by replacing hydroxy-terminated polybutadine (HTPB) binder by energetic polymer systems comprising of GAP and BAMO copolymers as polymer matrix in combination with TMETN/TEGDN/ BTTN/BDNPF/A as plasticizers.

Although materials like CL-20, FOX-7 was synthesized as an explosive of interest. It has also been evaluated as a component of propellants. Floreszek B [21] and Mueller D [22] have reported the effect of replacement of AP by FOX-7 in slurry cast composition. They determined burning rate of the propellant in sub scale rocket motor and observed marginal decrease in it

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on replacement of AP by FOX-7. It is predicted that a combination of HNF / ADN with energetic binders like GAP, BAMO, NIMMO can offer I_{sp} of the order of 300 s. However, Chen JK [23] and Hsieh WH [24] suggested validation such claim in a practically useful propellant.

Chatillon C [25] observed that unlike the other ingredients, aluminum particles can burn in a signficant portion of the chamber and produce a condensed phase that is carried out into the flowfield. Thereby, aluminum particles can affect appreciably combustion instabilities by acting as driving or, on the contrary, as damping mechanisms.

Use of eco friendly propellant is advocated by Mahanta A [26] as with AP oxidizer it emits plumes containing HCl. Addition of magnesium neutralized plumes in the range of 1-10 %, while sodium nitrate scavenged propellants (HTPB/$NaNO_3$/AP/Al) have the potential of reducing it by about 1 - 3 %.

Design of a solid propellant grain is governed by ballistic, processing, and structural integrity requirements. Pressure-time, thrust-time, acceleration, velocity, and trajectory are decided by propellant configuration, and are largely a geometric consideration. Shekhar H [27] proposed funnel port tubular propellant grain for neutral burning. Pressure developed by the burning of propellant depends upon along with other parameters geometry of the grain. Relation between web and mass burnt is established by form function relation; relation between web and surface area is established [28] by surface area relation. EgonG et-al [29] suggested a test method for service life prediction of propellant. Shekhar H [30] observed that an HTBP composite propellant behaves as compressible material in most of the regionsand near-failure region or at higher strains; Poisson's ratio is near 0.25. Miloš Predrag [31] suggested a specific methodology for optimization of star shape propellant grains in the sense of minimizing stress and strain without compromising the required internal ballistic performances. The design of solid propellant grain that provides neutral burning is important to optimize rocket motor performance.

III. Scramjet Combustor Geometry

The computational domain of the geometry and the governing equations of the solver are explained in this session, the schematic diagram of the scramjet combustor computational domain is shown below

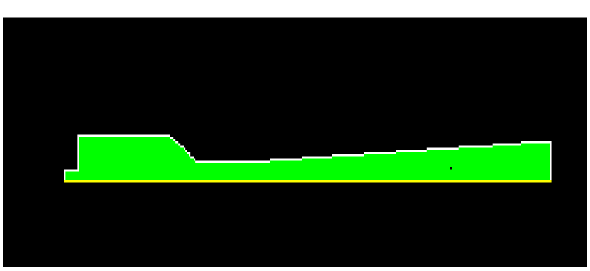

Fig. 2 : Computational domain grid generation

IV. Classification Of Solid-Propellant Combustion Models

Existing models of solid-propellant combustion can be broadly classified into three general categories: (1) simple models that do not account for chemical kinetics and typically solve only the mass and energy equations in the condensed and gas phases; (2) global-kinetics models based on simplified chemical reaction mechanisms in either, or in both, the gas and condensed phases; and (3) detailed models with elementary kinetics mechanisms in the gas phase, and thermal decomposition and subsequent reactions in the condensed phase. In addition, various ignition models have also been developed. Most of the existing analyses use global reactions to simulate ignition, but some recent efforts have modeled the entire process of ignition with detailed kinetics.

a) Combustion models based on global kinetics

Models of this type treat reduced chemical kinetics and solve both the energy and species transport equations. Global kinetics is immensely useful for multi-dimensional modeling, where the use of detailed mechanisms is not viable due to numerical stiffness problems attributed to the wide variety of time and length scales involved and limited computing sources.

V. Numerical Method

CFD software FLUENT was employed to compute the non reacting and reacting flow field of the above combustor. The inlet airflow has a Mach number of 2, total temperature of 1200 K and total pressure of 30 atm, which is identical to inflow conditions in Ref.7. In the simulation, solid fuel grain boundary was set to mass flow inlet with mass flow rate of 0.0197 kg/s. The pressure of combustor outlet was set to 1 atm. The two-equation RNG k-ε model was used to model the turbulence and standard wall functions were used to model the flow near the wall. Because of axisymmetry of model, only half of the combustor symmetry was computed. The entire computational domain was discretized using a total mesh size of 5,210. In the simulation of reacting flow field, HTPB was supposed that its pyrolysis only produced one gas C4H6. The combustion of C4H6 was modeled using a global one-step reaction mechanism, assuming complete conversion of the fuel to CO2 and H2O. The reaction equation is

$$C4H6+5.5O2 \rightarrow 4CO2+3H2O$$

This reaction was defined in terms of stoichiometric coefficients, formation enthalpies, and parameters that control the reaction rate. The reaction rate was determined assuming that turbulent mixing is the rate-limiting process, with the turbulence-chemistry interaction modeled using the eddy dissipation model.

a) The two-equation RNG k-ε model

The RNG model was developed using Re-Normalisation Group (RNG) methods by Yakhot et al to renormalise the Navier-Stokes equations, to account for the effects of smaller scales of motion. In the standard k-epsilon model the eddy viscosity is determined from a single turbulence length scale, so the calculated turbulent diffusion is that which occurs only at the specified scale, whereas in reality all scales of motion will contribute to the turbulent diffusion. The RNG approach, which is a mathematical technique that can be used to derive a turbulence model similar to the k epsilon, results in a modified form of the epsilon equation which attempts to account for the different scales of motion through changes to the production term.

By definition, two equation models include two extra transport equations to represent the turbulent properties of the flow. This allows a two equation model to account for history effects like convection and diffusion of turbulent energy.

Most often one of the transported variables is the turbulent kinetic energy, k. The second transported variable varies depending on what type of two-equation model it is. Common choices are the turbulent dissipation, ϵ, or the specific dissipation, ω. The second variable can be thought of as the variable that determines the scale of the turbulence (length-scale or time-scale), whereas the first variable, k, determines the energy in the turbulence.

i. *Transport Equations*

There are a number of ways to write the transport equations for k and ϵ, a simple interpretation where bouyancy is neglected is

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+P_k-\rho\epsilon$$

$$\frac{\partial}{\partial t}(\rho\epsilon)+\frac{\partial}{\partial x_i}(\rho\epsilon u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\epsilon}\right)\frac{\partial\epsilon}{\partial x_j}\right]+C_{1\epsilon}\frac{\epsilon}{k}P_k-C_{2\epsilon}^*\rho\frac{\epsilon^2}{k}$$

where $C_{2\epsilon}^* = C_{2\epsilon} + \dfrac{C_\mu \eta^3(1-\eta/\eta_0)}{1+\beta\eta^3}$

and $\eta = Sk/\epsilon$ and $S = (2S_{ij}S_{ij})^{1/2}$

With the turbulent viscosity being calculated in the same manner as with the standard k-epsilon model.

Constants

It is interesting to note that the values of all of the constants (except β) are derived explicitly in the RNG procedure. They are given below with the commonly used values in the standard k-epsilon equation in brackets for comparison:

$C_\mu = 0.0845$ (0.09)
$\sigma_k = 0.7194$ (1.0)
$\sigma_\epsilon = 0.7194$ (1.30)
$C_{\epsilon 1} = 1.42$ (1.44)
$C_{\epsilon 2} = 1.68$ (1.92)
$\eta_0 = 4.38$
$\beta = 0.012$ (derived from experiment)

b) Governing equations for compressible flow

For all flows, FLUENT solves conservation equations for mass and momentum. For flows involving heat transfer or compressibility, an additional equation for energy conservation is solved. For flows involving species mixing or reactions, a species conservation equation is solved.

i. *Non reacting flow*

In fluid dynamics, the continuity equation states that, in any steady state process, the rate at which mass enters a system is equal to the rate at which mass leaves the system.

The differential form of the continuity equation is

$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\mathbf{u})=0$$

where

- ρ is fluid density,
- t is time,
- **u** is the flow velocity vector field.

Momentum equation

$$\frac{\partial(\rho u)}{\partial t}+\nabla\cdot(\rho u v)=-\frac{\partial P}{\partial x}+\frac{\partial\tau_{xx}}{\partial x}+\frac{\partial\tau_{yx}}{\partial y}+\rho f_{xx}$$

Energy equation

$$\rho\frac{Dq}{Dt}=\rho\frac{D}{Dt}\left\{i+V+\frac{1}{2}u_i u_i\right\}+\frac{\partial}{\partial x_i}(pu_i)-\frac{\partial}{\partial x_j}(\tau_{ij}u_i)$$

or

$$\rho\frac{D}{Dt}\left[\frac{u_i u_i}{2}+e\right]-\rho k_i u_i-\frac{\partial}{\partial x_j}[\tau_{ji}u_i]+\frac{\partial q_i}{\partial x_i}=0,$$

ii. *Reacting flow*

Among all the above three equations there are two more equations for species transport model. When you choose to solve conservation equations for chemical species, FLUENT predicts the local mass fraction of each species, Yi, through the solution of a convection-diffusion equation for the ith species. This conservation equation takes the following general form:

$$\frac{\partial}{\partial t}(\rho Y_i)+\nabla\cdot(\rho\vec{v}Y_i)=-\nabla\cdot\vec{J}_i+R_i+S_i$$

Where Ri is the net rate of production of species i by chemical reaction (described later in this section) and Si is the rate of creation by addition from the dispersed phase plus any user-defined sources. An equation of this form will be solved for N-1 species where N is the total number of fluid phase chemical species present in the system. Since the mass fraction of the species must sum to unity, the Nth mass fraction is determined as one minus the sum of the N - 1 solved mass fractions. To minimize numerical error, the Nth species should be selected as that species with the overall largest mass fraction, such as N2 when the oxidizer is air.

Mass Diffusion in Turbulent Flows

In turbulent flows, FLUENT computes the mass diffusion in the following form:

$$\vec{J}_i = -\left(\rho D_{i,m} + \frac{\mu_t}{\mathrm{Sc}_t}\right)\nabla Y_i$$

Where Sct is the turbulent Schmidt number ($\frac{\mu_t}{\mathrm{Sct}}$ where μ_t is the turbulent viscosity and Dt is the turbulent diffusivity). The default Sct is 0.7. Note that turbulent diffusion generally overwhelms laminar diffusion, and the specification of detailed laminar diffusion properties in turbulent flows is generally not warranted.

VI. Simulation Results

a) *Non Reacting Flow field*

Non reacting flow field of the model were computed by setting solid fuel boundary to wall. Fig.3 shows cold flow field of the combustor geometry without fuel addition or reaction. From Fig. 3 Mach number map, it can be seen that inflow air was expanded at step corner and airflow Mach number increased from 2.0 to 2.5. Velocity is very low and static temperature is very high to 1150 K (Fig.4) in the recirculation zone. The high temperature is enough to ignite the solid grain. In the cylindrical section airflow has a maximum Mach number of 1.9. In the divergent section airflow is expanded largely with Mach number of combustor exit up to 3.4.

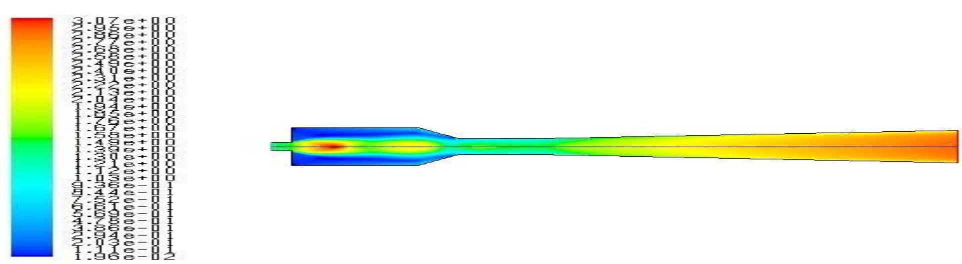

Fig. 3 : Mach number contour

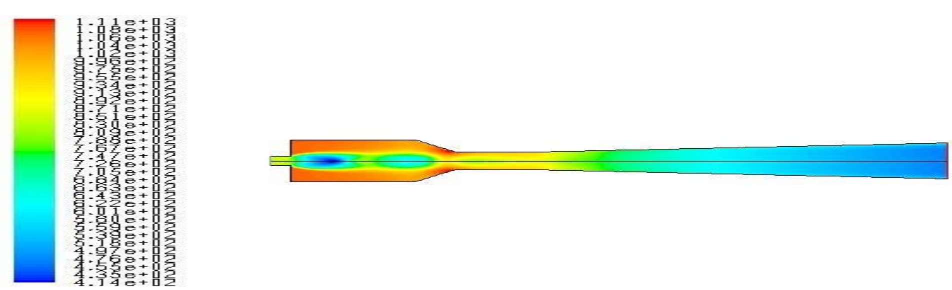

Fig. 4 : Static temperature contour

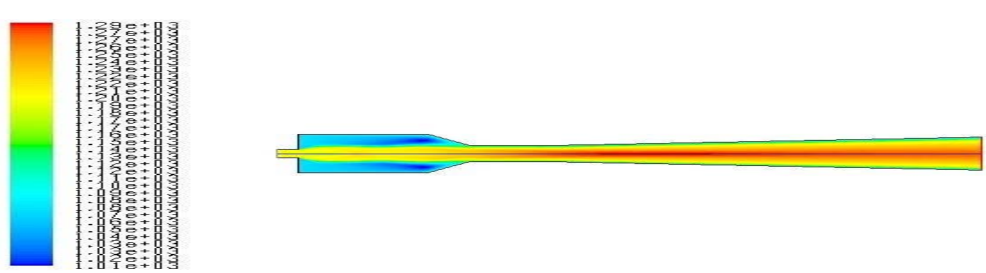

Fig. 5 : Total temperature contour

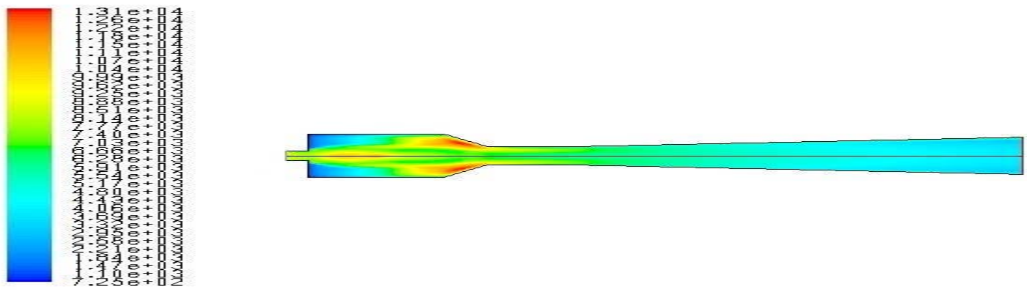

Fig. 6 : Turbulent intensity contour

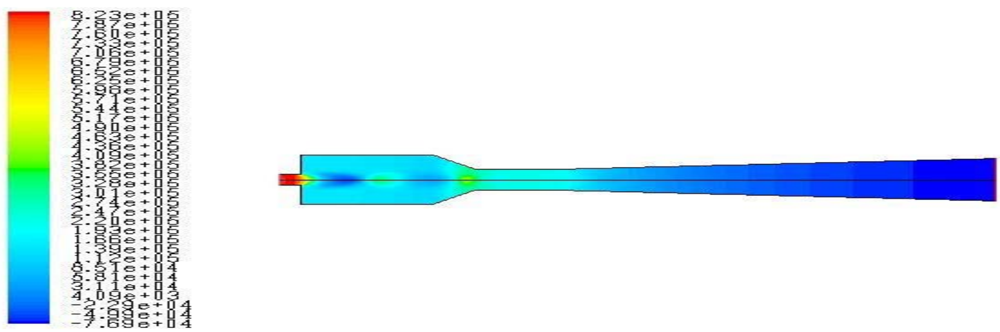

Fig. 7 : Static Pressure Contour

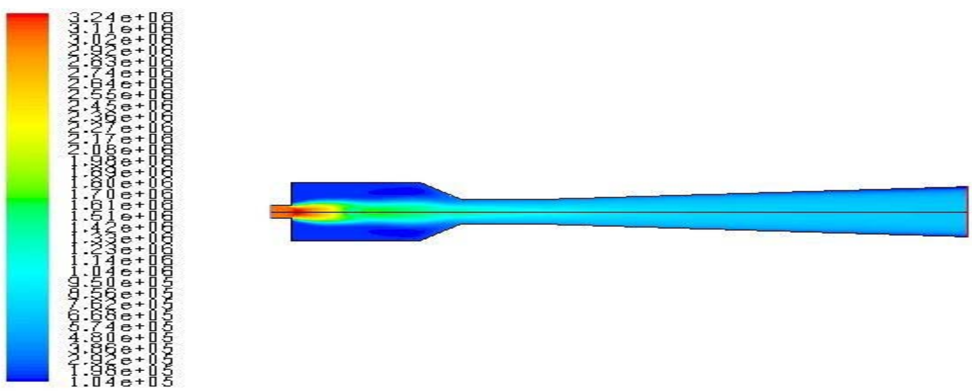

Fig. 8 : Total Pressure Contour

b) Reacting Flow field

Reacting flow fields of three combustor geometries are obtained by the reaction of C4H6 and O2. Fig.7-8 shows reacting flow field contours.

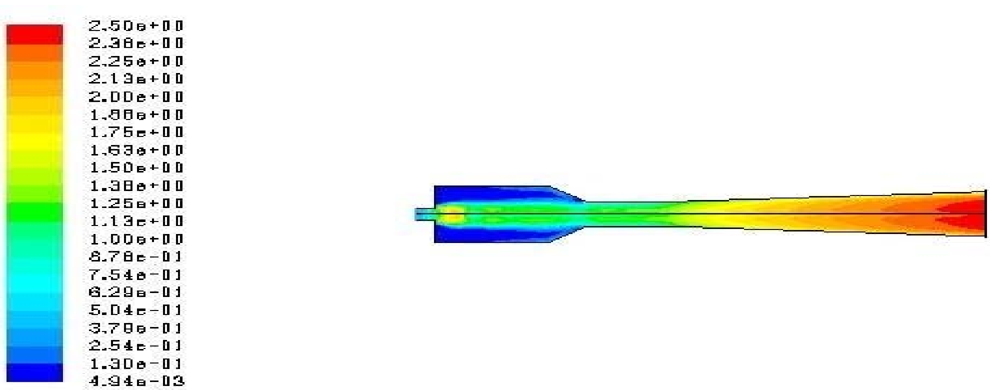

Fig. 9 : Mach Number Contour

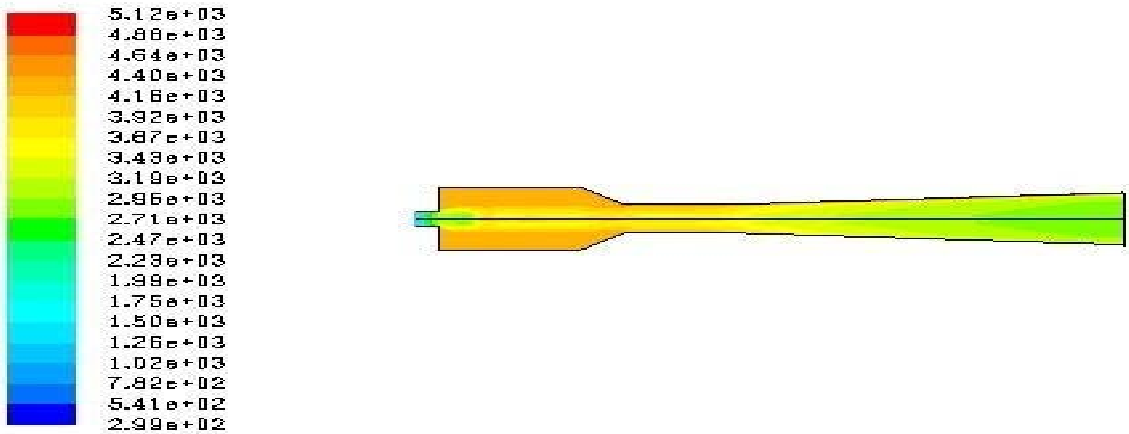

Fig. 10 : Static Temperature Contour

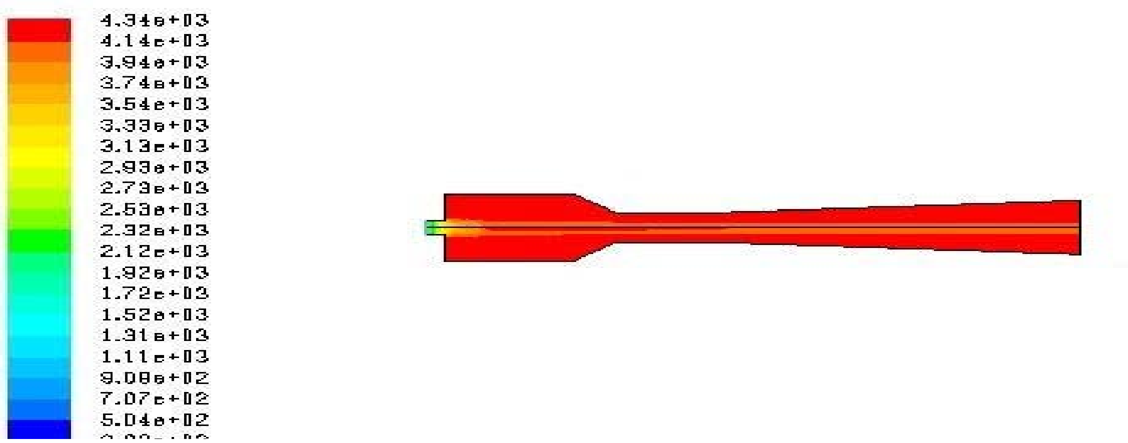

Fig. 11 : Total Temperature Contour

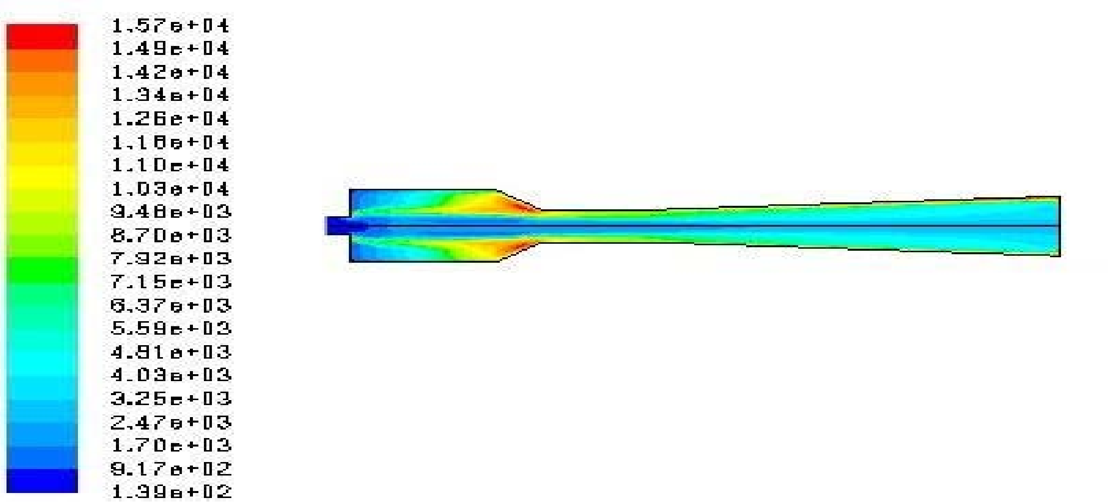

Fig. 12 : Turbulent Intensity Contour

VII. Results Discussion

a) Mach number

Figures 3 and 7 present the flow Mach number distribution of a non-reacting case and that of the present reacting case, respectively. Comparison reveals that the velocity field changes substantially. The inlet fan at the step corner, which served to elevate the Mach number from 2 to a maximum value of 3.07 in the non-reacting case, almost disappears in the reacting case, resulting in a maximum Mach number of 2.1. Broad areas of supersonic flow in the non-reacting case become subsonic due to the heat release from the chemical reactions. A mixed supersonic (at the center)/subsonic (at the circumference) jet is formed at the combustor exit when combustion takes place, replacing the almost whole supersonic non-reacting stream.

b) Temperature

Temperature distribution of the reacting flow field is presented in Fig. 10 and 11. The computation results reveal that sustained combustion can exist within the combustor for the inlet and geometry conditions under investigation. A diffusion flame with a maximum temperature of 3500K is formed supplying a substantial heat addition to the flow. The static and stagnation temperatures increase from 300 K and 1300 K at the inlet to mass-averaged values of 3150 K and 3450 K, respectively. The region between the wall and fame center is heated too due to the chemical reactions and the lateral heat transfer from the flame. At the combustor axis, the temperature remains almost unchanged.

c) Turbulent Intensity

The turbulent intensity is increasing from the intake to the section head of the cylinder and the value is higher as compared to the in other locations that means at the wall boundaries the turbulent value is decreases due to standard wall functions and in the case of reaction flow field the turbulent intensity .

VIII. Conclusion

Comparison of reacting and non reacting flow Mach numbers reveal that the velocity field changes substantially. The inlet fan at the step corner, which served to elevate the Mach number from 2 to a maximum value of 3.07 in the non-reacting case, almost disappears in the reacting case, resulting in a maximum Mach number of 2.1. Broad areas of supersonic flow in the non-reacting case become subsonic due to the heat release from the chemical reactions. A mixed supersonic (at the center)/subsonic (at the circumference) jet is formed at the combustor exit when combustion takes place, replacing the almost whole supersonic non-reacting stream. The computation results reveal that sustained combustion can exist within the combustor for the inlet and geometry conditions under investigation. A diffusion flame with a maximum temperature of3500 K is formed supplying a substantial heat addition to the flow. The static and stagnation temperatures increase from 300 K and 1300 K at the inlet to mass-averaged values of 3150 K and 3450 K, respectively. The region between the wall and fame center is heated too due to the chemical reactions and the lateral heat transfer from the flame. At the combustor axis, the temperature remains almost unchanged.

The pressure in combustion chamber is explained as static and total pressure. For the case of non reacting flow field the static and total pressure contours are shown in Fig 7-8.

The pressure in non reacting flow is accrued an value of 40 atmospheric pressure. Where as in reacting flow the combustion chamber pressure is more high due to the chemical specie reaction and gaseous products.

The turbulent intensity behavior of non reacting flow can be explained from the turbulent intensity contours as shown above. From non reacting flow field can we say that the turbulent intensity accrued a maximum value in the flame holding section and at the cylinder head inlet. But in the case of reacting the turbulent intensity is more higher as compared to the non reacting case.

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Evaluation of Performance and Emissions of A VCR DI Diesel Engine Fuelled with Preheated CsME

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Abstract - In the present work, a widely available cottonseed oil has been considered and converted to Cottonseed Methyl Ester (CsME). 100% CsME used as fuel on DI Diesel Engine with minor modifications like changing of compression ratio of the engine and preheating of CsME. Performance evaluation of single cylinder vertical water-cooled diesel engine is done with diesel, 100% preheated CsME. Various compression ratios such as 16.5:1, 17.5:1, 18.5:1 and 19:1 have been adopted for experimentation. CsME preheated to 520C is used at various compression ratios for the analysis of engine performance. The combination of increasing of compression ratio and preheating not only enhances the homogenization and vaporization but also enhances the rate of release of inbuilt oxygen of CsME. With CsME operation at 18.5:1 C.R and preheating (520C), the brake thermal efficiency is found to be 32.32 % at full load condition. It is found that the exhaust emissions are also low in these operating conditions.

Keywords : CsME, compression ratio, preheating, room temperature, variable compression ratio.

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Strictly as per the compliance and regulations of :

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Abstract - In the present work, a widely available cottonseed oil has been considered and converted to Cottonseed Methyl Ester (CsME). 100% CsME used as fuel on DI Diesel Engine with minor modifications like changing of compression ratio of the engine and preheating of CsME. Performance evaluation of single cylinder vertical water-cooled diesel engine is done with diesel, 100% preheated CsME. Various compression ratios such as 16.5:1, 17.5:1, 18.5:1 and 19:1 have been adopted for experimentation. CsME preheated to 52^{0}C is used at various compression ratios for the analysis of engine performance. The combination of increasing of compression ratio and preheating not only enhances the homogenization and vaporization but also enhances the rate of release of inbuilt oxygen of CsME. With CsME operation at 18.5:1 C.R and preheating (52^{0}C), the brake thermal efficiency is found to be 32.32 % at full load condition. It is found that the exhaust emissions are also low in these operating conditions. It is concluded from the present work, for better performance and low emissions with vegetable oils, the oil should first be converted to methy/ethyl esters and operated in a slightly increased compression ratio diesel engine with preheated biodiesel. After observing the performance and emission parameters, it is concluded that a compression ratio of 18.5:1 for the chosen engine is the best compression ratio with 52^{0}C preheated CsME.

Keywords : CsME, compression ratio, preheating, room temperature, variable compression ratio.

I. Introduction

The population of fossil fuel run vehicles is increasing in multifold each year leading to peak pollution levels. Mismatch between demand and supply of fossil fuels and fluctuating fuel prices and associated pollution problems making it difficult for the existence of fossil fuels in the long run. Vegetable oils are found to have its physical, thermal and chemical characteristics close to that of diesel oil. However, vegetable oils cannot be used directly because of its high viscosity. The raw vegetable oils used in engines without any modification results in poor performance and leads to wear of engine parts [Bari et al., 2002]. Vegetable oils cause formation of gummy substances at high temperatures and pressures. It is reported that these problems may cause engine failures such as piston ring sticking, injector chocking, formation of carbon deposits and deterioration of lubricating oil after the use of vegetable oil for long period of time [Avinash Kumar Agarwal, 2007]. Hence direct utilization of vegetable oils is not advisable on the diesel engine.

Methyl/Ethyl esters of vegetable oils may be obtained by pyrolosyis, transesterification, etc. Biodiesel, transesterificated vegetable oils, is promising alternate fuels for compression ignition engines. Bio-diesels are oxygenated fuels and their calorific values (8-10 kJ/kg) are comparable with petro diesels and they are localized fuels. Bio-diesels are renewable and bio-degradable. Several attempts are made to analyze the characteristics of a compression ignition engine fuelled with biodiesel derived from different vegetable oils which are grouped in edible and non-edible oils [Da Silva et al., 2003; Nwafor, 2004; Nabiet et al., 2006]. The calorific value, cetane number, heat of evaporation and stoichiometric air fuel ratio all these properties are very nearer to petroleum diesel and encourage to be adopted in diesel engines.

Hossain et al.(2010) reported that the cetane number of bio-diesels is higher than the diesel. If the vegetable oils are converted as esters of Methyl or Ethyl, they can be used in diesel engines. Nurun Nabi et al. (2010) reports the inbuilt oxygen of bio-diesel lower the adiabatic flame temperature, as a result NOx emission decrease linearly. Smoke opacity is a direct measure of smoke and soot. Agarwal et al. 2001 concluded that smoke opacity for bio-diesel is less than diesel. Qi et al. (2009) reported that the fuel properties of biodiesel are slightly different from those of diesel. The viscosity of biodiesel is evidently higher than that of diesel, especially at low temperatures. The specific gravity of the biodiesel is approximately 6.1% higher than that of diesel.

Arul Mozhi Selvan et al.(2009) reported that at higher compression ratios, the diesel-biodiesel ethanol blends have faster premixed combustion which leads to higher peak cylinder gas pressure. It is observed that the peak pressure increases with the increase in the brake mean effective pressure and compression ratio. It is observed that the peak heat release rate increases

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decreases with increase in the compression ratio and higher load conditions. The total combustion duration decreases with increase in the compression ratio.

In the present work, biodiesel (cotton seed methyl ester) is preheated to 52^{0}C temperature where the viscosity is equal to viscosity of diesel at room temperature. Along with this preheating, compression ratio is also varied. The collective effect of preheating of fuel and different compression ratios for the engine is studied and analyzed. On increasing of C.R, the intake air is compressed to higher pressure and all the air particles are much close to each other. When the fuel is injected into that air, the rate of reaction in between air and fuel particles will improve. Increase in the temperature of fuel, will lead to better atomization and reduction in particulate size. Combination of increasing of C.R of engine and temperature of the fuel will cause reduction of droplet size, quick evaporation and homogenization and as a result, efficient combustion will be there.

II. Experimental Set Up and Experimentation

The experimental setup consists of a single cylinder, four stroke, and naturally aspirated DI diesel engine with an arrangement to change the compression ratio. Optical pressure sensor is attached nearby the fuel injector in cylinder head to read the pressure signature. An auxiliary camshaft is provided to the engine to operate the valve mechanism. When the C.R is changed, cylinder head is displaced along with the valve operating mechanism. Crank angle encoder is connected to the auxiliary camshaft. A graph is plotted between the pressure signature and crank angle (P-θ diagrams) using "VCMRFE 5.73 combustion" software. The specifications of the test engine are given in Table 1. The test bed contains instruments for measuring various parameters such as engine torque, fuel consumption, air flow rate, fuel inlet temperature, combustion parameters (combustion pressure, heat release rate and exhaust emissions).

Experiments are performed with diesel at room temperature and CsME at 52^{0}C preheated temperature. Preheating of CsME is done by using three electric heaters which are directly fixed over the fuel flow line. The fuel temperature sensor has direct contact with the fuel which is being injected, which helps in the recording of exact temperature of the fuel entering into the combustion chamber. An electrical eddy current dynamometer is employed for measuring the engine torque. The fuel consumption is measured using a burette and stop watch. A damping tank and an orifice plate along with manometer are used to measure the air flow rate. To get P-θ and HRR graphs, a pressure sensor is fixed over the cylinder head and crank angle encoder is fixed at the camshaft. The exhaust gas temperature is measured with thermo couple and each reading is taken after the stabilization of exhaust gas temperature which indicates the stable running of the engine at a particular load. To measure the exhaust gas emissions crypton-290 five gas analyzer is used which is approved by ARAI. The engine runs at 1500rpm and readings are taken from no load to full load at different compression ratios such as 16.5:1, 17.5:1, 18.5:1, and 19:1 at preheated CsME. Experimental setup is shown in figure 1. The experiments are carried at no load to full load to evaluate the performance and combustion parameters of the engine.

Table 1 : Specifications of the VCR DI- Diesel Engine

Rated Horse power:	5 hp (3.73 kW)
Rated Speed:	1500rpm
No of Strokes:	4
Mode of Injection and injection pressure	Direct Injection, 200 kg/cm^2
No of Cylinders:	1
Stroke	110 mm
Bore	80 mm
Compression ratio	15:1 to 20:1
Method Of Loading	Eddy Current Dynamometer

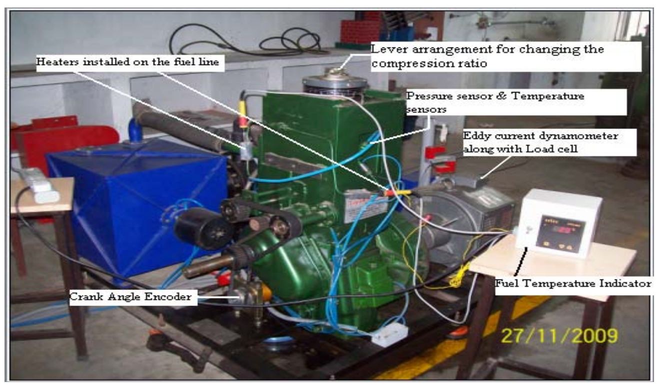

Fig. 1 : Engine setup for the experimentation

III. Results & Discussions

Experimental investigations are carried out on a Single-cylinder water cooled DI diesel engine adopting Cotton Seed Methyl Ester (CsME), with preheating at different compression ratios such as 16.5:1, 17.5:1, 18.5:1 and 19:1; to evaluate the performance of the engine. The preheating temperature is 52^{0}C. The graphs are plotted for each case to finally optimize the parameters with better performance, combustion and emissions of the engine. Tests conducted with diesel at room temperature and with standard compression ratio 16.5:1 are chosen as baseline characteristic. The results are analyzed at room temperature with diesel and preheated CsME at different compression ratios. The comparison of physical properties of CsME and Diesel oil are shown in Table 2.

Table 2 : Properties of CsME and Diesel oil.

Property	Diesel	CsME	ASTM
Chemical Formula	$C_{14.09}H_{24.78}$	$C_{54}H_{101}O_6$	
Density at 33°C Kg/m^3	830	866	D1298
Gross Calorific Value, KJ/Kg	43000	38,100	D240
Viscosity at 33 °C, cSt	3.28	6.16	D445
Cetane Number	45	53-55	D613
Flash Point, °C	50	200	D93
Acid Number, mg KOH/gm	0.2 Max	< 0.2	D664

a) Performance Analysis

Even though the Compression Ratio is one of the parameters to influence the performance as well as combustion and emissions, the viscosity of fuel is another parameter which governs the atomization, homogenization and vaporization and spray characteristics of the fuel. Further set of the experiments are conducted without changing the injection pressure of fuel. The viscosity of presently chosen vegetable oil even after converting into methyl ester i.e. the viscosity of CsME is more than that of petro-diesel, which is shown in Table 2. Generally for liquids, the viscosity decreases with increase in temperature. It is found that even after converting the cotton seed oil into their corresponding methyl esters, the viscosity could not be brought down to the level of petro-diesel fuel. Moreover, in order to utilize vegetable oils effectively, it is felt to preheat the CsME before it is supplied to the engine for combustion. Thus, with preheating, the viscosity of CsME will decrease and improves atomization and vaporization during the combustion.

The variation in viscosity of CsME with temperature and viscosity of petro diesel at room temperature are compared which is found to be equal (Fig. 2). At this temperature different compression ratio such as 16.5:1, 17.5:1, 18.5:1 and19:1 is considered and performance, combustion and exhaust gas analysis are carried out.

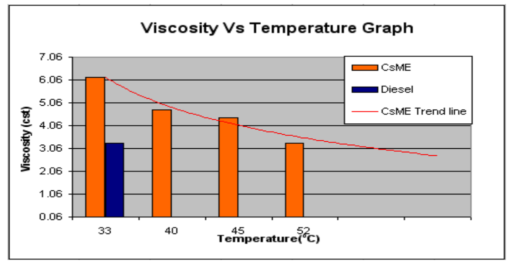

Fig. 2 : Comparison viscosities of Diesel and CsME at different temperatures

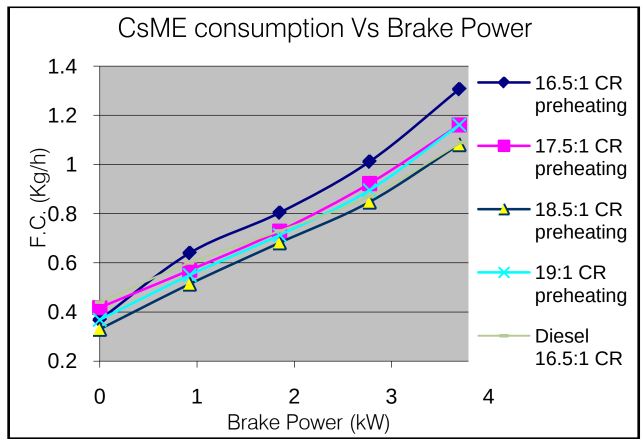

Fig. 3 : Fuel consumption Vs Brake Power at different compression ratios

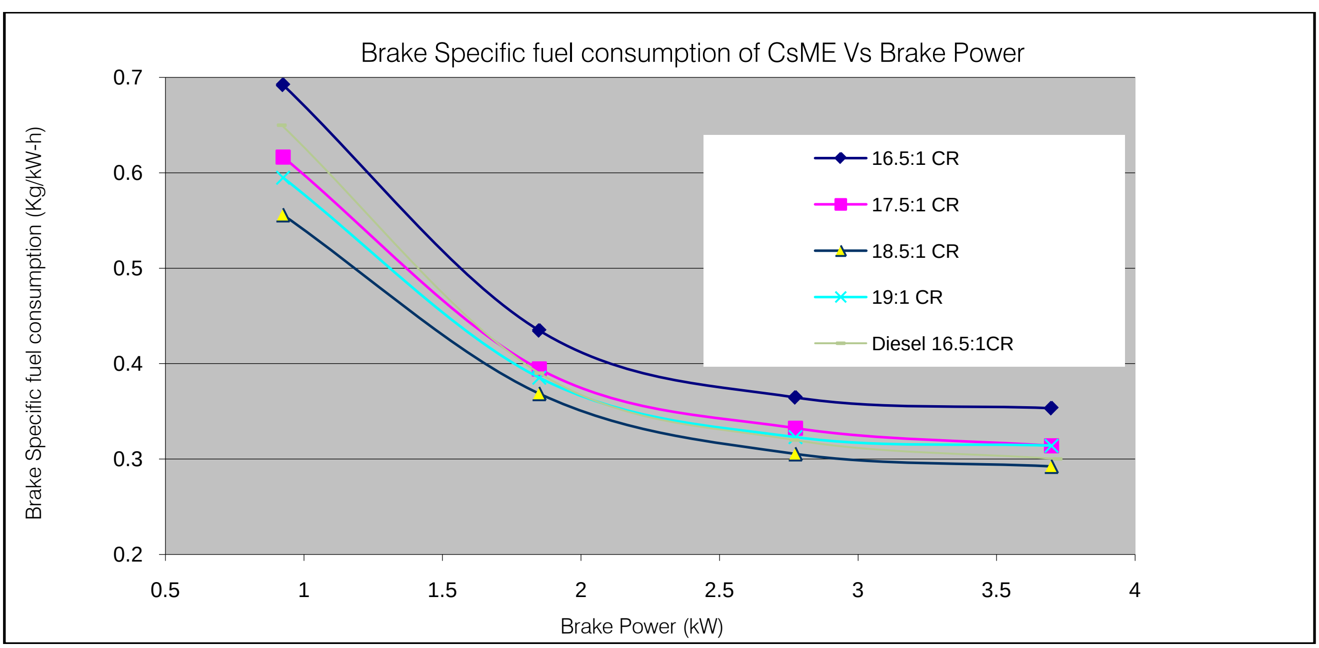

Fig. 4 : Brake Specific Fuel consumption Vs Brake Power at different compression ratios

From Fig.3 & Fig. 4, it is observed that on preheating, the gradual decrement of fuel consumption is obtained from 16.5:1 C.R to 18.5:1 C.R. The following table shows the fuel consumption per hour at Room Temperature (RT) and 52^{0}C with CsME application.

Table 3 : CsME Consumption at Full load operation

	16.5:1 CR (CsME) at 52^{0}C	16.5:1 CR (Diesel) at RT	17.5:1 CR (CsME) at 52^{0}C	18.5:1 CR (CsME) at 52^{0}C	19:1CR (CsME) at 52^{0}C
With prehe-ating	1.31 kg/hr	1.093 kg/hr	1.16 kg/hr	1.08 kg/hr	1.16 kg/hr

The consumption of diesel at room temperature with 16.5:1 C.R is 1.09285 kg/hr (Table 3), and the consumption of CsME at 18.5:1 C.R with 52^{0}C preheated temperature is 1.08 kg/hr (Table 3). This value is almost equal to the consumption of petro diesel even though calorific value of CsME is less than diesel. Preheating and increasing of compression ratio are the reasons for better combustion, resulting in lower consumption of CsME. On increasing of C.R, the intake air is compressed to higher pressure and all the air particles are much closer to each other. When the fuel is injected into the air, the rate of reaction in between air and fuel particles have improved. Combination of increasing in C.R of engine and inlet temperature of the fuel will further enhance evaporation and homogenization, and as a result efficient combustion is obtained. On preheating of CsME, the inbuilt oxygen release rate will improve; but on increasing of compression ratio the availability oxygen from air will decrease. These two parameters are balanced at 18.5:1 C.R and gives better results. On further increasing of compression ratio to 19:1 with preheating, it creates fluctuations in the flow of air and leads to unavailability of sufficient oxygen for combustion. This has resulted in increased fuel consumption at 19:1 C.R and reaches value of 1.16 kg/hr. Similar reflections are observed from the brake thermal efficiency versus brake power (Fig.5). Since the specific fuel consumption is inversely proportional to the thermal efficiency, the behaviour is proved in the present set of experiments. It indicates on preheating most of the thermal energy is converted into mechanical work. In this set of experiments C.R. of 18.5:1 yielded superior performance compared to other C.Rs. At full load, with preheating the brake thermal efficiency is 32.32 % at 18.5:1 C.R. On preheating of CsME at 16.5:1 C.R, the brake thermal efficiency is 26.74% which is 5.58% less than 18.5:1 C.R. At room temperature with 16.5:1 C.R for diesel operation, the brake thermal efficiency is 28.33% which is 4% less than CsME operation at 18.5:1CR. Comparison of brake thermal efficiencies is shown in Table 4.

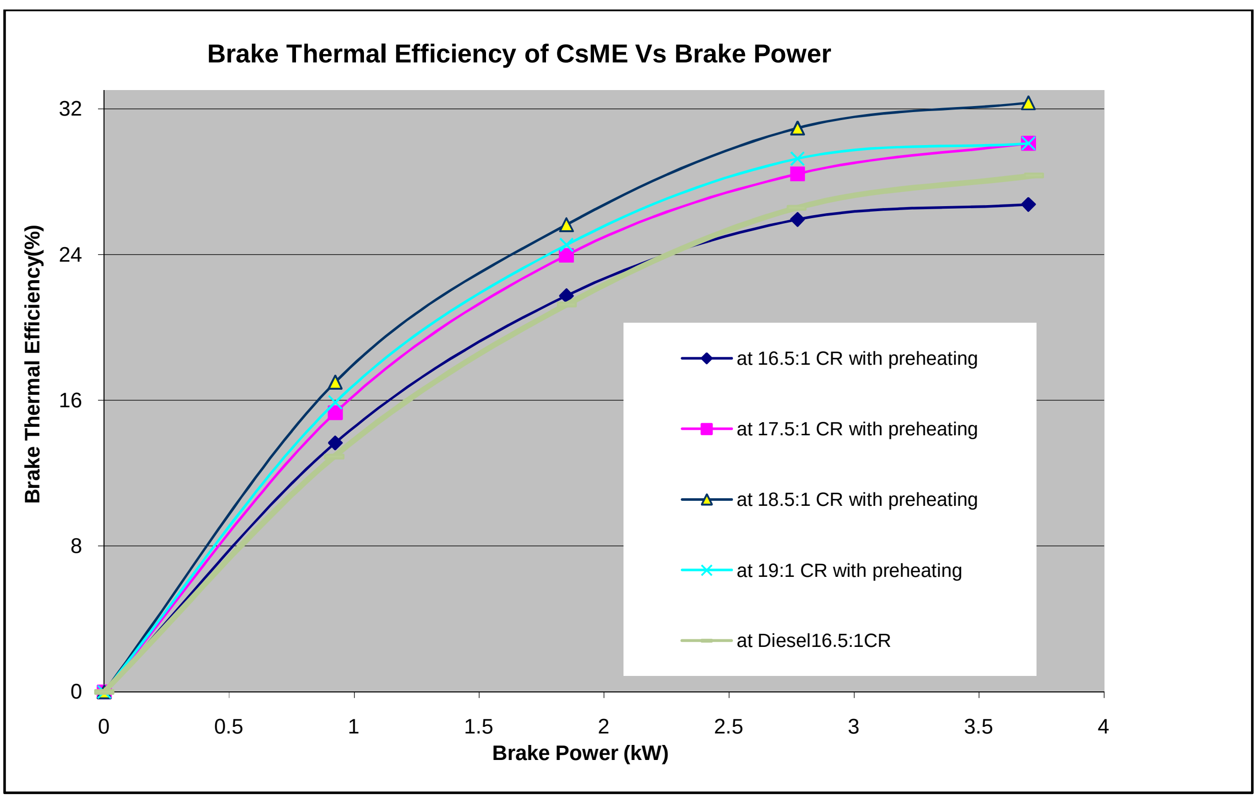

Fig. 5 : Brake Thermal Efficiency Vs Brake Power at different compression ratios

Table 4 : Comparison of brake thermal efficiencies at full load

Brake thermal efficiency (Diesel operation 16.5:1C.R) at RT	Brake thermal efficiency of CsME operation at 52^{0}C	
	16.5:1 C.R	18.5:1 C.R
28.33%	26.74%	32.32%

b) Emission analyses

As discussed above on the effect of preheating which improved the combustion leading to lower specific fuel consumption and better performance. This is further with the reduction in gaseous pollutants. On preheating, the levels of CO and HC in the exhaust gas are decreased significantly with the improved combustion.

From Fig. 6 at higher compression ratios after preheating, CO emission is minimum at 18.5:1 C.R. The amount of reduction in CO emission with CsME at 18.5:1 CR is 0.47% compared with CsME at 16.5:1 CR. The amount of CO emitted with CsME at 18.5:1 CR is marginally higher than diesel at standard compression ratio.

The variation of CO_2 on preheating at different compression ratios is not significant. The average variation at different compression ratios with respect to the load is 0.734%. It indicates that the formation of CO_2 during combustion at different compression ratios is almost equal; it is low at 18.5:1 CR shown in Fig.7.

The presence of HC in the exhaust gas is another parameter which reflects the incomplete combustion. The unburnt HC (Fig.8) in the exhaust gas is lower at higher compression ratios. It is lower at 17.5:1 & 18.5:1 C.R. At 19:1 C.R due to rich fuel combustion the presence of HC is slightly increased.

The increment of compression ratio will lead to the decrease of availability of oxygen from the free air; but due to preheating the release of molecular oxygen will improve. Compensation of decrement of oxygen availability from the free air with molecular oxygen causes the decrease of CO & HC. As a result, there is no much variation in free oxygen in the exhaust at preheating condition. The percentage of free oxygen is slightly higher at 18.5:1 C.R which supports the above statement (Fig.9).

On preheating at 16.5:1 C.R the exhaust gas temperature is higher (Fig.10). The delay period of CsME at 16.5:1 C.R is higher. The accumulation of fuel in the delay period is caused for higher temperatures. On increasing of compression ratio along with preheating, the delay period decreases and the peak temperature obtained are less. On preheating the exhaust gas temperature is lower at 18.5:1 C.R. At 19:1 C.R, the temperature is 609^{0}C which may be due to rich fuel combustion or after combustion.

From Fig.11 the NOx at 16.5:1 C.R of preheated CsME is 1465ppm. On preheating, release of molecular oxygen will be improved. At 18.5:1 C.R with preheating the value of NO_x is 1405 ppm. On preheating, the rate of combustion has increased. As a result, the oxygen will rapidly react with HC and later on will react with nitrogen. Even though the value of NO_x with preheating is higher, it is less than the diesel operation at room temperature. Comparison of NO_x is shown in Table 5.

Table 5 : Comparison of NO_x at full load

NO_x(Diesel operation 16.5:1CR)at RT	NO_x CsME operation at 52^{0}C	
	16.5:1 CR	18.5:1 CR
1570 ppm	1465ppm	1405 ppm

On preheating at 18.5:1 compression ratio, the smoke values are less at all other compression ratios including diesel at 16.5:1 CR is shown in figure 12. From the exhaust gas analysis of preheated CsME, 18.5:1 CR gives better results in the environmental aspect.

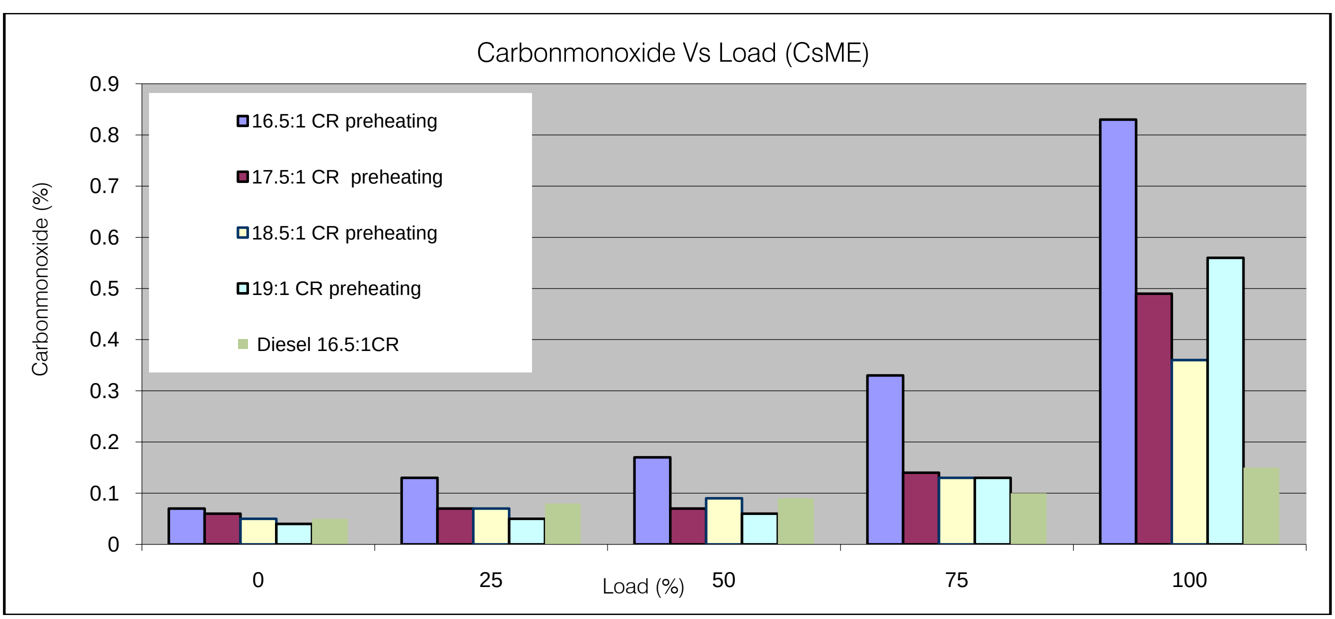

Fig. 6 : Carbon monoxide Vs Load at different compression ratios

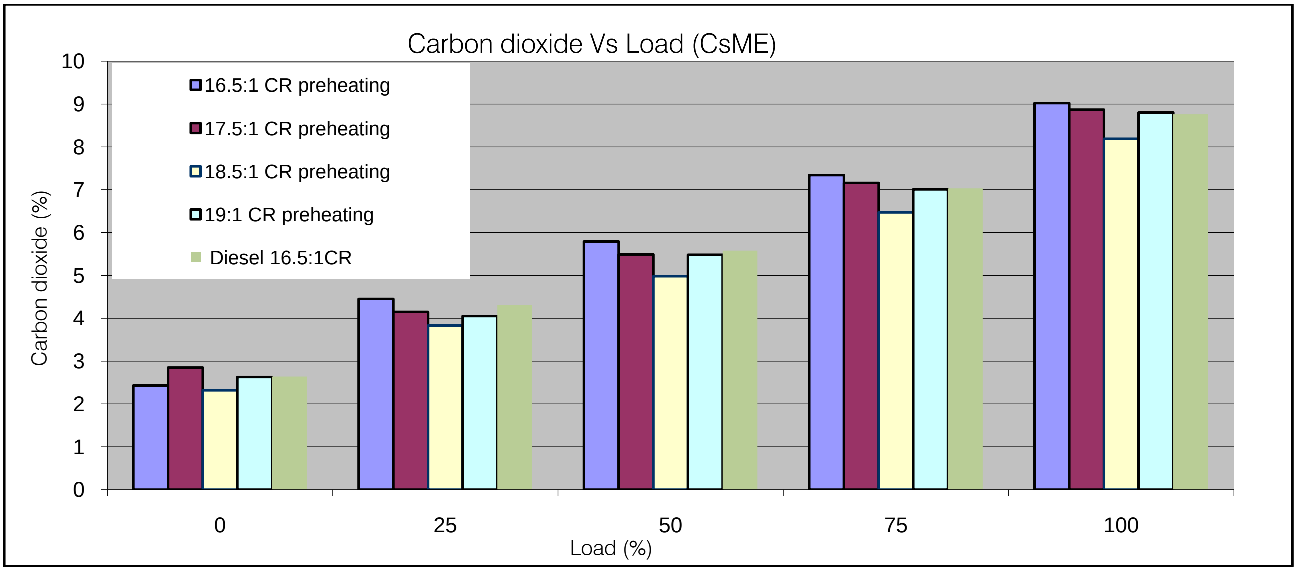

Fig. 7 : Carbon dioxide Vs Load at different compression ratios

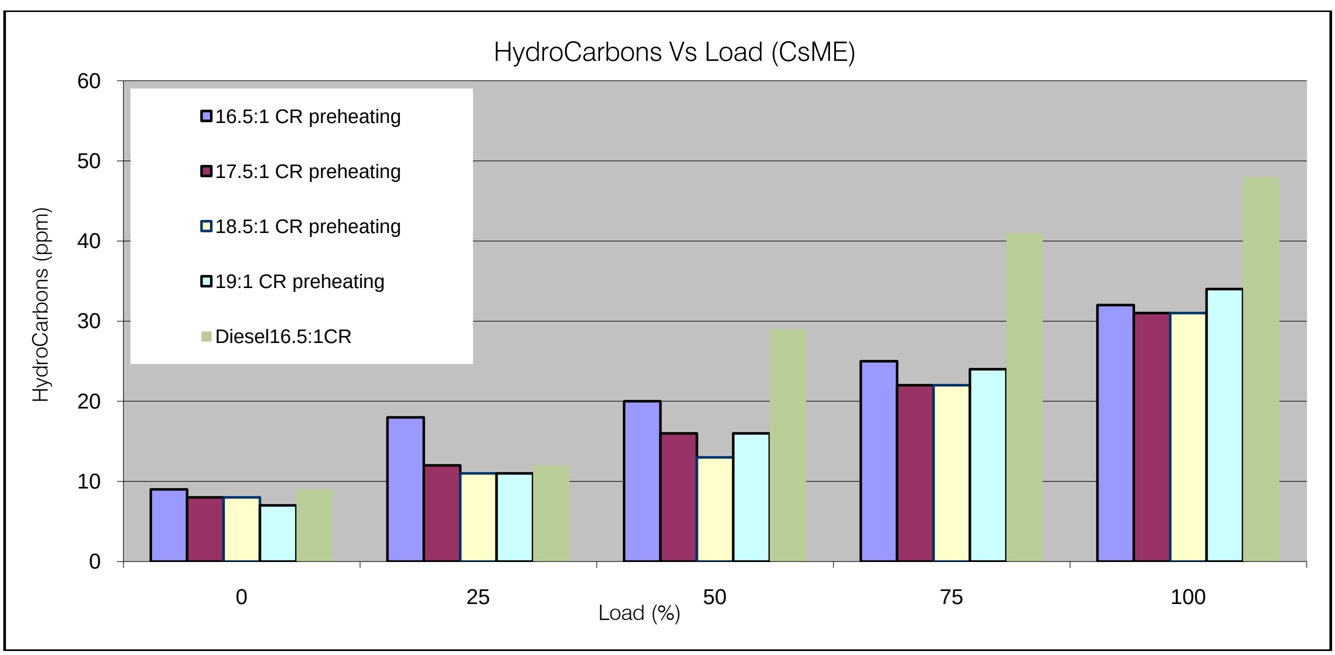

Fig. 8 : Hydrocarbons Vs Load at different compression ratios

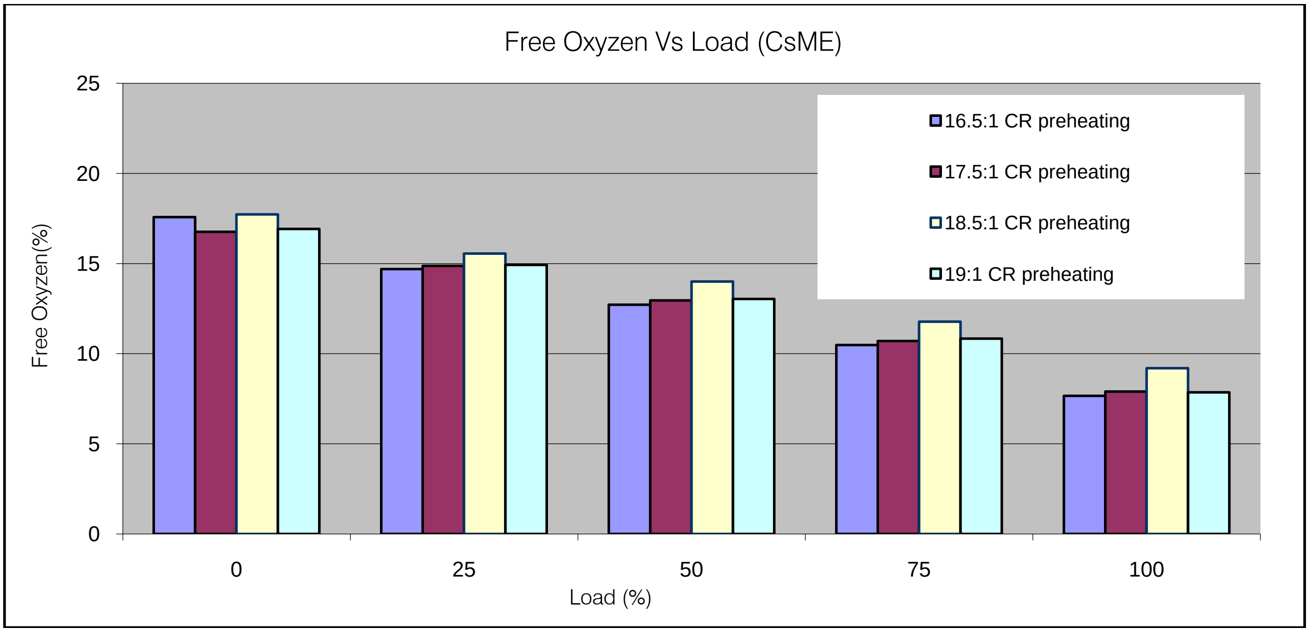

Fig. 9 : Free Oxyzen Vs Load at different compression ratios

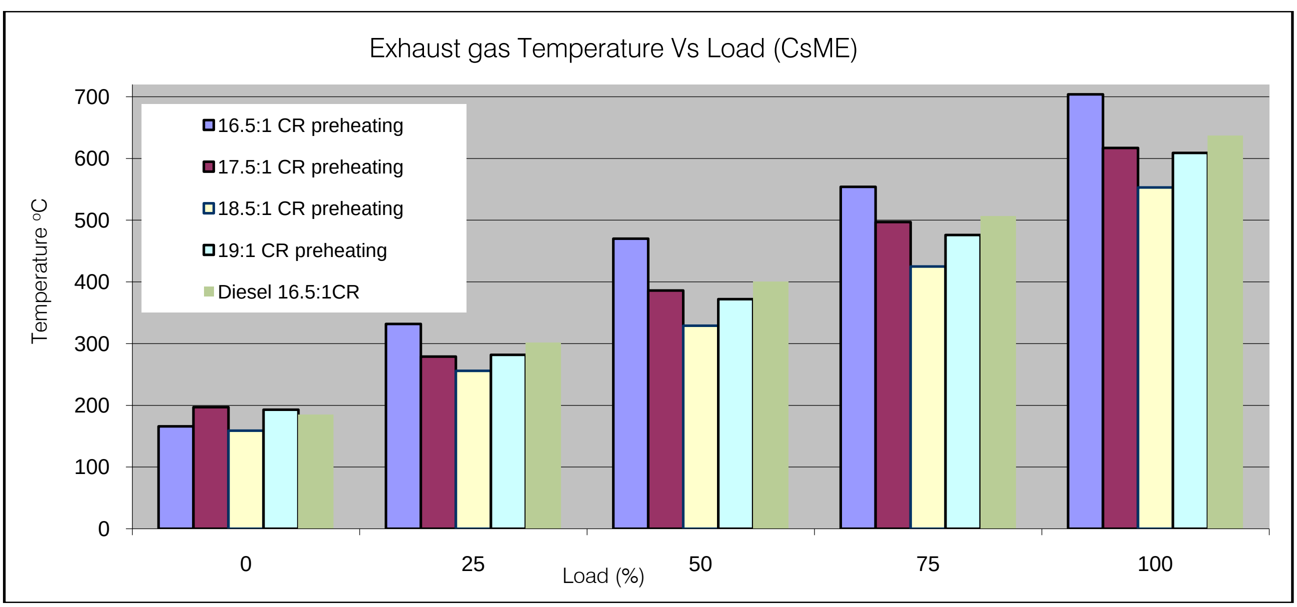

Fig. 10 : Exhaust Gas Temperature Vs Load at different compression ratios

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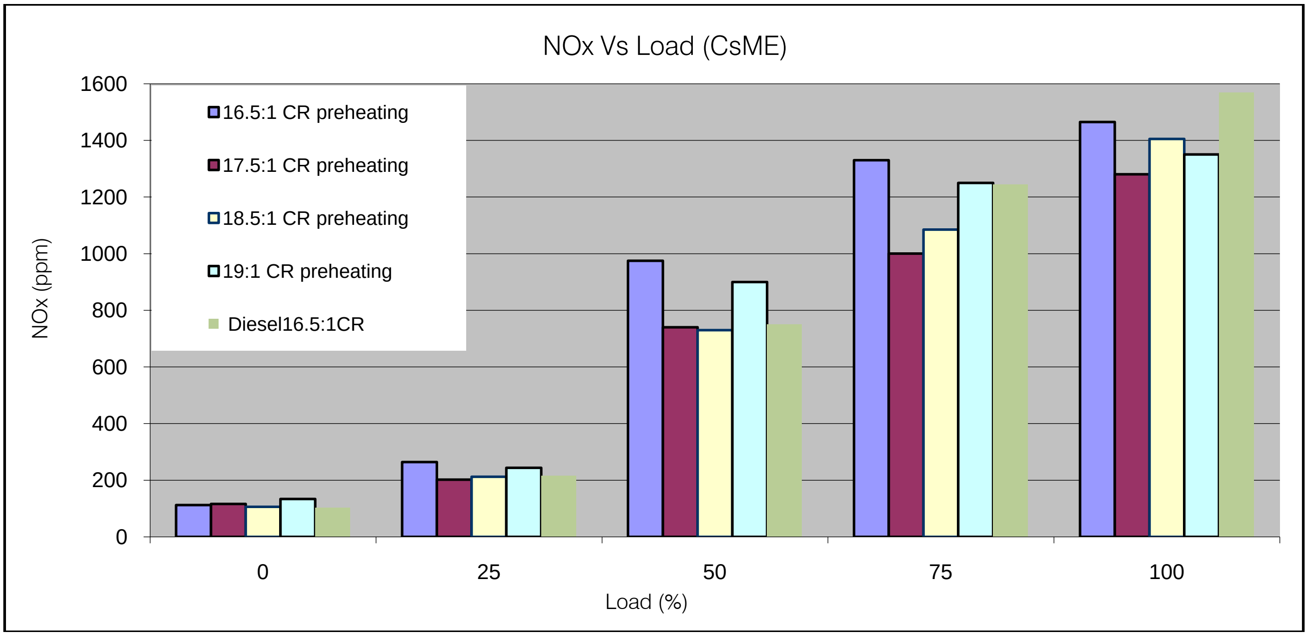

Fig. 11 : NO_x Vs Load at different compression ratios

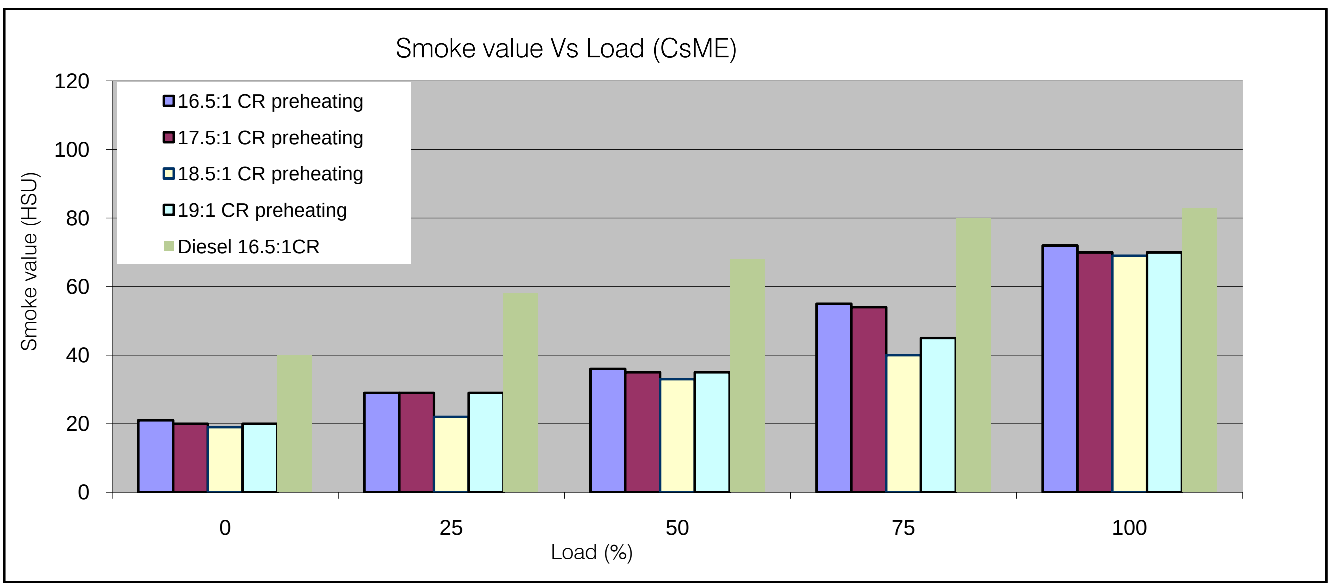

Fig. 12 : Smoke value Vs Load at different compression ratios

IV. Conclusions

The performance characteristic, combustion parameters and emissions in the exhaust are analyzed and compared with conventional fuel. The results are elaborately discussed based on the experimental investigations carried out with the use of cottonseed methyl esters with preheated in variable compression ratio engine. The following conclusions are arrived.

1. With increase in the compression ratio, the temperature and pressure of air which is participating in combustion will be more than normal operating conditions. It influences the physical delay period of combustion of the fuel i.e., the physical delay period is decreased on increasing of compression ratio.
2. For CsME, application at C.R 18.5:1 gives good results. The consumption of diesel at room temperature with C.R 16.5:1 is 1.09285 kg/hr, and the consumption of CsME at C.R 18.5:1 with 52^0C preheated temperature is 1.08 kg/hr. This value is almost equal to consumption of petro-diesel even though calorific value of CsME is less than diesel fuel. Preheating and increasing of compression ratio are the reasons for better combustion, and the engine operation under such conditions can be treated as economical.

2. For CsME, application at C.R 18.5:1 gives good results. The consumption of diesel at room temperature with C.R 16.5:1 is 1.09285 kg/hr, and the consumption of CsME at C.R 18.5:1 with 52^0C preheated temperature is 1.08 kg/hr. This value is almost equal to consumption of petro-diesel even though calorific value of CsME is less than diesel fuel. Preheating and increasing of compression ratio are the reasons for better combustion, and the engine operation under such conditions can be treated as economical.
3. With preheated CsME operation at full load, the brake thermal efficiency is 32.32 % at C.R 18.5:1 .On diesel operation at 16.5:1 C.R, the brake thermal efficiency is 28.33% which is 3.99% less than 18.5:1 C.R.
4. With preheating, the CO and HC in the exhaust gas are decreased and it indicates better combustion.
5. The value of NO_x with preheating is higher, but it is less than the diesel operation at room temperature. The value of NO_x with diesel operation at room temperature is 1570 PPM and it is 10.5% higher than CsME and C.R 18.5:1 at 52^0C.
6. Brake specific fuel consumption is also low. Thus the engine operation at C.R 18.5:1 with CsME at 52^0C preheating is superior to diesel fuel operation and is preferable for the CsME to adopt in the existing diesel engine.

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Design, Simulation, and Prototyping of Single Composite Leaf Spring for Light Weight Vehicle

By Shishay Amare Gebremeskel
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Abstract - Reducing weight while increasing or maintaining strength of products is getting to be highly important research issue in this modern world. Composite materials are one of the material families which are attracting researchers and being solutions of such issue. In this project reducing weight of vehicles and increasing or maintaining the strength of their spare parts is considered. As leaf spring contributes considerable amount of weight to the vehicle and needs to be strong enough, a single E-glass/Epoxy leaf spring is designed and simulated following the design rules of the composite materials considering static loading only. The constant cross section design of leaf springs is employed to take advantages of ease of design analysis and its manufacturing process. And it is shown that the resulting design and simulation stresses are much below the strength properties of the material, satisfying the maximum stress failure criterion. The designed composite leaf spring has also achieved its acceptable fatigue life. This particular design is made specifically for light weight three wheeler vehicles. Its prototype is also produced using hand lay-up method.

Keywords : leaf spring, E-Glass/Epoxy composite, constant cross section design, weight reduction and strength, Hand-lay-up.

GJRE-A Classification : FOR Code: 290401p

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Strictly as per the compliance and regulations of :

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Keywords : leaf spring, E-Glass/Epoxy composite, constant cross section design, weight reduction and strength, Hand-lay-up.

I. Introduction

a) Motivation on composite leaf spring

It is known that the failure nature of steel leaf springs is usually catastrophic. It is very important to reduce accidents and to replace steel leaf springs by gradually failing FRP (fibre reinforced polymer) composite material. Another point is to reduce weight of the vehicle while required strength is maintained, which is possible by FRP composite materials.

b) Objective

i. General Objective

This project has a general objective of designing, simulating, and prototyping of a single leaf spring for light weight, three wheeler vehicles, from composite material.

ii. Specific Objectives

- Selecting proper composite material,
- Design analysis and model simulation,
- Prototype manufacturing.

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c) Scope and limitation of the project

This project covers the design, simulation and prototyping of the single E-glass/Epoxy composite leaf spring for a light weight three wheeler vehicle. But the design is limited to the static loading only.

II. Literature Review

A composite material is the combination of two or more materials that produce a synergistic effect so that the combination produces aggregate properties that are different from any of those of its constituents attain independently. This is intentionally being done today to get different design, manufacturing as well as service advantages of products. Up on those products leaf spring is the focus of this project for which researches are running to get the best composite material, which meets the current requirement of strength and weight reduction in one, to replace the existing steel leaf spring. Here researches on this area are well reviewed showing the back ground of this project, as follows.

a) Basics of composite materials and their application on leaf springs

To meet the need of natural resources conservation, automobile manufacturers are attempting to reduce the weight of vehicles in recent years. The interest in reducing the weight of automobile parts has necessitated the use of better material, design, and manufacturing processes. The suspension leaf spring is one of the potential elements for weight reduction in automobiles as it leads to the reduction of un-sprung weight of automobile. The elements whose weight is not transmitted to the suspension spring are called the un-sprung elements of the automobile. This includes wheel assembly, axles, and part of the weight of suspension spring and shock absorbers. The leaf spring accounts for 10-20% 0f the un-sprung weight. The reduction of un-sprung weight helps in achieving improved ride characteristics and increased fuel efficiency. The cost of materials constitutes nearly 60-70% 0f the vehicle's cost and contributes to the better quality and performance of the vehicle.

The introduction of fibre reinforced plastics (FRP) made it possible to reduce the weight of machine element without any reduction of the load carrying capacity. Because of FRP material's high elastic strain energy storage capacity and high strength-to-weight ratio compared with those of steel, multi-leaf 33steel springs are being replaced by mono-leaf FRP springs. FRP springs also have excellent fatigue resistance and durability. But the weight reduction of the leaf spring is achieved not only by material replacement but also by design optimization [6].

Weight reduction has been the main focus of automobile manufacturers in the present scenario. The leaf spring suspension accounts for about 10-20% of vehicle un-sprung weight. Thus it becomes a potential unit for weight reduction. The weight reduction can be achieved by choosing better materials and optimized design etc. The replacement of steel with optimally designed composite leaf spring can provide 93% weight reduction. Moreover the composite leaf spring has lower stresses compared to steel spring. All these will result in fuel saving which will make countries energy independent because fuel saved is fuel produced [12]. Composite leaf springs in particular in light trucks deal with the cargo load, comfort, and safety aspects. Fibre reinforced epoxy coil springs have been known for years. Now a process for mass production has been developed. The era of electrically driven cars requires a change of thinking. It will be essential to reduce the weight of the vehicle. The question, "Battery **or** Passenger?" would be answered in a consumer-friendly manner, "Battery **and** Passenger". A significant amount of today's automotive composite applications are still parts which support the structure or are parts of the car body such as fenders, trunk lids, hoods. However the new generation of electrically driven cars require chassis and other load bearing structures made from CFRP (Carbon Fibre Reinforced Polymers). Epoxy carbon and glass composites have proven their outstanding mechanical, thermo-mechanical and fatigue resistance properties [18].

b) Approaches for design, analysis, modelling and simulation of a composite leaf spring

Based on the specific strain energy of steel spring and some composite materials, the E-glass/epoxy is selected as the spring material. Many attempts have been made to substitute more economic resins for the epoxy but all attempts to use polyester or vinyl ester resins have been unsuccessful to date. The stored elastic strain energy in a leaf spring varies directly with the square of maximum allowable stress and inversely with the modulus of elasticity both in the longitudinal and transverse directions according to:

$$S = \frac{1}{2}\frac{\sigma_t^2}{\rho E} \text{---------------2.1}$$

Where S is the strain energy, σ_t *is* the allowable stress, E is the modulus of elasticity and ρ is the density.

A life data analysis method is used. Two constants in their relation on the basis of experimental results are proposed. It is proved that the analytical formula predicts the fatigue life of component with E-glass/epoxy composite material, using Hwang and Han relation:

$$N = \{B(1-r)\}^{1/C} \text{-------------2.2}$$

Where, N is the number of cycles to failure; B = 10.33; C = 0.14012; $r = \frac{\sigma_{max}}{\sigma_u}$; σ_{max} is the maximum stress; σ_u is the ultimate tensile strength and r is the applied stress level.

Design and experimental fatigue analysis of composite multi leaf spring using glass fibre reinforced polymer are carried out using life data analysis, in this particular literature. Compared to steel spring, the composite leaf spring is found to have 67.35 % lesser stress, 64.95 % higher stiffness and 126.98 % higher natural frequency than that of existing steel leaf spring. The conventional multi leaf spring weighs about 13.5 kg whereas the E-glass/Epoxy multi leaf spring weighs only 4.3 kg. Thus the weight reduction of 68.15 % is achieved. Besides the reduction of weight, the fatigue life of composite leaf spring is predicted to be higher than that of steel leaf spring. Life data analysis is found to be a tool to predict the fatigue life of composite multi leaf spring. It is found that the life of composite leaf spring is much higher than that of steel leaf spring. The 3D FEM model of leaf spring is simulated using ANSYS [2].

Venkatesan and Devaraj [7] also used three-dimensional finite element method of analysis. They pointed that the leaf spring behaves like a simply supported beam and the flexural analysis is done considering it as a simply supported beam. The simply supported beam is subjected to both bending stress and transverse shear stress. Flexural rigidity is an important parameter in the leaf spring design and test out to increase from two ends to the centre. They tried to access three design approaches; i) constant thickness, varying width design, ii) constant width, varying thickness design and iii) constant cross-section design. Out of the above mentioned design concepts. The constant cross-section design method is selected due to the following reasons: due to its capability for mass production and accommodation of continuous reinforcement of fibres. Since the cross-section area is constant throughout the leaf spring, same quantity of reinforcement fibre and resin can be fed continuously during manufacturing. It is also quite suitable for filament winding process.

Shivashankar, Vijayarangan, and Pradeep [12] stated that taking the advantages of mass production and continuous fibre accommodation, composite leaf spring with constant sectional area is designed using Genetic Algorithm (GA) method. The weight of the composite leaf spring can be reduced by 53.5% by applying the GA optimization technique. Composite mono leaf spring reduces the weight by 85% for E-

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Glass/Epoxy over conventional leaf spring. The reduction of 93%weight is achieved by replacing conventional steel spring with an optimally designed composite mono-leaf spring.

Here experimental and numerical methods of analysis are employed. The element SHELL 99, SOLID 46 is the best suited for modelling of composite material. SHELL 99 is an 8 – node, 3D shell element with six degree of freedom at each node. The advantage of SOLID 46 is that we can stack several elements to model more than 250 layers. Here selected element was SOLID 46.Static Analysis is performed and the procedure consists of, Build the Model and Defining Parameters. The parameters for building the composite leaf spring are; Young's modulus, (EXX) value, Poison ratio, Y(PRXY) value, Length of cantilever beam, Width of cantilever beam, and Height of cantilever beam. Experimental results from testing the leaf springs under static loading containing the stresses and deflection are calculated. These results are also compared with FEA. The weight of the leaf spring is reduced considerably about 85 % by replacing steel leaf spring with composite leaf spring. Thus, the objective of reducing the un-sprung mass is achieved to some extent. Also, the stresses in the composite leaf spring are much lower than that of the steel spring [13].

Krishan and Aggarwal [4] followed a finite element approach for design and stress-deflection analysis of a multi leaf spring using CAE tools (i.e CATIA, ANSYS). The found that when the leaf spring is fully loaded, a variation of 0.632 % in deflection is observed between the experimental and FEA result, and same in case of half load, which validates the model and analysis. On the other hand, bending stress in both the cases is also close to the experimental results. The maximum value of equivalent stresses is below the Yield Stress of the material that leads to safe design from failure.

c) Manufacturing process of composite leaf spring

In the present scenario the main focus of automobile manufacturers is weight reduction of the automobile. Weight reduction can be achieved mainly by introducing the better material, design optimization and better manufacturing processes. In automobiles, leaf spring is one of the potential parts for weight reduction as it accounts for 10% - 20% of the un-sprung weight. Composite materials have made it possible to reduce the weight of leaf spring without any reduction in load carrying capacity and stiffness. Composite materials are now used extensively in place of metal parts [1].

Jadhao.et.al discussed about the manufacturing system of leaf spring. Using plywood as a mould material, prototype was fabricated as per desired dimension. The constant cross section design, which ensures the fibre pass continuously without interruption along length direction, which is advantageous to fibre reinforced structure, was employed. The glass fibres were cut to desired length, so that they can be deposited on mould layer- by-layer during fabrication of composite leaf spring. Apply the wax/gel. Prepare the solution of resin & Place the first layer of glass fibre chopped mat on mould followed by epoxy resin solution over mat. Wait for 5-10 min. Repeat the procedure till the desired thickness was obtained. The duration of the process may take up to 25- 30 min. And finally remove the leaf spring from mould [13].

Fig. 2.1 : Leaf springs with constant cross section design.

The constant cross section design is selected due to its capability for mass production, and to accommodate continuous reinforcement of fibres and also it is quite suitable for hand lay-up technique. Many techniques can be suggested for the fabrication of composite leaf spring. Composite leaf spring was fabricated using wet filament winding technique. In the present work, the hand lay-up process was employed. The templates (mould die) were made from wood and plywood according to the desired profile obtained from the computer algorithm. The glass fibres were cut to the desired lengths, so that they can be deposited on the template layer by layer during fabrication. In the conventional hand lay-up technique, a releasing agent (gel/wax) was applied uniformly to the mould which had good surface finish. This is followed by the uniform application of epoxy resin over glass fibre. Another layer is layered and epoxy resin is applied and a roller was used to remove all the trapped air. This process continued till the required dimensions were obtained. Care must be taken during the individual lay-up of the layers to eliminate the fibre distortion, which could result in lowering the strength and rigidity of the spring as a whole. The duration of the process may take up to 30 min. The mould is allowed to cure about 4 – 5 days at room temperature. Mono composite leaf springs with and without eye ends was fabricated by using above said technique [5].

The amount of elastic energy that can be stored by a leaf spring varies directly with the square of maximum allowable stress and inversely with the modulus of elasticity both in the longitudinal direction. Composite materials like the E-Glass/Epoxy in the direction of fibres have good characteristics for storing strain energy. So, the lay-up is selected to be unidirectional along the longitudinal direction of the spring. The unidirectional lay-up may weaken the spring at the mechanical joint area and require strengthening the spring in this region [5].

III. Design Analysis Of Composite Leaf Spring

a) Specific Design Data

Here Weight and initial measurements of three wheeler "Model: BA200ZK" light vehicle are taken.

Weight of vehicle= 380 kg

Maximum load carrying capacity= 390 kg

Total weight= 380 + 390 = 770 kg;

Taking factor of safety (FS) = 2, acceleration due to gravity (g)= 10 m/s^2

There for; Total Weight (W') = 770*10*2 = 15400 N

Since the vehicle is 3-wheeler, a single leaf spring corresponding to one of the wheels takes up one third of the total weight.

$F = \frac{15400}{3} = 5140$ N

From the material point of view a *unidirectional Glass/Epoxy* composite material is selected. It is selected due to its relative advantages stated in the literature review above, mainly high strength to weight ratio and high capacity of storing strain energy in the longitudinal direction of the fibres.

The properties of Glass/Epoxy composite material are given as follows [20].

E_1(modulus of elasticity along the longitudinal direction) = 54 GPa,

E_2(modulus of elasticity along the longitudinal direction)= 18 GPa,

G_{12}(shear modulus)= 9 GPa,

ν_{12}(major poison's ratio) = 0.25,

X_t= 1035 MPa, Y_t= 28 MPa, X_c= 1035 MPa, Y_c= 138 MPa,S= 41 MPa

Where,

$X_t$and $X_c$are longitudinal tensile and compressive strengths respectively,

Y_t and $Y_c$are transverse tensile and compressive strengths respectively, and

S is shear strength.

From Shiva and Vijayaranga [5] for E-glass/ Epoxy;

Maximum stress (σ_{max}) = 473 MPa

Maximum deflection(δ_{max}) = 105 mm

Measured data of the above statedlight weight three-wheelervehicle:

Straight length of the leaf spring (L) = 900 mm

Leaf span of load free curved leaf spring (L') = 880 mm

From ManasPatnaik, L.P. Koushik, and Manoj Mathew [19];

$\frac{C}{L'} = 0.089$; where C is the camber length and L' is the leaf span.

Thus C = 0.089*L' = 0.089*880 = 78 mm

b) Analysis

Since the leaf spring is fixed with the axle at its centre, only half of itis considered for analysis purpose;

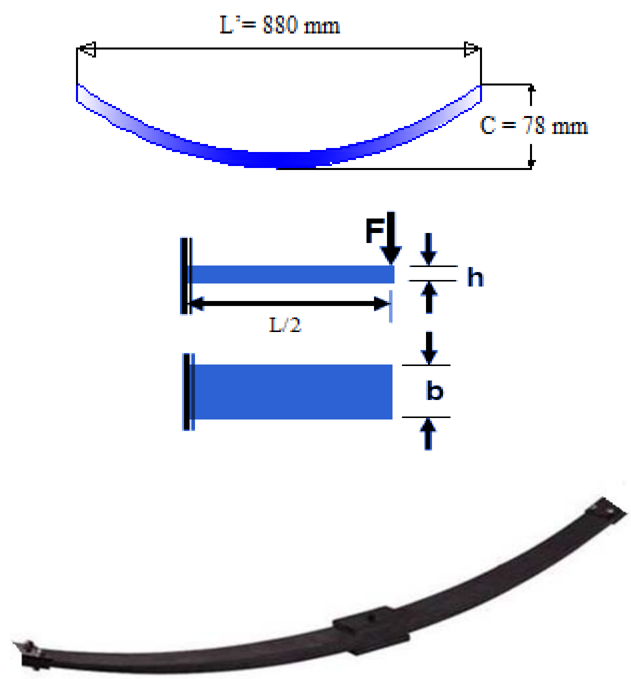


Fig. 3.1 : Important dimensions and free body diagram to analyse half of the leaf spring

Since analysing half of the leaf spring is enough, half of the applied force would have been taken. But here we took as it is to account over loadings of the vehicle and flexures of the leaf spring.

Hence, L/2 = 450 mm, F = 5140 N, h=? and b=?

Calculating for 'h' and 'b' dimensions which are capable of withstanding the loading behaviour of the composite (E-glass/ Epoxy) leaf spring is the result of this design.

From equations of strength of materials we have;

$\sigma_{max} = \frac{6FL}{bh^2}$-----------3.1

$\delta_{max} = \frac{4FL^3}{Ebh^3}$-----------3.2

Solving equations 3.1 and 3.2 simultaneously for 'h' (thickness of the leaf spring);

$h = \frac{\sigma_{max} L^2}{E\delta_{max}}$------------3.3

Since we consider half of the leaf spring we substitute 'L/2' instead of 'L' to calculate 'h' and 'b'. As the ends of the leaf spring are hinged, the entire leaf spring will only be loaded under tension. Therefore, we consider only the longitudinal properties. Equation 3.3 will be written as:

$$h = \frac{\sigma_{max}\,(L/2)^2}{E_1\delta_{max}} = \frac{473*10^6*(450)^2*10^{-6}}{54*10^9*105*10^{-3}}$$

h = 17 mm

Rearranging equation 3.1 and solving for the width 'b';

$$b = \frac{6F(L/2)}{\sigma_{max}\,h^2} = \frac{6*5140*450*10^{-3}}{473*10^6*(17)^2*10^{-6}} = 102 \text{ mm}$$

Calculating the bending stress(σ_b);

$$\sigma_b = \frac{M*y}{I} \text{-------------3.4;}$$

Where 'M' is the bending moment, 'y' is the distance from the neutral axis= h/2 and 'I' is the moment of inertia.

M= F*L/2= 5140*0.450= 2313 Nm

$$I = \frac{bh^3}{12} = \frac{0.102*(0.017)^3}{12} = 4.18*10^{-8}\text{m}^4$$

y = 17/2= 8.5 mm

Therefore, $\sigma_b = \frac{2313*0.0085}{4.18*10^{-8}}$ = 470.35 MPa

Since we use unidirectional orientation of fibres and pure tensile loading nature of the leaf spring is considered, we took plane stress condition as the leaf is thin plate. Thus the bending stress, completely, is responsible to the longitudinal stress; $\sigma_1 = \sigma_b$.

$$\sigma_1 = 470.35\ MPa$$

Stress along the transverse direction will be;

$$\sigma_2 = \frac{F}{b*\left(\frac{L}{2}\right)} = \frac{5140}{102*450*10^{-6}} = 0.112 \text{ MPa}$$

The shear stress will also be calculated as follows;

$$\tau_{12} = \frac{F}{A_S} = \frac{5140}{17*102*10^{-6}} = 3 \text{ MPa}$$

Now we need to calculate the strains to cross check with the simulation results of the product model of the leaf spring.

$$\begin{Bmatrix}\varepsilon_1\\ \varepsilon_2\\ \gamma_{12}\end{Bmatrix} = \begin{bmatrix} S_{11} & S_{12} & 0\\ S_{12} & S_{22} & 0\\ 0 & 0 & S_{66}\end{bmatrix}\begin{Bmatrix}\sigma_1\\ \sigma_2\\ \tau_{12}\end{Bmatrix} \text{----------------3.5}$$

Where ε_{ij} = strain matrix, S_{ij} = compliance matrix and σ^{ij} = stress matrix

$S_{11} = \frac{1}{E_1} = \frac{1}{54\ GPa}$ = 18.5*10^{-12} Pa^{-1}; $S_{22} = \frac{1}{E_2} = \frac{1}{18GPa}$ = 55.6*10^{-12} Pa^{-1}

$S_{12} = \frac{-\gamma_{12}}{E_1} = \frac{-0.25}{54GPa}$ = -4.63*10^{-12} Pa^{-1}; $S_{66} = \frac{1}{G_{12}} = \frac{1}{9GPa}$ = 111.1*10^{-12} Pa^{-1}

Substituting the values of compliance and stress matrices' elements in to equation 3.5;

$$\begin{Bmatrix}\varepsilon_1\\ \varepsilon_2\\ \gamma_{12}\end{Bmatrix} = \begin{bmatrix} 18.50*10^{-12} & -4.63*10^{-12} & 0\\ -4.63*10^{-12} & 55.6*10^{-12} & 0\\ 0 & 0 & 111.1*10^{-12}\end{bmatrix}\begin{Bmatrix}470.35*10^6\\ 0.112*10^6\\ 3*10^6\end{Bmatrix}$$

ε_1 = 8.7*10^{-3}; ε_2 = 2.17*10^{-3}; γ_{12} = 3.333*10^{-4}

We can calculate the fatigue life, number of cycles to fail, of the composite leaf spring using equation 2.2 [2].

$$N = \{B(1-r)\}^{1/C};$$

$$r = \frac{473\ MPa}{1035\ MPa} = 0.457; \text{ then}$$

$$N = \{10.33(1-0.457)\}^{1/0.14012} = 221.16*10^3 \text{ cycles.}$$

c) Modelling and simulation of composite leaf spring

A single E-glass/ Epoxy leaf spring is modelled and simulated using Abaqus/ CAE 6.10 and the stresses, strains and displacements are obtained as follows.

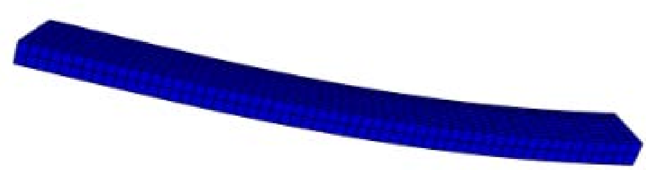


Fig. 4.1 : CAE solid model of single E-glass/Epoxy leaf spring

As the simulation with 8565 nodes and an element type of C3D20R is well done, the following results are observed.

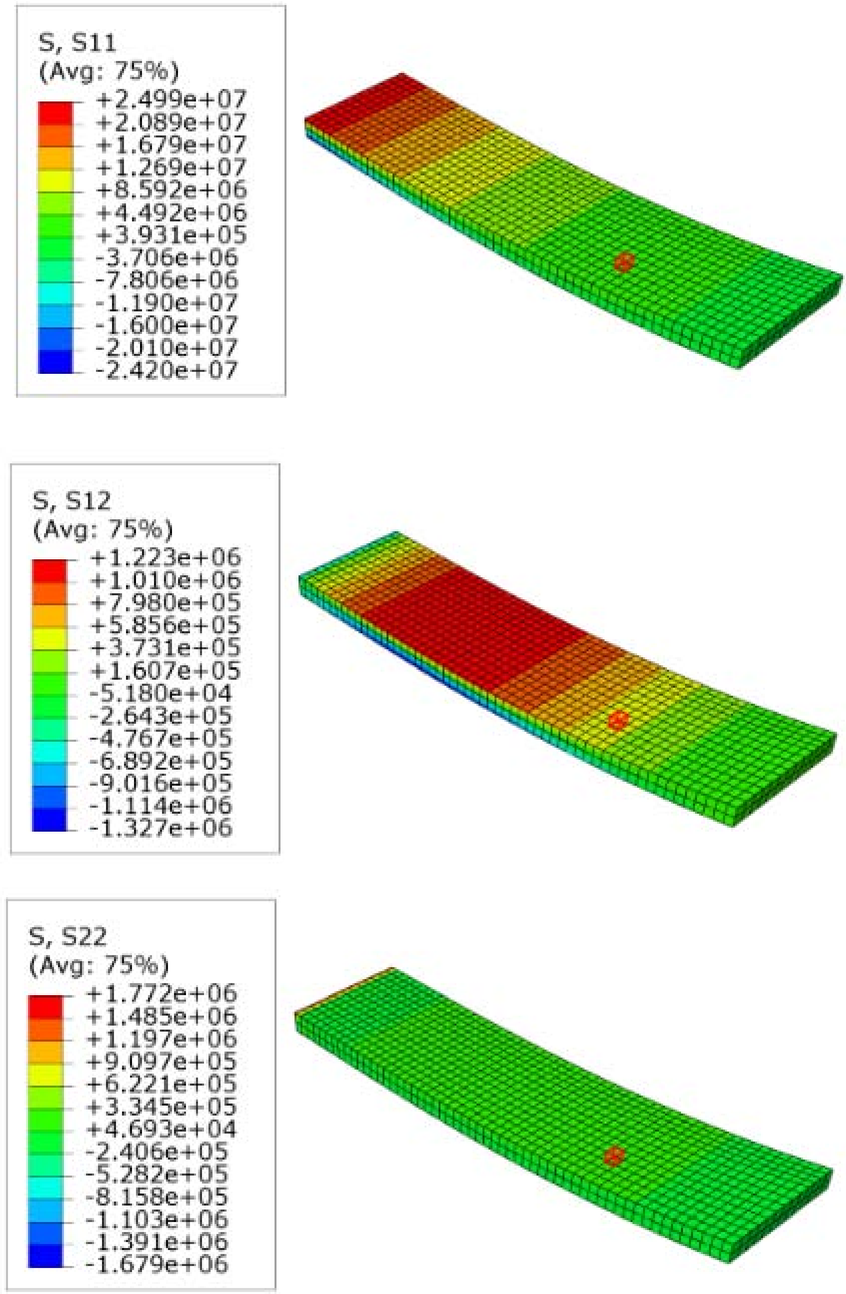
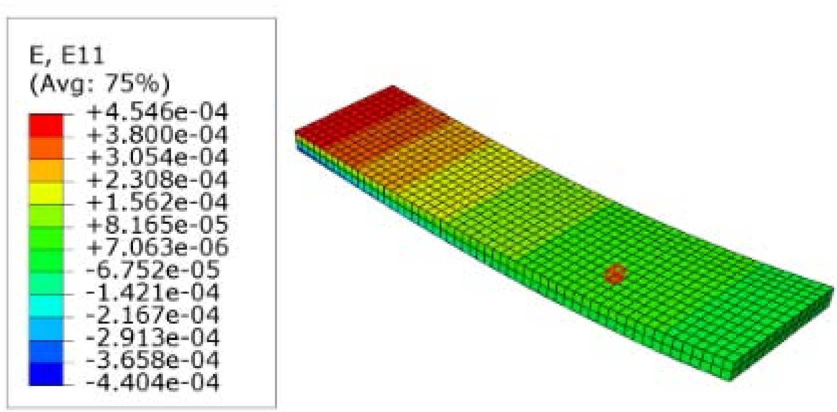


Fig. 4.2 : Simulation results of longitudinal, shear and transverse stresses



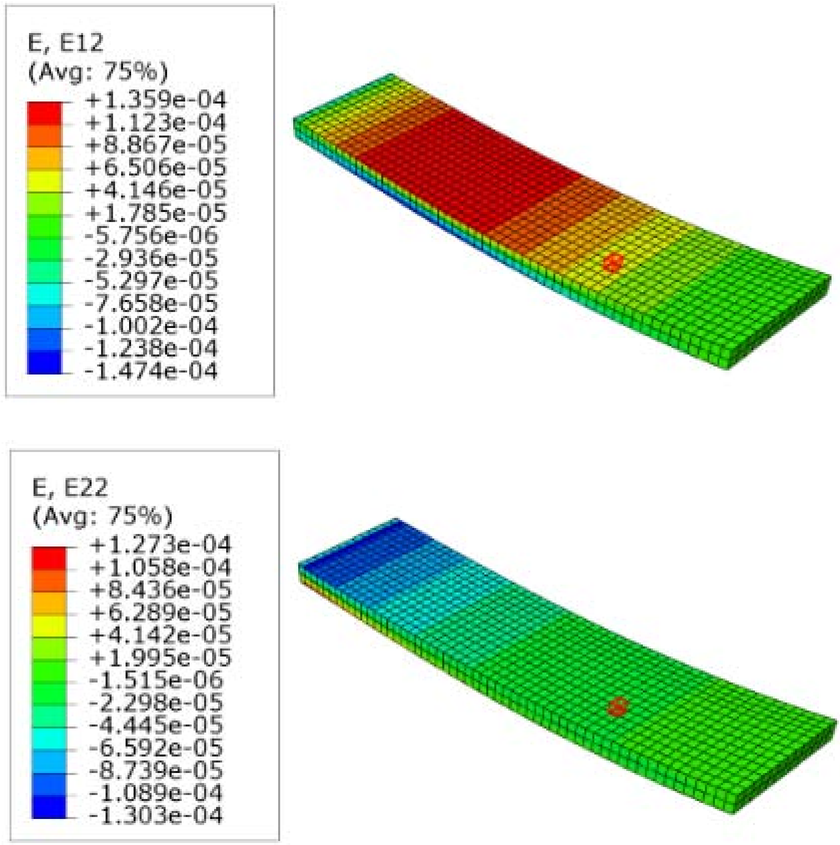


Fig. 4.3 : Simulation results of longitudinal, shear and transverse strains

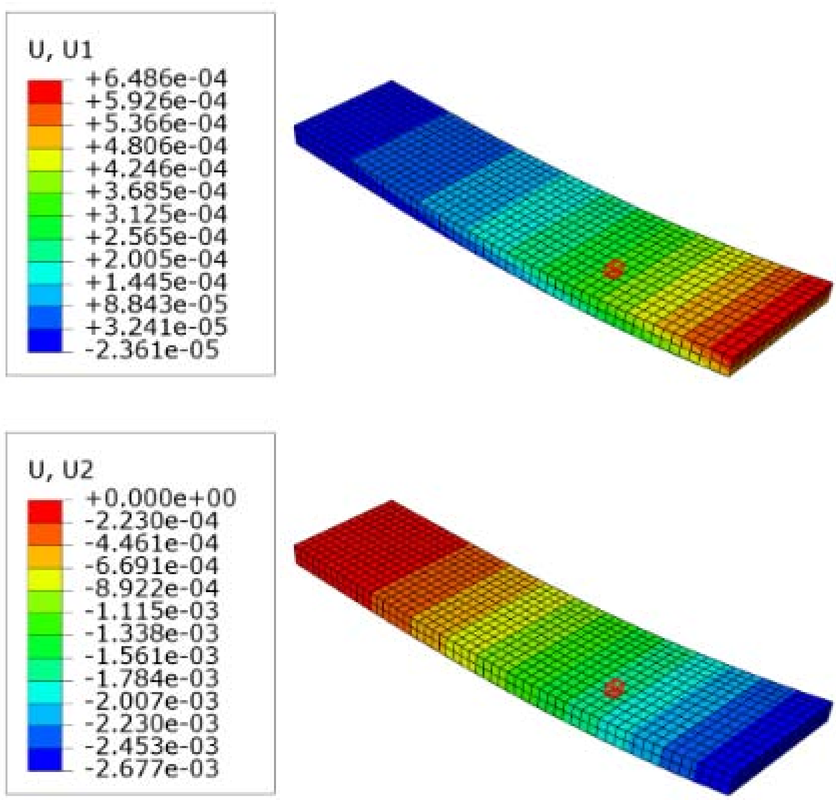


Fig. 4.4 : Simulation results of longitudinal and transverse displacements

IV. Prototype Manufacturing

We used a hand-lay-up method to produce the prototype of a single composite leaf spring. The constant cross section design is used which accommodate continuous reinforcement of fibres and quite suitable for hand lay-up technique. 40 layers of E-glass fibre of 0.4 mm thick each are used to achieve 17 mm thickness of the designed leaf spring.

The steps below are followed during prototyping:

- Preparing moulds as per the shape of the leaf spring and the setup.
- Preparing stiffener and clamping plates.
- Cutting fibres to desired dimensions.
- Applying wax/gel on the fibre side of the lower mould for ease of removal.
- Preparing mixture of epoxy resin and polyamine hardener.
- Apply the mixture just above the wax.
- Start laying up the first ply and apply the matrix on it again, repeat the same procedure up to the desired thickness.
- Apply the matrix well on the topmost layer and Cover the upper mould after the wax film is done on its fibre side.
- Put the stiffener on the covered mould and clamp tightly using the plates and c-clamps.
- Allow the composite leaf spring to cure enough at room temperature.
- Remove it from the set up and trim the excess material.

Fig. 5.1 : E-glass/ Epoxy composite leaf spring curing on the mould set up.

Fig. 5.2 : Untrimmed E-glass/ Epoxy composite leaf spring prototype

Fig. 5.3 : Trimmed final prototype of E-glass/Epoxy composite leaf spring

V. Results And Discussions

Since the shear stress (τ_{12}= 3 MPa) multiplied by a factor of '9' (9*3 = 27 MPa) is much less than the shear strength (S=41 MPa) of the specified composite material, E-glass/Epoxy. Specifying the criteria (9*τ_{12}< S), design is safe even for the flexural failure.

Using maximum stress failure criterion [20], the design and simulation results are evaluated as follows.

Table 6.1 : Comparison of the strength properties with the design and simulation results

Strength properties and design and simulation results of E-glass/Epoxy single composite leaf spring					
Strength properties	Design stresses	Design strains	Simulation stresses	Simulation strains	Simulation displacements(mm)
X_t=1035MPa	$\sigma_1 = 470.35\ MPa$	ε_1 = 8.7*10^{-3}	S_{11}= 25MPa	E_{11}= 4.5*10^{-4}	U_1= 0.65
Y_t= 28 MPa	σ_2=0.112 MPa	ε_2 = 2.17*10^{-3}	S_{22}= 1.8MPa	E_{22}= 1.3*10^{-4}	U_2= -2.68
S= 41 MPa	τ_{12} = 3 MPa	γ_{12}=3.333*10^{-4}	S_{12}= 1.3MPa	E_{12}= 1.5*10^{-4}	

When we compare the values, tabulated in Table 6.1 above, both the design and simulation stress values are much less than that of strength properties of the material. Therefore the maximum stress failure criterion is satisfied, hence safe design of the product. It can also be observed that the simulation strains are less in order of one tenth than that of design strains. The nodal displacementU_2(-2.68 mm) corresponds to the deflection of the leaf spring along its transverse direction, which is very small compared to the considered maximum deflection δ_{max} (105 mm) and the camber C (78 mm).

The fatigue life of the designed single E-glass/ Epoxy composite leaf spring is predicted and obtained as N= 221.16*10^3 cycles. This shows the acceptable life or good resistance of the material to failure under fatigue loading.

VI. Conclusion And Recommendation

As reducing weight and increasing strength of products are high research demands in the world, composite materials are getting to be up to the mark of satisfying these demands. In this project reducing weight of vehicles and increasing the strength of their spare parts is considered. As leaf spring contributes considerable amount of weight to the vehicle and needs to be strong enough, a single E-glass/Epoxy leaf spring is designed and simulated following the design rules of the composite materials. And it is shown that the resulting design and simulation stresses are much below the strength properties of the material satisfying the maximum stress failure criterion. It has achieved an acceptable fatigue life of 221.16*10^3 cycles. This particular design is made specifically for light weight three wheeler vehicles. Its prototype is also produced using hand lay-up method. It is recommended that any interested researcher has to go through this project and do the dynamic analysis of the design, since only the static loading case is considered here.

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Acceleration Analysis of 3DOF Parallel Manipulators

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Abstract - This paper presents a new approach to the velocity and acceleration analyses 3DOF parallel manipulators. Building on the definition of the 'acceleration motor', the forward and inverse velocity and acceleration equations are formulated such that the relevant analysis can be integrated under a unified framework that is based on the generalized Jacobian. A new Hessian matrix of serial kinematic chains (or limbs) is developed in an explicit and compact form using Lie brackets. This idea is then extended to cover parallel manipulators by considering the loop closure constraints. A 3- PRS parallel manipulator with coupled translational and rotational motion capabilities is analyzed to illustrate the generality and effectiveness of this approach.

Keywords : Acceleration analysis, Kinematics, Parallel manipulators.

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Acceleration Analysis of 3DOF Parallel Manipulators

Hassen Nigatu [α], Ajit Pal Singh [σ], Solomon Seid [ρ]

Abstract - This paper presents a new approach to the velocity and acceleration analyses 3DOF parallel manipulators. Building on the definition of the 'acceleration motor', the forward and inverse velocity and acceleration equations are formulated such that the relevant analysis can be integrated under a unified framework that is based on the generalized Jacobian. A new Hessian matrix of serial kinematic chains (or limbs) is developed in an explicit and compact form using Lie brackets. This idea is then extended to cover parallel manipulators by considering the loop closure constraints. A 3-PRS parallel manipulator with coupled translational and rotational motion capabilities is analyzed to illustrate the generality and effectiveness of this approach.

Keywords : Acceleration analysis, Kinematics, Parallel manipulators.

I. Introduction

Lower mobility parallel manipulators having fewer than six degrees of freedom (DOF) continue to draw interest from both industry and academia because they regularly offer improved balance between speed, accuracy, rigidity and reconfigurability when compared with conventional machine tools and industrial robots having serial architectures.

Velocity, accuracy, stiffness and rigid body dynamic behaviours are important performance factors that's should be considered in the design of lower mobility parallel manipulators. Particularly in circumstances where high speed is the priority, rigid body dynamics become a major concern for the dynamic manipulability evaluation, motor sizing and controller design, all of which involve acceleration analysis as the prerequisite.

Although general, systematic approaches are available for velocity analysis of lower mobility parallel manipulators using either kinematic influence coefficient methods or screw theory based methods (Huang et al., 2000; Joshi & Tsai, 2002; Jhu et al., 2007) it is by no means an easy task to use these approaches for acceleration analysis owing to the nonlinearity arising from the second order partial derivatives.

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A number of approaches have been proposed for acceleration analysis of either serial or parallel manipulators. The most straightforward method is to take time derivatives of a set of velocity constraint equations. This, however, involves a tedious and laborious process as shown by many case-by-case studies (Tsai, 2000; Khalil & Guegan, 2004; Li et al., 2005; Callegari et al., 2006). Therefore, a recursive matrix method was proposed in order to reduce computational burdens (Staicu & Zhang, 2008; Staicu, 2009). Having a goal of achieving a general and compact form of the Hessian matrix, the kinematic influence coefficient method was proposed for dealing with the acceleration analysis of serial manipulators (Thomas & Twsar, 1982). This idea was then extended to cover full and lower mobility parallel manipulators (Huang, 1985a; Huang, 1985b; Zhu, 2005; Huang, 2006; Zhu et al., 2007). Along this track, kinematic analysis of a number of parallel manipulators with different architectures has been carried out (Fang & Huang, 1997; Lu, 2006; Lu, 2008). Despite the plausibility and merits of the kinematic influence coefficient method, only an implicit form of the Hessian matrix can be achieved because of the unavoidable partial derivative implementations. Recently, an approach for acceleration analysis was proposed that introduced an auxiliary Hessian matrix derived from the differentiation of the auxiliary Jacobian of a class of parallel manipulators containing a passive properly constrained limb (Lu & Hu, 2007a; Lu & Hu, 2007b; Lu & Hu, 2008). Its suitability for other types of parallel manipulators, however, remains an issue to be investigated. Screw theory based approaches (Hunt, 1978; Mohamed & Duffy, 1985; Kumar, 1992; Ling & Huang, 1995; Bonev et al., 2003; Fang & Tsai, 2003; Zoppi, 2006) could potentially be the most powerful method for acceleration analysis. In order to overcome the difficulty of expressing the twist derivatives in a screw form, a novel term named the "accelerator" (Sugimoto, 1990) or "acceleration motor" (Brand, 1947) was proposed and employed for the acceleration analysis of serial and parallel kinematic chains (Rico & Duffy, 1996; Rico & Duffy, 2000). However, the terms associated with the second derivatives in the acceleration equations can only be written in a lengthy form of Lie brackets rather than in a compact form of the Hessian matrix.

Drawing primarily on the generalized Jacobian but also on the strengths of the kinematic influence coefficient method and the concept of accelerator, we propose a new approach for acceleration analysis of lower mobility parallel manipulators. Its goal is to achieve an explicit and compact form of the Hessian matrix. Having outlined in Section I the significance of acceleration analysis and its existing problems, the paper is organized as follows. Sections II and III systematically develop the formulations of forward/inverse velocity and acceleration models of serial and parallel kinematic chains, leading to new expressions of the Hessian matrices in a general and compact form. A practical illustration is presented in Section IV before conclusions are drawn in Section V.

II. Velocity Analysis

Based upon the authors' previous work (Huang et al., 2011), this section briefly addresses the velocity analysis of an *f*-DOF parallel manipulator using the "generalized Jacobian" and adds extensions necessary to its use in acceleration analysis. Without loss generality, assume that the manipulator is composed of l ($f \le l \le f+1$) limbs connecting the platform with the base, each essentially containing n_i ($i=1,2,\cdots,l$) 1-DOF joints with at most one of them actuated. Thus, two families of parallel manipulators can be taken into account. The first family covers fully parallel manipulators having *f* constrained active limbs ($n_i < 6$ for all limbs). The second family contains those having *f* unconstrained active limbs (i.e. $n_i = 6$ for each of these *f* limbs) plus one properly constrained passive limb designated by $l = f+1$. Any other parallel manipulators not belonging to these two families can be dealt with in a manner similar to that used below.

It has been shown (Huang et al., 2011) that entire set of the variational twists of the platform spans a 6-dimensional vector space T, known as the twist space. As the dual space of T, the entire set of wrenches exerted on the platform spans a 6-dimensional vector space W, named the wrench space. For an *f*-DOF manipulator, T can be decomposed into an *f* dimensional subspace, $\mathrm{T}_a \subseteq \mathrm{T}$, and a 6-*f* dimensional subspace, $\mathrm{T}_c \subseteq \mathrm{T}$, known respectively as the twist subspaces of permissions and restrictions. Correspondingly, W can also be decomposed into two subspaces, $\mathrm{W}_a \subseteq \mathrm{W}$ and $\mathrm{W}_c \subseteq \mathrm{W}$, known as the wrench subspaces of actuations and constraints. It has been proved that the following commutative relationships hold:

$$\text{Direct sum: } \mathrm{T} = \mathrm{T}_a \oplus \mathrm{T}_c,\ \mathrm{W} = \mathrm{W}_a \oplus \mathrm{W}_c \tag{1a}$$

$$\text{Orthogonality: } \mathrm{W}_a = \mathrm{T}_c^{\perp},\ \mathrm{W}_c = \mathrm{T}_a^{\perp} \tag{1b}$$

$$\text{Duality: } \mathrm{W}_a = \mathrm{T}_a^{*},\ \mathrm{W}_c = \mathrm{T}_c^{*} \tag{1c}$$

a) Velocity analysis of a limb

Let $\hat{\$}_{ta,j_a,i} \in \mathrm{T}_{a,i}$ ($j_a = 1,2,\cdots,n_i$), $\hat{\$}_{wa,k_a,i} \in \mathrm{W}_{a,i}$ ($k_a = 1,2,\cdots,n_i$), $\hat{\$}_{tc,j_c,i} \in \mathrm{T}_{c,i}$ ($j_c = 1,2,\cdots,6-n_i$) and $\hat{\$}_{wc,k_c,i} \in \mathrm{W}_{c,i}$ ($k_c = 1,2,\cdots,6-n_i$) be the basis elements of four vector subspaces associated with the *i*th limb. Note that the commutative relationships given in Eq. (1a, b, c) also hold for each limb since all limbs share the same platform. The variational twist of the platform can then be represented by a linear combination of the basis elements of $\mathrm{T}_{a,i}$ and $\mathrm{T}_{c,i}$

$$\begin{aligned}\$_t &= \$_{ta} + \$_{tc} = \$_{ta,i} + \$_{tc,i} \\ &= \sum_{j_a=1}^{n_i} \delta\rho_{a,j_a,i}\hat{\$}_{ta,j_a,i} + \sum_{j_c=1}^{6-n_i} \delta\rho_{c,j_c,i}\hat{\$}_{tc,j_c,i},\quad i=1,2,\cdots,l \\ &= \boldsymbol{J}_i \delta\boldsymbol{\rho}_i\end{aligned} \tag{2}$$

where,

$$\$_t = \begin{pmatrix}\delta\boldsymbol{r}^{\mathrm{T}} & \delta\boldsymbol{\alpha}^{\mathrm{T}}\end{pmatrix}^{\mathrm{T}}$$

$$\boldsymbol{J}_i = \begin{bmatrix}\boldsymbol{J}_{a,i} & \boldsymbol{J}_{c,i}\end{bmatrix}$$

$$\boldsymbol{J}_i = \begin{bmatrix}\boldsymbol{J}_{a,i} & \boldsymbol{J}_{c,i}\end{bmatrix}$$

$$\boldsymbol{J}_{a,i} = \begin{bmatrix}\hat{\$}_{ta,1,i} & \cdots & \hat{\$}_{ta,n_i,i}\end{bmatrix}$$

$$\boldsymbol{J}_{c,i} = \begin{bmatrix}\hat{\$}_{tc,1,i} & \cdots & \hat{\$}_{tc,6-n_i,i}\end{bmatrix}$$

$$\delta\boldsymbol{\rho}_i = \begin{pmatrix}\delta\boldsymbol{\rho}_{a,i}^{\mathrm{T}} & \delta\boldsymbol{\rho}_{c,i}^{\mathrm{T}}\end{pmatrix}^{\mathrm{T}}$$

$$\delta\boldsymbol{\rho}_{a,i} = \begin{pmatrix}\delta\rho_{a,1,i}\ \delta\rho_{a,2,i} \cdots \delta\rho_{a,n_i,i}\end{pmatrix}^{\mathrm{T}}$$

$$\delta\boldsymbol{\rho}_{c,i} = \begin{pmatrix}\delta\rho_{c,1,i}\ \delta\rho_{c,2,i} \cdots \delta\rho_{c,6-n_i,i}\end{pmatrix}^{\mathrm{T}}$$

$\delta\boldsymbol{r}$ and $\delta\boldsymbol{\alpha}$ denote, respectively, the linear variation of the reference point and the angular variation of the platform. $\hat{\$}_{ta,j_a,i}$ and $\delta\rho_{a,j_a,i}$ ($\hat{\$}_{tc,j_c,i}$ and $\delta\rho_{c,j_c,i}$) are the j_ath (j_cth) unit screw of permissions (restrictions) and its intensity. $\boldsymbol{J}_i$ is a 6×6 matrix known as the "generalized Jacobian" of a limb having connectivity of $n_i \le 6$.

For velocity analysis, which considers only ideal motions of the platform, relevant terms in Eq. (2) are replaced by:

$$\delta\boldsymbol{\rho}_i = \begin{pmatrix}\delta\boldsymbol{\rho}_{a,i}^{\mathrm{T}} & \delta\boldsymbol{\rho}_{c,i}^{\mathrm{T}}\end{pmatrix}^{\mathrm{T}} \to \dot{\boldsymbol{\theta}}_i = \begin{pmatrix}\dot{\boldsymbol{\theta}}_{a,i}^{\mathrm{T}} & \boldsymbol{0}^{\mathrm{T}}\end{pmatrix}^{\mathrm{T}}$$

$$\delta\boldsymbol{\rho}_{a,i} \to \dot{\boldsymbol{\theta}}_{a,i}$$

$$\delta\boldsymbol{\rho}_{c,i} \to \boldsymbol{0}$$

$$\dot{\boldsymbol{\theta}}_{a,i} = \begin{pmatrix}\dot{\theta}_{a,1,i} & \dot{\theta}_{a,1,i} & \cdots & \dot{\theta}_{a,n_i,i}\end{pmatrix}^{\mathrm{T}}$$

$$\$_t = \begin{pmatrix}\delta\boldsymbol{r}^{\mathrm{T}} & \delta\boldsymbol{\alpha}^{\mathrm{T}}\end{pmatrix}^{\mathrm{T}} \to \$_t = \begin{pmatrix}\boldsymbol{v}^{\mathrm{T}} & \boldsymbol{\omega}^{\mathrm{T}}\end{pmatrix}^{\mathrm{T}}$$

where, $\dot\theta_i$ are individual joint velocities. Thus (Huang et al., 2011)

$$\$_t = \boldsymbol{J}_i\dot{\boldsymbol{\theta}}_i,\ i=1,2,\cdots,l \tag{3}$$

where, $\$_t = \left(\boldsymbol{v}^{\mathrm{T}} \quad \boldsymbol{\omega}^{\mathrm{T}}\right)^{\mathrm{T}}$ becomes the velocity twist: $\boldsymbol{v}$ and $\boldsymbol{\omega}$ are the linear velocity of the reference point and the angular velocity of the platform. $\dot\theta_{a,j_a,i}$ ($k_a=1,2,\cdots,n_i$) represents the joint rate of the j_ath joint in limb i.

Using the commutative relationships given in Eq. (1) and taking inner products on both sides of Eq. (2) with $\hat{\$}_{wa,k_a,i}$ $(k_a=1,2,\cdots,n_i)$ and $\hat{\$}_{wc,k_c,i}$ ($k_c=1,2,\cdots,6-n_i$) leads, after the same replacements, to

$$\dot{\boldsymbol{\theta}}_i = \boldsymbol{J}_i^{-1}\$_t,\ i=1,2,\cdots,l \tag{4}$$

$$\boldsymbol{J}_i^{-1} = \begin{bmatrix} \boldsymbol{J}_{a,i}^L \\ \boldsymbol{J}_{c,i}^L \end{bmatrix}$$

$$\boldsymbol{J}_{a,i}^L = \begin{bmatrix} \hat{\$}^{\mathrm{T}}_{wa,1,i} \big/ \hat{\$}^{\mathrm{T}}_{wa,1,i}\hat{\$}_{ta,1,i} \\ \vdots \\ \hat{\$}^{\mathrm{T}}_{wa,n_i,i} \big/ \hat{\$}^{\mathrm{T}}_{wa,n_i,i}\hat{\$}_{ta,n_i,i} \end{bmatrix}$$

$$\boldsymbol{J}_{c,i}^L = \begin{bmatrix} \hat{\$}^{\mathrm{T}}_{wc,1} \big/ \hat{\$}^{\mathrm{T}}_{wc,1}\hat{\$}_{tc,1} \\ \vdots \\ \hat{\$}^{\mathrm{T}}_{wc,6-n_i,i} \big/ \hat{\$}^{\mathrm{T}}_{wc,6-n_i,i}\hat{\$}_{tc,6-n_i,i} \end{bmatrix}$$

Here the superscript L simply identifies that the matrix applies to a single limb. Thus, we have

$$\dot{\boldsymbol{\theta}}_{a,i} = \boldsymbol{J}_{a,i}^L\$_t,\ i=1,2,\cdots,l \tag{5}$$

b) Velocity analysis of a parallel manipulator

Building upon the work in Section 2.1, the velocity modeling of a parallel manipulator can be carried out with little extra effort. Let $\hat{\$}_{wa,g_k,k}$ be the unit wrench of actuations associated with the one actuated joint, numbered g_k, in the kth ($k=1,2,\cdots,f$) limb and $\hat{\$}_{wc,k_c,i}$ be the k_cth ($k_c=1,2,\ldots,6-n_k$) unit wrench of constraints in the ith ($i=1,2,\cdots,l$) limb. Again, using the commutative relationships given in Eq. (1), taking inner products on both sides of Eq. (2) with $\hat{\$}_{wa,g_k,k}$ and $\hat{\$}_{wc,k_c,i}$, respectively, and making replacements as at Eq. (3) results in

$$\boldsymbol{J}\$_t = \dot{\boldsymbol{q}} \tag{6}$$

where,

$$\boldsymbol{J} = \begin{bmatrix} \boldsymbol{J}_a \\ \boldsymbol{J}_c \end{bmatrix}$$

$$\boldsymbol{J}_a = \begin{bmatrix} \hat{\$}^{\mathrm{T}}_{wa,g_1,1} \big/ \hat{\$}^{\mathrm{T}}_{wa,g_1,1}\hat{\$}_{ta,g_1,1} \\ \hat{\$}^{\mathrm{T}}_{wa,g_2,2} \big/ \hat{\$}^{\mathrm{T}}_{wa,g_2,2}\hat{\$}_{ta,g_2,2} \\ \vdots \\ \hat{\$}^{\mathrm{T}}_{wa,g_f,f} \big/ \hat{\$}^{\mathrm{T}}_{wa,g_f,f}\hat{\$}_{ta,g_f,f} \end{bmatrix}$$

$$\boldsymbol{J}_c = \begin{bmatrix} \boldsymbol{J}_{c,1} \\ \boldsymbol{J}_{c,2} \\ \vdots \\ \boldsymbol{J}_{c,l} \end{bmatrix}$$

$$\boldsymbol{J}_{c,i} = \begin{bmatrix} \hat{\$}^{\mathrm{T}}_{wc,1,i} \big/ \hat{\$}^{\mathrm{T}}_{wc,1,i}\hat{\$}_{tc,1,i} \\ \hat{\$}^{\mathrm{T}}_{wc,2,i} \big/ \hat{\$}^{\mathrm{T}}_{wc,2,i}\hat{\$}_{tc,2,i} \\ \vdots \\ \hat{\$}^{\mathrm{T}}_{wc,6-n_i,i} \big/ \hat{\$}^{\mathrm{T}}_{wc,6-n_i,i}\hat{\$}_{tc,6-n_i,i} \end{bmatrix}$$

$$\dot{\boldsymbol{q}} = \left(\dot{\boldsymbol{q}}_a^{\mathrm{T}} \quad \boldsymbol{0}^{\mathrm{T}}\right)^{\mathrm{T}}$$

$$\dot{\boldsymbol{q}}_a = \left(\dot q_{a,g_1,1} \quad \dot q_{a,g_2,2} \quad \cdots \quad \dot q_{a,g_f,f}\right)^{\mathrm{T}}$$

In order to distinguish the joint rates of actuated joints from those of the passive joints, we use $\dot q_{a,g_k,k}$ to represent the rate of actuated joint numbered g_k in the kth limb. For convenience, $\dot q_{a,g_k,k}$ will be simplified as $\dot q_k$ in what follows. $\boldsymbol{J}$ is an $\left(f+\sum_{i=1}^{l}(6-n_i)\right)\times 6$ matrix known as the generalized Jacobian of parallel manipulators with $f\le 6$ DOF. Since $\left(f+\sum_{i=1}^{l}(6-n_i)\right)\ge 6$, the left pseudo-inverse of $\boldsymbol{J}$ exists. Using superscript P to identify explicitly platform terms, this leads to

$$\$_t = \boldsymbol{J}^{+}\dot{\boldsymbol{q}} = \boldsymbol{J}_a^P\dot{\boldsymbol{q}}_a,\ \boldsymbol{J}^{+} = \left(\boldsymbol{J}^{\mathrm{T}}\boldsymbol{J}\right)^{-1}\boldsymbol{J}^{\mathrm{T}} = \left[\boldsymbol{J}_a^P \quad \boldsymbol{J}_c^P\right] \tag{7}$$

Substituting Eq. (7) into Eq. (4), $\dot{\boldsymbol{\theta}}_i$ can then be expressed in terms of $\dot{\boldsymbol{q}}$

$$\dot{\boldsymbol{\theta}}_i = \boldsymbol{J}_i^{-1}\boldsymbol{J}^{+}\dot{\boldsymbol{q}} = \boldsymbol{J}_i^{LP}\dot{\boldsymbol{q}},\ i=1,2,\cdots,l \tag{8}$$

where, $\boldsymbol{J}_i^{LP} = \boldsymbol{J}_i^{-1}\boldsymbol{J}^{+}$ is a $6\times\left(f+\sum_{i=1}^{l}(6-n_i)\right)$ matrix.

Furthermore, the linear map between $\dot{\boldsymbol{q}}_a$ and $\dot{\boldsymbol{\theta}}_{a,i}$ is

$$\dot{\boldsymbol{\theta}}_{a,i} = \boldsymbol{J}_{a,i}^L\boldsymbol{J}_a^P\dot{\boldsymbol{q}}_a = \boldsymbol{J}_{a,i}^{LP}\dot{\boldsymbol{q}}_a,\ i=1,2,\cdots,l \tag{9}$$

where,

$\boldsymbol{J}_{a,i}^{LP} = \boldsymbol{J}_{a,i}^L\boldsymbol{J}_a^P$ is a $n_i\times f$ matrix.

III. Acceleration Analysis

Following the scheme in Section II, acceleration analysis will first be carried out on an n_i-DOF limb, with the results then being extended to cover an f-DOF parallel manipulator.

a) *Acceleration analysis of a limb*

Taking the variation of Eq. (2) and expressing the derivatives of screws in the form of Lie brackets as given in (Gallardo et al., 2003), yields

$$\boldsymbol{A} = \boldsymbol{J}_i \delta^2 \boldsymbol{\rho}_i + \$_i, \quad i = 1, 2, \cdots, l \tag{10}$$

where,

$$\boldsymbol{A} = \left(\left(\delta^2 \boldsymbol{r} - \delta\boldsymbol{\alpha} \times \delta\boldsymbol{r} \right)^{\mathrm{T}} \quad \left(\delta^2 \boldsymbol{\alpha} \right)^{\mathrm{T}} \right)^{\mathrm{T}}$$

$$\delta^2 \boldsymbol{\rho}_i = \left(\left(\delta^2 \boldsymbol{\rho}_{a,i} \right)^{\mathrm{T}} \quad \left(\delta^2 \boldsymbol{\rho}_{c,i} \right)^{\mathrm{T}} \right)^{\mathrm{T}}$$

$$\delta^2 \boldsymbol{\rho}_{a,i} = \left(\delta^2 \rho_{a,1,i} \quad \delta^2 \rho_{a,2,i} \quad \cdots \quad \delta^2 \rho_{a,n_i,i} \right)^{\mathrm{T}}$$

$$\delta^2 \boldsymbol{\rho}_{c,i} = \left(\delta^2 \rho_{c,1,i} \quad \delta^2 \rho_{c,2,i} \quad \cdots \quad \delta^2 \rho_{c,6-n_i,i} \right)^{\mathrm{T}}$$

$$\begin{aligned} \$_i = & \left[\delta\rho_{a,1,i} \hat{\$}_{ta,1,i} \quad \delta\rho_{a,2,i} \hat{\$}_{ta,2,i} + \cdots + \delta\rho_{c,6-n_i,i} \hat{\$}_{tc,6-n_i,i} \right] \\ & + \left[\delta\rho_{a,2,i} \hat{\$}_{ta,2,i} \quad \delta\rho_{a,3,i} \hat{\$}_{ta,3,i} + \cdots + \delta\rho_{c,6-n_i,i} \hat{\$}_{tc,6-n_i,i} \right] \\ & + \cdots + \left[\delta\rho_{c,5-n_i,i} \hat{\$}_{tc,5-n_i,i} \quad \delta\rho_{c,6-n_i,i} \hat{\$}_{tc,6-n_i,i} \right] \end{aligned}$$

$\delta^2 \boldsymbol{r}$, $\delta^2 \boldsymbol{\alpha}$, $\delta^2 \rho_{a,j_a,i}$, and $\delta^2 \rho_{c,j_c,i}$ denote, respectively, the variation of $\delta \boldsymbol{r}$, $\delta \boldsymbol{\alpha}$, $\delta \rho_{a,j_a,i}$, and $\delta \rho_{c,j_c,i}$. The bracket $[* \quad *]$ in $\$_i$ denotes the Lie product (Gallardo, 2006).

From the properties of the Lie product, $\$_i$ can also be written as

$$\$_i = \$_{a,i} + \$_{ac,i} + \$_{c,i} \tag{11}$$

where,

$$\begin{aligned} \$_{a,i} = & \delta\rho_{a,1,i}\delta\rho_{a,2,i} \left[\hat{\$}_{ta,1,i} \; \hat{\$}_{ta,2,i} \right] + \cdots + \delta\rho_{a,1,i}\delta\rho_{a,n_i,i} \left[\hat{\$}_{ta,1,i} \; \hat{\$}_{ta,n_i,i} \right] \\ & + \delta\rho_{a,2,i}\delta\rho_{a,3,i} \left[\hat{\$}_{ta,2,i} \; \hat{\$}_{ta,n_i,i} \right] + \cdots + \delta\rho_{a,2,i}\delta\rho_{a,n_i,i} \left[\hat{\$}_{ta,2,i} \; \hat{\$}_{ta,n_i,i} \right] \\ & + \cdots + \delta\rho_{a,n_i-1,i}\delta\rho_{a,n_i,i} \left[\hat{\$}_{ta,n_i-1,i} \; \hat{\$}_{ta,n_i,i} \right] \end{aligned}$$

$$\begin{aligned} \$_{ac,i} = & \delta\rho_{a,1,i}\delta\rho_{c,1,i} \left[\hat{\$}_{ta,1,i} \; \hat{\$}_{tc,1,i} \right] + \cdots + \delta\rho_{a,1,i}\delta\rho_{c,6-n_i,i} \left[\hat{\$}_{ta,1,i} \; \hat{\$}_{tc,6-n_i,i} \right] \\ & + \delta\rho_{a,2,i}\delta\rho_{c,1,i} \left[\hat{\$}_{ta,2,i} \; \hat{\$}_{tc,1,i} \right] + \cdots + \delta\rho_{a,2,i}\delta\rho_{c,6-n_i,i} \left[\hat{\$}_{ta,2,i} \; \hat{\$}_{tc,6-n_i,i} \right] \\ & + \cdots \\ & + \delta\rho_{a,n_i,i}\delta\rho_{c,1,i} \left[\hat{\$}_{ta,n_i,i} \; \hat{\$}_{tc,1,i} \right] + \cdots + \delta\rho_{a,n_i,i}\delta\rho_{c,6-n_i,i} \left[\hat{\$}_{ta,n_i,i} \; \hat{\$}_{tc,6-n_i,i} \right] \end{aligned}$$

$$\begin{aligned} \$_{c,i} = & \delta\rho_{c,1,i}\delta\rho_{c,2,i} \left[\hat{\$}_{tc,1,i} \; \hat{\$}_{tc,2,i} \right] + \cdots + \delta\rho_{c,1,i}\delta\rho_{c,6-n_i,i} \left[\hat{\$}_{tc,1,i} \; \hat{\$}_{tc,6-n_i,i} \right] \\ & + \delta\rho_{c,2,i}\delta\rho_{c,3,i} \left[\hat{\$}_{tc,2,i} \; \hat{\$}_{tc,3,i} \right] + \cdots + \delta\rho_{c,2,i}\delta\rho_{c,6-n_i,i} \left[\hat{\$}_{tc,2,i} \; \hat{\$}_{tc,6-n_i,i} \right] \\ & + \cdots + \delta\rho_{c,5-n_i,i}\delta\rho_{c,6-n_i,i} \left[\hat{\$}_{tc,5-n_i,i} \; \hat{\$}_{tc,6-n_i,i} \right] \end{aligned}$$

Then, Eq. (10) can be rewritten as

$$\boldsymbol{A} = \boldsymbol{J}_i \delta^2 \boldsymbol{\rho}_i + \delta\boldsymbol{\rho}_i^{\mathrm{T}} \boldsymbol{H}_i \delta\boldsymbol{\rho}_i, \quad i = 1, 2, \cdots, l \tag{12}$$

$$\boldsymbol{H}_i = \begin{bmatrix} \boldsymbol{H}_{a,i} & \boldsymbol{H}_{ac,i} \\ \boldsymbol{0} & \boldsymbol{H}_{c,i} \end{bmatrix}$$

$$\boldsymbol{H}_{a,i} = \begin{bmatrix} \boldsymbol{0} & \left[\hat{\$}_{ta,1,i} \; \hat{\$}_{ta,2,i} \right] & \left[\hat{\$}_{ta,1,i} \; \hat{\$}_{ta,3,i} \right] & \cdots & \left[\hat{\$}_{ta,1,i} \; \hat{\$}_{ta,n_i,i} \right] \\ \boldsymbol{0} & \boldsymbol{0} & \left[\hat{\$}_{ta,2,i} \; \hat{\$}_{ta,3,i} \right] & \cdots & \left[\hat{\$}_{ta,2,i} \; \hat{\$}_{ta,n_i,i} \right] \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \boldsymbol{0} & \boldsymbol{0} & \cdots & \boldsymbol{0} & \left[\hat{\$}_{ta,n_i-1,i} \; \hat{\$}_{ta,n_i,i} \right] \\ \boldsymbol{0} & \boldsymbol{0} & \cdots & \boldsymbol{0} & \boldsymbol{0} \end{bmatrix}$$

$$\boldsymbol{H}_{ac,i} = \begin{bmatrix} \left[\hat{\$}_{ta,1,i} \; \hat{\$}_{tc,1,i} \right] & \cdots & \left[\hat{\$}_{ta,1,i} \; \hat{\$}_{tc,6-n_i,i} \right] \\ \vdots & \vdots & \vdots \\ \left[\hat{\$}_{ta,n_i,i} \; \hat{\$}_{tc,1,i} \right] & \cdots & \left[\hat{\$}_{ta,n_i,i} \; \hat{\$}_{tc,6-n_i,i} \right] \end{bmatrix}$$

$$\boldsymbol{H}_{c,i} = \begin{bmatrix} \boldsymbol{0} & \left[\hat{\$}_{tc,1,i} \; \hat{\$}_{tc,2,i} \right] & \left[\hat{\$}_{tc,1,i} \; \hat{\$}_{tc,3,i} \right] & \cdots & \left[\hat{\$}_{tc,1,i} \; \hat{\$}_{tc,6-n_i,i} \right] \\ \boldsymbol{0} & \boldsymbol{0} & \left[\hat{\$}_{tc,2,i} \; \hat{\$}_{tc,3,i} \right] & \cdots & \left[\hat{\$}_{tc,2,i} \; \hat{\$}_{tc,6-n_i,i} \right] \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \boldsymbol{0} & \boldsymbol{0} & \cdots & \boldsymbol{0} & \left[\hat{\$}_{tc,5-n_i,i} \; \hat{\$}_{tc,6-n_i,i} \right] \\ \boldsymbol{0} & \boldsymbol{0} & \cdots & \boldsymbol{0} & \boldsymbol{0} \end{bmatrix}$$

$\boldsymbol{H}_i \in \mathbb{R}^{6\times6\times6}$ is known as the Hessian matrix of the ith limb. It is a three-dimensional matrix having six layers, each containing a 6×6 upper triangular matrix as shown in Fig. 1, where $[* \quad *]_{K_i}$ ($K_i = 1, 2, \cdots, 6$) denotes the K_ith element of the Lie bracket $[* \quad *]$. The constituent parts of $\boldsymbol{H}_i$, $\boldsymbol{H}_{a,i} \in \mathbb{R}^{6\times n_i \times n_i}$, $\boldsymbol{H}_{ac,i} \in \mathbb{R}^{6\times n_i \times (6-n_i)}$ and $\boldsymbol{H}_{c,i} \in \mathbb{R}^{6\times (6-n_i) \times (6-n_i)}$, are also three-dimensional matrices having six layers.

In acceleration analysis where only ideal motions of the platform are considered, replacements can be made in Eq. (12) such that:

$$\delta\boldsymbol{\rho}_i = \left(\delta\boldsymbol{\rho}_{a,i}^{\mathrm{T}} \quad \delta\boldsymbol{\rho}_{c,i}^{\mathrm{T}} \right)^{\mathrm{T}} \rightarrow \dot{\boldsymbol{\theta}}_i = \left(\dot{\boldsymbol{\theta}}_{a,i}^{\mathrm{T}} \quad \boldsymbol{0}^{\mathrm{T}} \right)^{\mathrm{T}}$$

$$\delta^2 \boldsymbol{\rho}_i = \left(\left(\delta^2 \boldsymbol{\rho}_{a,i} \right)^{\mathrm{T}} \quad \left(\delta^2 \boldsymbol{\rho}_{c,i} \right)^{\mathrm{T}} \right)^{\mathrm{T}} \rightarrow \ddot{\boldsymbol{\theta}}_i = \left(\ddot{\boldsymbol{\theta}}_{a,i}^{\mathrm{T}} \quad \boldsymbol{0} \right)^{\mathrm{T}}$$

$$\boldsymbol{A} = \left(\left(\delta^2 \boldsymbol{r} - \delta\boldsymbol{\alpha} \times \delta\boldsymbol{r} \right)^{\mathrm{T}} \left(\delta^2 \boldsymbol{\alpha} \right)^{\mathrm{T}} \right)^{\mathrm{T}} \rightarrow \boldsymbol{A} = \left(\left(\dot{\boldsymbol{v}} - \boldsymbol{\omega} \times \boldsymbol{v} \right)^{\mathrm{T}} \dot{\boldsymbol{\omega}}^{\mathrm{T}} \right)^{\mathrm{T}}$$

Thus,

$$\boldsymbol{A} = \boldsymbol{J}_i \ddot{\boldsymbol{\theta}}_i + \dot{\boldsymbol{\theta}}_i^{\mathrm{T}} \boldsymbol{H}_i \dot{\boldsymbol{\theta}}_i, \quad i = 1, 2, \cdots, l \tag{13}$$

or

$$A = J_{a,i}\ddot{\theta}_{a,i} + \dot{\theta}_{a,i}^{\mathrm{T}} H_{a,i}\dot{\theta}_{a,i}, \quad i = 1,2,\cdots,l \tag{14}$$

where, $A = \left((\dot{v} - \omega \times v)^{\mathrm{T}} \ \ \dot{\omega}^{\mathrm{T}} \right)^{\mathrm{T}}$ becomes the accelerator of an $n_i - \mathrm{DOF}$ limb with $\dot{v}$ and $\dot{\omega}$ being the linear acceleration of the reference point and the angular acceleration of the platform (Gallardo, 2003). The K_ith element in A has the expression

$$A_{K_i} = J_{i,K_i}\ddot{\theta}_i + \dot{\theta}_i^{\mathrm{T}} H_{i,K_i}\dot{\theta}_i, \quad i = 1,2,\cdots,l \tag{15}$$

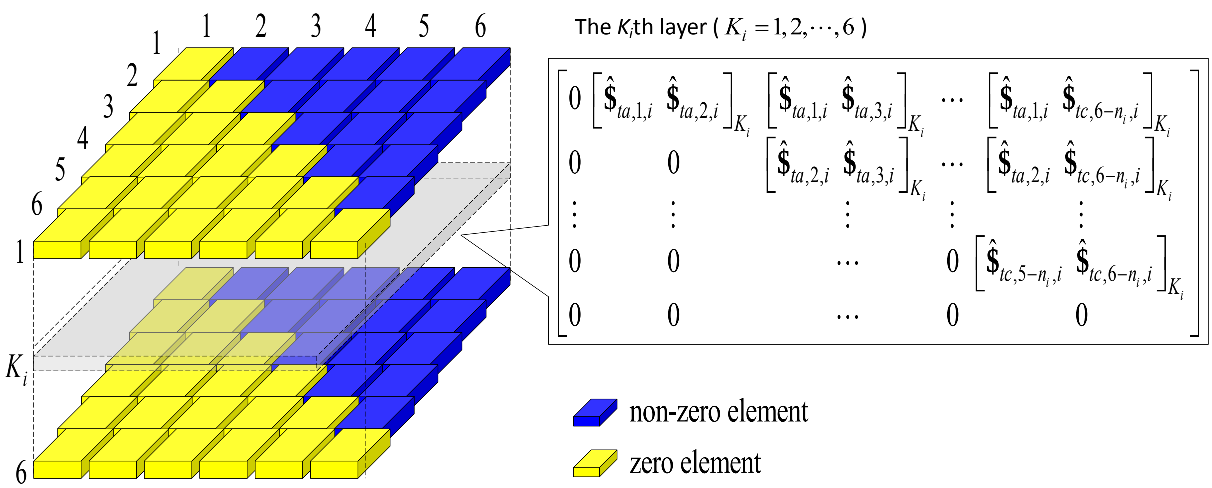


Fig. 1 : Hessian matrix, H_i, of the ith limb.

where, J_{i,K_i} is the K_ith row of J_i, while H_{i,K_i} is the K_ith layer of H_i.

In addition, the inverse acceleration equation of the *i*th limb can easily be obtained, by recalling Eq. (4), as

$$\ddot{\theta}_i = J_i^{-1}\left(A - \$_t^{\mathrm{T}} J_i^{-\mathrm{T}} H_i J_i^{-1} \$_t \right), \quad i = 1,2,\cdots,l \tag{16}$$

i. *Acceleration analysis of a parallel manipulator*

Following the same approach as at Eq. (6), the acceleration equation of a parallel manipulator is obtained by taking inner products on both sides of Eq. (13) with $\hat{\$}_{wa,g_k,k}$ and $\hat{\$}_{wc,k_c,i}$, respectively, and noting the relationship given in Eq. (8), to give

$$JA = \ddot{q} + \dot{q}^{\mathrm{T}} H \dot{q} \tag{17}$$

where,

$$\ddot{q} = \left(\ddot{q}_a^{\mathrm{T}} \ \ 0 \right)^{\mathrm{T}}$$

$$\ddot{q}_a = \left(\ddot{q}_{a,g_1,1} \ \ \ddot{q}_{a,g_2,2} \ \ \cdots \ \ \ddot{q}_{a,g_f,f} \right)^{\mathrm{T}}$$

Here, $\ddot{q}_{a,g_k,k}$ is the acceleration of the actuated joint numbered g_k in the *k*th limb ($k = 1,2,\cdots,f$). For convenience, $\ddot{q}_{a,g_k,k}$ will be simplified as $\ddot{q}_k$ in what follows. $H \in \mathbb{R}^{N\times N\times N}$ ($N = f + \sum_{i=1}^{l}(6 - n_i)$) is known as the Hessian matrix of an *f*-DOF parallel manipulator. It is a three dimensional matrix composed of $H_a \in \mathbb{R}^{f\times N\times N}$ and $H_c \in \mathbb{R}^{\sum_{i=1}^{l}(6-n_i)\times N\times N}$. The expression for the K_ath (K_cth) layer of H_a (H_c) is given in Fig. 2. Eq. (17) readily yields the inverse acceleration equation of a parallel manipulator,

$$\ddot{q} = JA - \$_t^{\mathrm{T}} J^{\mathrm{T}} H J \$_t \tag{18}$$

Moreover, multiplying both sides of Eq. (17) by the left pseudo-inverse of J gives the forward acceleration equation of a parallel manipulator:

$$A = J^{+}\left(\ddot{q} + \dot{q}^{\mathrm{T}} H \dot{q} \right) \tag{19}$$

Furthermore, substituting Eqs. (8) and (19) into Eq. (16) expresses the joint acceleration in the *i*th limb in terms of the velocity and acceleration of the actuated joints:

$$\ddot{\theta}_i = J_i^{LP}\left(\ddot{q} + \dot{q}^{\mathrm{T}} H \dot{q} \right) - J_i^{-1} \dot{q}^{\mathrm{T}} \left(J_i^{LP} \right)^{\mathrm{T}} H_i J_i^{LP} \dot{q}, \tag{20}$$

$$i = 1,2,\cdots,l$$

The above analyses formulate the forward/inverse velocity and acceleration equations of lower mobility parallel manipulators in a consistent manner under the umbrella of the generalized Jacobian. The velocity and acceleration of each $1 - \mathrm{DOF}$ actuated joint of the manipulator can be evaluated using Eqs. (8) and (20). Note, also, that the velocity and acceleration analyses given for a limb are also valid for serial manipulators with $f \leq 6$ DOF.

IV. An Example

Detailed execution of velocity and acceleration analyses for a 3-PRS parallel manipulator serves to illustrate the generality and effectiveness of the proposed approach.

Fig. 3 shows a schematic diagram of a 3-PRS parallel manipulator which is used as a 3-axis module named the Sprint Z3 (Wahl, 2002) as part of a 5-axis high-speed machining cell for extra large components. The manipulator consists of a base, a platform, and three identical limbs, each connecting the base with the platform in sequence by an actuated prismatic joint, a revolute joint, and a spherical joint.

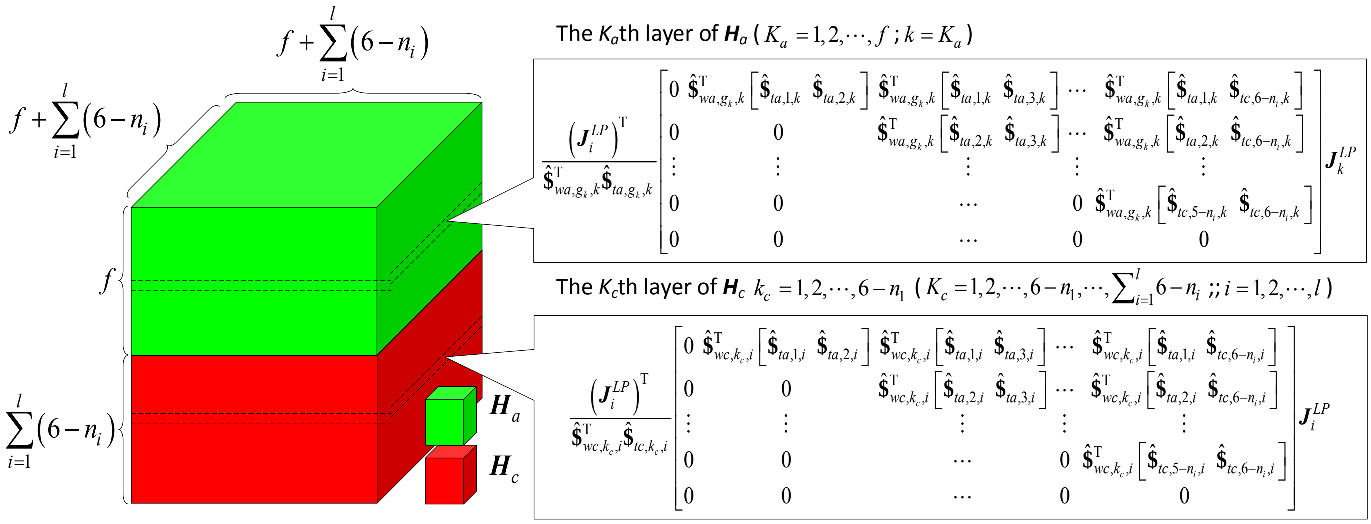


Fig. 2 : Hessian matrix, *H*, of a parallel manipulator.

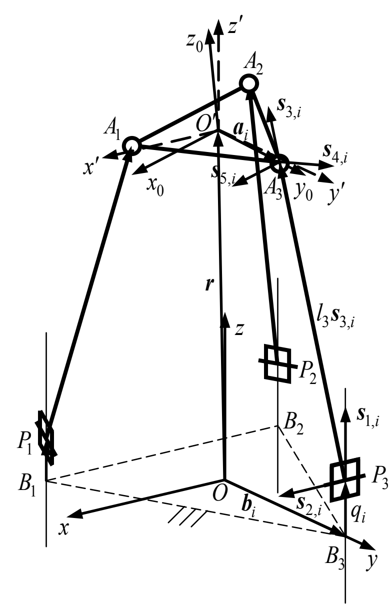
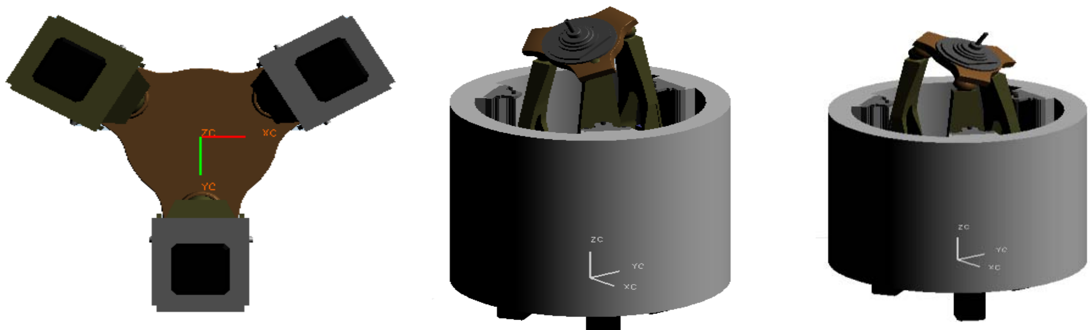


Fig. 3 : Schematic diagram of Sprint Z3 head.



4-a 4-b 4-c

Fig. 4 : (a) Shows the motor configuration, (b) The platform tilted with θ=20^0 about X_c, and (c) The platform tilted with 20^0 about Y_c.

Fig. 4 (a, b, and c) shows the CAD model of the selected example 3-PRS parallel kinematic machine, which helps to visualize and internalize the physical mechanism.

a) Inverse kinematics

A reference frame R is attached to the base and a body fixed frame R_0 to the platform, with O and O' located at the centers of the equilateral triangles $\Delta B_1B_2B_3$ and $\Delta A_1A_2A_3$, as shown. The z and z_0 axes are normal to the planes of those triangles, the x axis is parallel to $\overline{B_2B_1}$ and the x_0 axis is parallel to $\overline{A_2A_1}$. Also, an instantaneous reference frame R' is set with its origin at point O' and its three orthogonal axes remaining always parallel to those of R. Consequently, the orientation matrix of R_0 with respect to R can be obtained using three Euler angles, ψ, θ and ϕ in terms of precession, nutation, and body rotation according to the *z-x-z* convention

$$\boldsymbol{R}=\mathrm{Rot}(z,\psi)\mathrm{Rot}(x',\theta)\mathrm{Rot}(z'',\phi)$$

$$=\begin{bmatrix} \mathrm{C}\psi\mathrm{C}\phi-\mathrm{S}\psi\mathrm{C}\theta\mathrm{S}\phi & -\mathrm{C}\psi\mathrm{S}\phi-\mathrm{S}\psi\mathrm{C}\theta\mathrm{C}\phi & \mathrm{S}\psi\mathrm{S}\theta \\ \mathrm{S}\psi\mathrm{C}\phi+\mathrm{C}\psi\mathrm{C}\theta\mathrm{S}\phi & -\mathrm{S}\psi\mathrm{S}\phi+\mathrm{C}\psi\mathrm{C}\theta\mathrm{C}\phi & -\mathrm{C}\psi\mathrm{S}\theta \\ \mathrm{S}\theta\mathrm{S}\phi & \mathrm{S}\theta\mathrm{C}\phi & \mathrm{C}\theta \end{bmatrix} \quad (21)$$

where, 'S' and 'C' represent 'sin' and 'cos', respectively. Then, the position vector, $\boldsymbol{r}=(x \quad y \quad z)^{\mathrm{T}}$, of O' can be expressed as

$$\boldsymbol{r}=\boldsymbol{b}_i+q_i\boldsymbol{s}_{1,i}+l_3\boldsymbol{s}_{3,i}-\boldsymbol{a}_i,\ i=1,2,3 \quad (22)$$

where,

$$q_i\boldsymbol{s}_{1,i}=\overline{B_iP_i}$$

$$\boldsymbol{s}_{1,i}=(0 \quad 0 \quad 1)^{\mathrm{T}}$$

$$l_3\boldsymbol{s}_{3,i}=\overline{P_iA_i}$$

$$\boldsymbol{b}_i=(b_{ix} \quad b_{iy} \quad b_{iz})^{\mathrm{T}}=b(\cos\beta_i \quad \sin\beta_i \quad 0)^{\mathrm{T}}$$

$$\boldsymbol{a}_i=\boldsymbol{R}\boldsymbol{a}_{i0}=(a_{ix} \quad a_{iy} \quad a_{iz})^{\mathrm{T}}$$

$$\boldsymbol{a}_{i0}=a(\cos\beta_i \quad \sin\beta_i \quad 0)^{\mathrm{T}}$$

$$\beta_i=\frac{11\pi}{6}-(i-1)\frac{2\pi}{3},\ i=1,2,3$$

$\boldsymbol{b}_i$ and $\boldsymbol{a}_i$ are the position vectors of A_i and B_i measured in R; $\boldsymbol{a}_{i0}$ is the position vector of A_i measured in R_0; *a* and *b* are the radii of the platform and base, respectively; $q_i=\theta_{a,1,i}$ is the joint variable of the actuated prismatic joint in the *i*th limb.

The constraint imposed by the revolute joint restricts the translational motion of A_i along the axis of the revolute joint in limb *i*. This leads to three additional constraint equations,

$$(\boldsymbol{r}+\boldsymbol{a}_i)^{\mathrm{T}}\boldsymbol{s}_{2,i}=0,\ i=1,2,3 \quad (23)$$

where, $\boldsymbol{s}_{2,i}=(\sin\beta_i \quad -\cos\beta_i \quad 0)^{\mathrm{T}}$. Taking ψ, θ, and z as three generalized coordinates, Eq. (23) requires that

$$\phi=-\psi \quad (24)$$

$$x=-\frac{1}{2}a\mathrm{S}2\psi(1-\mathrm{C}\theta) \quad (25)$$

$$y=-\frac{1}{2}a\mathrm{C}2\psi(1-\mathrm{C}\theta) \quad (26)$$

Thus the three desired motions, ψ, θ, and z, can be considered as three independent Cartesian variables, leaving the translations along the x and y axes, and rotation about the z' axis (angle ϕ) as the constrained variables. Given a set of ψ, θ, and z, the inverse position problem is determined by

$$q_i=(\boldsymbol{r}+\boldsymbol{a}_i-\boldsymbol{b}_i-l_3\boldsymbol{s}_{3,i})^{\mathrm{T}}\boldsymbol{s}_{1,i},\ i=1,2,3 \quad (27)$$

$$\boldsymbol{s}_{3,i}=\begin{pmatrix}s_{3x,i} & s_{3y,i} & s_{3z,i}\end{pmatrix}^{\mathrm{T}},\ s_{3x,i}=\frac{1}{l_3}\left(x+a_{ix}-b_{ix}\right)$$

$$s_{3y,i}=\frac{1}{l_3}\left(y+a_{iy}-b_{iy}\right),\ s_{3z,i}=\sqrt{1-s_{3x,i}^2-s_{3y,i}^2}$$

b) Velocity analysis

Given the bases for the four vector subspaces of its ith limb (Huang et al., 2011), the generalized Jacobians of the ith limb and the generalized Jacobian of the manipulator can be formulated as follows.
For the ith limb ($i=1,2,3$):

$$\boldsymbol{J}_i=\begin{bmatrix}\boldsymbol{J}_{a,i} & \boldsymbol{J}_{ci}\end{bmatrix} \tag{28}$$

$$\boldsymbol{J}_{a,i}=\begin{bmatrix}\hat{\$}_{ta,1,i} & \hat{\$}_{ta,2,i} & \hat{\$}_{ta,3,i} & \hat{\$}_{ta,4,i} & \hat{\$}_{ta,5,i}\end{bmatrix}$$
$$=\begin{bmatrix}\boldsymbol{s}_{1,i} & \left(\boldsymbol{a}_i-l_3\boldsymbol{s}_{3,i}\right)\times\boldsymbol{s}_{2,i} & \boldsymbol{a}_i\times\boldsymbol{s}_{3,i} & \boldsymbol{a}_i\times\boldsymbol{s}_{4,i} & \boldsymbol{a}_i\times\boldsymbol{s}_{5,i}\\ \boldsymbol{0} & \boldsymbol{s}_{2,i} & \boldsymbol{s}_{3,i} & \boldsymbol{s}_{4,i} & \boldsymbol{s}_{5,i}\end{bmatrix}$$

$$\boldsymbol{J}_{c,i}=\hat{\$}_{tc,1,i}=\begin{pmatrix}\left(\boldsymbol{a}_i-l_3\boldsymbol{s}_{3,i}\right)\times\boldsymbol{n}_{1,i}\\ \boldsymbol{n}_{1,i}\end{pmatrix}$$

For the parallel manipulator:

$$\boldsymbol{J}=\begin{bmatrix}\boldsymbol{J}_a\\ \boldsymbol{J}_c\end{bmatrix} \tag{29}$$

$$\boldsymbol{J}_a=\begin{bmatrix}\boldsymbol{s}_{3,1}^{\mathrm{T}}/\boldsymbol{s}_{1,1}^{\mathrm{T}}\boldsymbol{s}_{3,1} & \left(\boldsymbol{a}_1\times\boldsymbol{s}_{3,1}\right)^{\mathrm{T}}/\boldsymbol{s}_{1,1}^{\mathrm{T}}\boldsymbol{s}_{3,1}\\ \boldsymbol{s}_{3,2}^{\mathrm{T}}/\boldsymbol{s}_{1,2}^{\mathrm{T}}\boldsymbol{s}_{3,2} & \left(\boldsymbol{a}_2\times\boldsymbol{s}_{3,2}\right)^{\mathrm{T}}/\boldsymbol{s}_{1,2}^{\mathrm{T}}\boldsymbol{s}_{3,2}\\ \boldsymbol{s}_{3,3}^{\mathrm{T}}/\boldsymbol{s}_{1,3}^{\mathrm{T}}\boldsymbol{s}_{3,3} & \left(\boldsymbol{a}_3\times\boldsymbol{s}_{3,3}\right)^{\mathrm{T}}/\boldsymbol{s}_{1,3}^{\mathrm{T}}\boldsymbol{s}_{3,3}\end{bmatrix}$$

$$\boldsymbol{J}_c=\frac{1}{l_3}\begin{bmatrix}\boldsymbol{s}_{2,1}^{\mathrm{T}}/\boldsymbol{s}_{1,1}^{\mathrm{T}}\boldsymbol{s}_{3,1} & \left(\boldsymbol{a}_1\times\boldsymbol{s}_{2,1}\right)^{\mathrm{T}}/\boldsymbol{s}_{1,1}^{\mathrm{T}}\boldsymbol{s}_{3,1}\\ \boldsymbol{s}_{2,2}^{\mathrm{T}}/\boldsymbol{s}_{1,2}^{\mathrm{T}}\boldsymbol{s}_{3,2} & \left(\boldsymbol{a}_2\times\boldsymbol{s}_{2,2}\right)^{\mathrm{T}}/\boldsymbol{s}_{1,2}^{\mathrm{T}}\boldsymbol{s}_{3,2}\\ \boldsymbol{s}_{2,3}^{\mathrm{T}}/\boldsymbol{s}_{1,3}^{\mathrm{T}}\boldsymbol{s}_{3,3} & \left(\boldsymbol{a}_3\times\boldsymbol{s}_{2,3}\right)^{\mathrm{T}}/\boldsymbol{s}_{1,3}^{\mathrm{T}}\boldsymbol{s}_{3,3}\end{bmatrix}$$

where, $\boldsymbol{s}_{j_a,i}$ is a unit vector along the j_ath 1-DOF joint of the ith limb; $\boldsymbol{n}_{1,i}=\boldsymbol{s}_{1,i}\times\boldsymbol{s}_{2,i}$. The joint axes are arranged such that $\boldsymbol{s}_{1,i}\perp\boldsymbol{s}_{2,i}$ and $\boldsymbol{s}_{2,i}\perp\boldsymbol{s}_{3,i}$; $\boldsymbol{s}_{3,i}$, $\boldsymbol{s}_{4,i}$ and $\boldsymbol{s}_{5,i}$ are coincident with three rotational axes of the spherical joint, with $\boldsymbol{s}_{3,i}$ aligned along the rod. Substituting Eq. (29) into Eqs. (6) and Eq. (7) generates the inverse and forward velocity equations of the manipulator

$$\dot{\boldsymbol{q}}=\boldsymbol{J}\$_t \tag{30}$$

$$\$_t=\boldsymbol{J}^{-1}\dot{\boldsymbol{q}} \tag{31}$$

where, $\dot{\boldsymbol{q}}=\begin{pmatrix}\dot{\boldsymbol{q}}_a^{\mathrm{T}} & \boldsymbol{0}^{\mathrm{T}}\end{pmatrix}^{\mathrm{T}}$ and $\dot{\boldsymbol{q}}_a=\begin{pmatrix}\dot{q}_1 & \dot{q}_2 & \dot{q}_3\end{pmatrix}^{\mathrm{T}}$.

c) Acceleration analysis

The Hessian matrix, $\boldsymbol{H}$, of the manipulator can be found by substituting the expressions just found for $\hat{\$}_{ta,j_a,i}$ ($j_a=1,2,\ldots,5$), $\hat{\$}_{tc,1,i}$ and Jacobians $\boldsymbol{J}_i$ and $\boldsymbol{J}$ into the forms shown in Figure 2 and Eq. (17) to give

$$\boldsymbol{H}_{a,K_a}=\frac{\left(\boldsymbol{J}_i^{LP}\right)^{\mathrm{T}}\boldsymbol{M}_{a,i}\boldsymbol{J}_i^{LP}}{\boldsymbol{s}_{1,i}^{\mathrm{T}}\boldsymbol{s}_{3,i}},\ K_a=i=1,2,3 \tag{32}$$

$$\boldsymbol{H}_{c,K_c}=\frac{\left(\boldsymbol{J}_i^{LP}\right)^{\mathrm{T}}\boldsymbol{M}_{c,i}\boldsymbol{J}_i^{LP}}{l_3\boldsymbol{s}_{1,i}^{\mathrm{T}}\boldsymbol{s}_{3,i}},\ K_c=i=1,2,3 \tag{33}$$

where,

$$\boldsymbol{J}_i^{LP}=\boldsymbol{J}_i^{-1}\boldsymbol{J}^{-1}$$

$$\boldsymbol{M}_{a,i}=\begin{bmatrix}\boldsymbol{M}_{a1,i} & \boldsymbol{0}\\ \boldsymbol{0} & \boldsymbol{M}_{a2,i}\end{bmatrix}$$

$$\boldsymbol{M}_{a1,i}=\begin{bmatrix}0 & \boldsymbol{s}_{3,i}^{\mathrm{T}}\boldsymbol{n}_{1,i} & 0 & \boldsymbol{s}_{3,i}^{\mathrm{T}}\left(\boldsymbol{s}_{1,i}\times\boldsymbol{s}_{4,i}\right) & \boldsymbol{s}_{3,i}^{\mathrm{T}}\left(\boldsymbol{s}_{1,i}\times\boldsymbol{s}_{5,i}\right)\\ 0 & 0 & 0 & l_3\boldsymbol{s}_{4,i}^{\mathrm{T}}\boldsymbol{s}_{2,i} & l_3\boldsymbol{s}_{5,i}^{\mathrm{T}}\boldsymbol{s}_{2,i}\end{bmatrix}$$

$$\boldsymbol{M}_{a2,i}=\begin{bmatrix}0\\ -l_3\boldsymbol{s}_{4,i}^{\mathrm{T}}\boldsymbol{n}_{1,i}\\ l_3\left(\boldsymbol{s}_{5,i}\times\boldsymbol{s}_{3,i}\right)^{\mathrm{T}}\left(\boldsymbol{s}_{3,i}\times\boldsymbol{n}_{1,i}\right)\\ 0\end{bmatrix}$$

$$\boldsymbol{M}_{c,i}=\begin{bmatrix}\boldsymbol{0} & \boldsymbol{M}_{c1,i}\\ \boldsymbol{0} & \boldsymbol{0}\end{bmatrix}$$

$$\boldsymbol{M}_{c1,i}=\begin{bmatrix}-\boldsymbol{s}_{3,i}^{\mathrm{T}}\boldsymbol{n}_{1,i} & -\boldsymbol{s}_{4,i}^{\mathrm{T}}\boldsymbol{n}_{1,i} & -\boldsymbol{s}_{5,i}^{\mathrm{T}}\boldsymbol{n}_{1,i} & -1\\ -l_3 & 0 & -l_3\boldsymbol{s}_{5,i}^{\mathrm{T}}\boldsymbol{s}_{3,i} & -l_3\boldsymbol{s}_{3,i}^{\mathrm{T}}\boldsymbol{n}_{1,i}\end{bmatrix}$$

Here, $\boldsymbol{H}_{a,K_a}$ ($\boldsymbol{H}_{c,K_c}$) represents the K_ath (K_cth) layer of $\boldsymbol{H}_a$ ($\boldsymbol{H}_c$). Then, substituting Eqs. (32) and (33) into Eqs. (18) and (19), the inverse and forward acceleration equations of the manipulator are

$$\ddot{\boldsymbol{q}}=\boldsymbol{J}\boldsymbol{A}-\$_t^{\mathrm{T}}\boldsymbol{J}^{\mathrm{T}}\boldsymbol{H}\boldsymbol{J}\$_t \tag{34}$$

$$\boldsymbol{A}=\boldsymbol{J}^{-1}\left(\ddot{\boldsymbol{q}}+\dot{\boldsymbol{q}}^{\mathrm{T}}\boldsymbol{H}\dot{\boldsymbol{q}}\right) \tag{35}$$

where, $\ddot{\boldsymbol{q}}=\begin{pmatrix}\ddot{\boldsymbol{q}}_a^{\mathrm{T}} & \boldsymbol{0}\end{pmatrix}^{\mathrm{T}}$ and $\ddot{\boldsymbol{q}}_a=\begin{pmatrix}\ddot{q}_1 & \ddot{q}_2 & \ddot{q}_3\end{pmatrix}^{\mathrm{T}}$.

d) Coordinate transformation for numerical simulation

Numerical simulations for the inverse velocity and acceleration, require the explicit relationships of the velocity twist and accelerator to the first and second derivatives of three independent coordinates, ψ, θ, and z because they are used for path planning.

Taking the time derivative of Eqs. (25) and (26) gives

$$\boldsymbol{v} = \dot{\boldsymbol{r}} = \boldsymbol{J}_v \dot{\boldsymbol{g}}_c \tag{36}$$

$$\boldsymbol{J}_v = \begin{bmatrix} -a\mathrm{C}2\psi(1-\mathrm{C}\theta) & -0.5a\mathrm{S}2\psi\mathrm{S}\theta & 0 \\ a\mathrm{S}2\psi(1-\mathrm{C}\theta) & -0.5a\mathrm{C}2\psi\mathrm{S}\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad \dot{\boldsymbol{g}}_c = \begin{pmatrix} \dot{\psi} \\ \dot{\theta} \\ \dot{z} \end{pmatrix}$$

Then, taking the time derivative of Eq. (36) results in

$$\dot{\boldsymbol{v}} = \boldsymbol{J}_v \ddot{\boldsymbol{g}}_c + \dot{\boldsymbol{g}}_c^{\mathrm{T}} \boldsymbol{H}_v \dot{\boldsymbol{g}}_c \tag{37}$$

where, $\boldsymbol{H}_v \in \mathbb{R}^{3\times3\times3}$ is a three dimensional matrix with $\boldsymbol{H}_{v,i}$ $(i=1,2,3)$ being its ith layer;

$$\ddot{\boldsymbol{g}}_c = \begin{pmatrix} \ddot{\psi} \\ \ddot{\theta} \\ \ddot{z} \end{pmatrix}, \quad \boldsymbol{H}_{v,1} = \begin{bmatrix} 2a\mathrm{S}2\psi(1-\mathrm{C}\theta) & -a\mathrm{C}2\psi\mathrm{S}\theta & 0 \\ -a\mathrm{C}2\psi\mathrm{S}\theta & -0.5a\mathrm{S}2\psi\mathrm{C}\theta & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$\boldsymbol{H}_{v,2} = \begin{bmatrix} 2a\mathrm{C}2\psi(1-\mathrm{C}\theta) & a\mathrm{S}2\psi\mathrm{S}\theta & 0 \\ a\mathrm{S}2\psi\mathrm{S}\theta & -0.5a\mathrm{C}2\psi\mathrm{C}\theta & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$\boldsymbol{H}_{v,3} = \boldsymbol{0}_{3\times3}$$

The angular velocity vector of the platform, $\boldsymbol{\omega} = (\omega_x \quad \omega_y \quad \omega_z)^{\mathrm{T}}$, can be derived by recalling, e.g. (Angeles, 2003), the standard matrix expression for the $\boldsymbol{\omega}\times$ operator

$$\begin{bmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{bmatrix} = \dot{\boldsymbol{R}}\boldsymbol{R}^{\mathrm{T}} \tag{38}$$

and directly comparing elements, to give

$$\boldsymbol{\omega} = \boldsymbol{J}_\omega \dot{\boldsymbol{g}}_c \tag{39}$$

$$\boldsymbol{J}_\omega = \begin{bmatrix} -\mathrm{S}\psi\mathrm{S}\theta & \mathrm{C}\psi & 0 \\ \mathrm{C}\psi\mathrm{S}\theta & \mathrm{S}\psi & 0 \\ 1-\mathrm{C}\theta & 0 & 0 \end{bmatrix}$$

Taking the time derivative of Eq. (39) gives

$$\dot{\boldsymbol{\omega}} = \boldsymbol{J}_\omega \ddot{\boldsymbol{g}}_c + \dot{\boldsymbol{g}}_c^{\mathrm{T}} \boldsymbol{H}_\omega \dot{\boldsymbol{g}}_c \tag{40}$$

where, $\boldsymbol{H}_\omega \in \mathbb{R}^{3\times3\times3}$ is also a three dimensional matrix with $\boldsymbol{H}_{\omega,i}$ $(i=1,2,3)$ being its ith layer;

$$\boldsymbol{H}_{\omega,1} = \begin{bmatrix} -\mathrm{C}\psi\mathrm{S}\theta & -\mathrm{S}\psi & 0 \\ -\mathrm{S}\psi\mathrm{C}\theta & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$\boldsymbol{H}_{\omega,2} = \begin{bmatrix} -\mathrm{S}\psi\mathrm{S}\theta & \mathrm{C}\psi & 0 \\ \mathrm{C}\psi\mathrm{C}\theta & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$\boldsymbol{H}_{\omega,3} = \begin{bmatrix} 0 & 0 & 0 \\ \mathrm{S}\theta & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Then, given $\dot{\boldsymbol{g}}_c$ and $\ddot{\boldsymbol{g}}_c$, $\dot{\boldsymbol{q}}_a = (\dot{q}_1 \quad \dot{q}_2 \quad \dot{q}_3)^{\mathrm{T}}$ and $\ddot{\boldsymbol{q}}_a = (\ddot{q}_1 \quad \ddot{q}_2 \quad \ddot{q}_3)^{\mathrm{T}}$ can be evaluated using Eqs. (36)-(40), (6), and (18).

Consider now a specific system having the geometry: $a = 250\ \mathrm{mm}$, $b = 312.5\ \mathrm{mm}$, and $l_3 = 540\ \mathrm{mm}$

Also, assume as an example that the path and motion rules of the platform are:

$$\ddot{\psi}(t) = \begin{cases} \ddot{\psi}_{\max}\sin\left(\frac{2\pi}{T}t\right) & 0 \le t \le t_1 \\ 0 & t_1 < t \le t_2 \\ -\ddot{\psi}_{\max}\sin\left(\frac{2\pi}{T}t\right) & t_2 < t \le t_3 \end{cases} \tag{41}$$

$$\dot{\psi}(t) = \begin{cases} -\ddot{\psi}_{\max}\left(\frac{T}{2\pi}\right)\cos\left(\frac{2\pi}{T}t\right) + \frac{\dot{\psi}_{\max}}{2} & 0 \le t \le t_1 \\ \dot{\psi}_{\max} & t_1 < t \le t_2 \\ \ddot{\psi}_{\max}\left(\frac{T}{2\pi}\right)\cos\left(\frac{2\pi(t-t_2)}{T}\right) + \frac{\dot{\psi}_{\max}}{2} & t_2 < t \le t_3 \end{cases} \tag{42}$$

$$\psi(t) = \begin{cases} -\ddot{\psi}_{\max}\left(\frac{T}{2\pi}\right)^2 \sin\left(\frac{2\pi}{T}t\right) + \frac{\dot{\psi}_{\max}}{2}t & 0 \le t \le t_1 \\ \dot{\psi}_{\max}t - \frac{\dot{\psi}_{\max}}{4}T & t_1 < t \le t_2 \\ \left(\begin{array}{l} \ddot{\psi}_{\max}\left(\frac{T}{2\pi}\right)^2 \sin\left(\frac{2\pi}{T}(t-t_2)\right) \\ +\frac{\dot{\psi}_{\max}}{2}(t+t_2) - \frac{\dot{\psi}_{\max}}{4}T \end{array}\right) & t_2 < t \le t_3 \end{cases} \tag{43}$$

$\theta = 40°$, $\dot{\theta} = 0\ \mathrm{rad/s}$, $\ddot{\theta} = 0\ \mathrm{rad/s^2}$, $z = 645\ \mathrm{mm}$, $\dot{z} = 0\ \mathrm{m/s}$, $\ddot{z} = 0\ \mathrm{m/s^2}$

where, T is the cycle time; $0 \sim t_1$, $t_1 \sim t_2$ and $t_2 \sim t_3$ are the times used for acceleration, uniform motion, and deceleration.

$$T = \frac{\dot{\psi}_{\max}\pi}{\ddot{\psi}_{\max}}, \quad t_1 = t_3 - t_2 = \frac{T}{2}, \quad \psi(t_3) = 2\pi \tag{44}$$

Substituting into Eq. (44) the givens $\dot{\psi}_{\max} = 1.47\ \mathrm{rad/s}$ and $\ddot{\psi}_{\max} = 11.96\ \mathrm{rad/s^2}$ results in $T = 0.3852\ \mathrm{s}$, $t_1 = 0.1926\ \mathrm{s}$, $t_2 = 4.2857\ \mathrm{s}$, $t_3 = 4.4783\ \mathrm{s}$

When the platform of the manipulator moves according to the preceding rules, the velocity/acceleration of the actuated joints, the linear velocity/acceleration of the reference point O', and the angular velocity/acceleration of the platform versus time can be evaluated using the proposed approach. These results, shown in Fig. 4, have been verified by a CAD model of the manipulator. There was no discernable difference between the results obtained using this approach and the CAD software.

V. Conclusion

This paper presents a general and systematic approach for the forward and inverse velocity and acceleration analysis of lower mobility parallel manipulators using screw theory. With this approach, the process of acceleration modeling of serial and parallel kinematic chains can be integrated into the unified framework of the generalized Jacobian. It results in a new Hessian matrix being developed in a general and compact form. This allows rigid body dynamic modeling of lower mobility manipulators to be integrated into a single mathematical framework.

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Design, Construction and Modeling of a Mechanical Portable Barbecue Machine

By Lawrence Gyansah
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Abstract - It is an undisputable fact that the existing skewers we come across our various homes and roadsides are heavy and thus, are not easily carried around. Their source of heat which is charcoal is also a danger to the environment in that the process of even acquiring the charcoal promotes deforestation which is tantamount to global warming. The operator is exposed to unfriendly working conditions since the flow of heat cannot be easily controlled. The emission of smoke during operation on the larger skewers pollutes the environment and more importantly, can cause cancer of the respiratory systems. Ashes can be present in the products which can change their taste. Moreover, it is difficult to attain uniform heat distribution. It is by these observations that the initiation of the portable gas barbecue is designed. The primary objective is to provide a barbecue which is portable that is, can be moved from place to place with ease. This design seeks to eliminate the health hazards associated with the use of charcoal in the larger skewers as their source of heat. Notwithstanding, this design in reality would be a perfect substitute if not an alternative to the use of the larger skewers.

Keywords : skewer, design, construction, heat, charcoal, radiation, satay, modeling, construction.

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Strictly as per the compliance and regulations of :

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Abstract - It is an undisputable fact that the existing skewers we come across our various homes and roadsides are heavy and thus, are not easily carried around. Their source of heat which is charcoal is also a danger to the environment in that the process of even acquiring the charcoal promotes deforestation which is tantamount to global warming. The operator is exposed to unfriendly working conditions since the flow of heat cannot be easily controlled. The emission of smoke during operation on the larger skewers pollutes the environment and more importantly, can cause cancer of the respiratory systems. Ashes can be present in the products which can change their taste. Moreover, it is difficult to attain uniform heat distribution. It is by these observations that the initiation of the portable gas barbecue is designed. The primary objective is to provide a barbecue which is portable that is, can be moved from place to place with ease. This design seeks to eliminate the health hazards associated with the use of charcoal in the larger skewers as their source of heat. Notwithstanding, this design in reality would be a perfect substitute if not an alternative to the use of the larger skewers. Moreover, with its safe operating conditions, economical usage, faster cooking time rate, complete burning processes, environmentally friendly characteristics, uniform heat distribution and heat regulating abilities; the portable gas barbecue is not only the best alternative but also, an excellent substitute with regard to the existing local skewers.

Keywords : skewer, design, construction, heat, charcoal, radiation, satay, modeling, construction.

I. Introduction

The problem facing users of the larger skewers (i.e. Mechanical barbecue machine) is their immobility in that they cannot easily be moved to convenient places at the right time (Ullman, 2010). Their source of heat which is charcoal is dangerous to the environment. There is excessive heat radiation which can sometimes cause hand burns and also over burnt satay processes. Operators of the larger skewering machines are at risk of dangerously unprotected exposure of unwanted gases and excess heat. That is, larger skewer operators encounter several undesirable health hazards (Norton, 1999). Ashes can be present in the products which can change their taste. Moreover, it is difficult to attain uniform heat distribution. A perfect substitute is to design a portable gas barbecue which almost always can eradicate all these mishaps. The research is strictly based on designing a mini skewer that will comply with customer needs. This project involves the fabrication, modeling and construction of a mini skewer with a specification regarding strength, material and cost. The skewering machine, as simple in its use, will provide better serviceability, higher efficiency, low cost, and better heat radiation controllability. The main objectives of this paper are:

- To design a portable gas barbecue machine.
- To ensure safe operation of the machine.
- To eliminate the problems associated with the use of the local skewers.

II. Background History

Satay (i.e. sate) is a dish of marinated, skewered and grilled meats, served with a sauce. Satay may consist of diced or sliced chicken, goat, mutton, beef, pork, fish, tofu, or other meats. It may be served with a spicy peanut sauce dip, or peanut gravy, slivers of onions and cucumbers, and ketupat (Bittman, 2008). Pork satay can be served in a pineapple-based satay sauce or cucumber relish. An Indonesian version uses a soya-based dip.

Fig. 2.1 : Satay Products Served in Peanut Sauce

Satay may have originated in Java Sumatra, Indonesia. Satay is available almost anywhere in Indonesia, where it has become a national dish. It is also popular in many other Southeast Asian countries and African countries, such as: Malaysia, Singapore, Brunei, Thailand, Southern Philippines, Netherlands and Ghana, Liberia respectively.

Satay is a very popular delicacy in Indonesia; Indonesia's diverse ethnic groups' culinary arts have

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produced a wide variety of satays. In Africa, satay can be obtained from a travelling satay vendor, from a street-side tent-restaurant, in an upper-class restaurant, or during traditional celebration feasts. Close analogues are *yakitori* from Japan, *shish kebab* from Turkey and Ghana, *chuanr* from China and *sosatie* from South Africa.

Arabs were known to grill their meat on swords before roasting and Middle-Eastern Nomads would barbecue their meat on metal skewers known as *kebabs or sharwarma*. The spice trade which brought Arab traders to Southeast Asia led to the spread of Arab culinary culture to the Indonesians and eventually to Malaysia and Singapore.

Similarly, during the Turkish invasion of Cyprus, kebabs or sharwarma were adopted by the locals and is today a popular dish amongst the Greeks and the Cypriots besides the Turkish, the Egyptians and the Arabs. The dish spread beyond to Northern India with even Beijing residents savouring fiery flavoured kebabs today. The uniqueness of satay in Asia is that wooden skewers are used unlike metal in their Arab counterpart. The satay sauce, made up of ground peanuts and other spices, was first introduced in the Philippines by the Spanish from South America used to marinate the pieces of meat; the remaining sauce is used as a dip after the meat of the satay is grilled. *Turmeric* is a compulsory ingredient used to marinate satay, which gives the dish its characteristic yellowish colour. Meats commonly used include beef, mutton, lamb, pork, venison, fish, shrimp, squid, chicken, rabbit and even tripe. Some have also used more exotic meats, such as turtle, crocodile, horse, lizard, and snake meat (Bittman, 2008).

A barbecue machine or skewer is a device for cooking food by applying heat directly from below. There are several varieties of such grills, with most falling into one of two categories: gas-fueled and charcoal (Hale, 2000). There is a great debate over the merits of charcoal or gas for use as the cooking method between barbecue grillers (York, 2003). Almost all competition grillers use charcoal, most often in large, custom designed brick or steel grills (i.e. in Ghana). Grilling existed in the Americas since pre-colonial times. The Arawak people used a wooden structure to roast meat on, which was called *barbacoa* in Spanish. The word referred to the wooden structure and not the act of grilling, but this word was eventually applied to the pit style cooking techniques used in the Southeastern United States.

There are various types of barbecue machines which are put into use worldwide. These include electric barbecue machines, cell barbecue grill, barbecue grill netting, and barbecue machine. All these grilled designed machines have their limitations as mentioned in the introduction. Especially in Ghana, grill machines are constructed from empty fuel drums machined into two halves longitudinally with improper welding practices at the welded joints (see Fig.2.2). Most local skewers lack hygienic standards in Ghana. The top is always opened to the atmosphere which invites dust and finally adulterates the grilled products (See Fig.2.3). It is on these limitations that a new design, construction and modeling of a mechanical portable barbecue machine are needed. This paper seeks to fabricates, models and constructs a mini skewer with specification regarding strength, materials and costs. The skewering machine, as simple in its use, will provide better serviceability, portability, higher efficiency, low cost, durability, good hygienic standard and better heat radiation controllability.

Fig. 2.2 : Local Barbecue Machine in Ghana

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Fig. 2.3 : Roasted Meat on Local Skewer Exposed to Dirty and Dusty Environment

III. Design Concept

A new or better machine is one which is more economical in the overall cost of production and operation. The design of this portable barbecue is to modify the existing designs into a new idea by adopting a new material and a manufacturing method. The design of the mini satay skewering machine (i.e, portable barbecue machine) must be compliance to several aspects. The design consideration must be done carefully, so that the design can be fabricated by the industries in Africa especially Ghana. Design parameters involve; materials design and selection, fuel selection, modeling and construction (i.e. using CAD Software), mathematical modeling, design specifications and proposed design.

IV. Materials Design and Selection

The selection of a proper material for engineering purposes is one of the most difficult problems for the designer. The best material is one which serves the desired objective at the minimum cost. The following factors are considered in the selection of material for the design of the portable barbecue machine:

- Availability of the material.
- Suitability of the material for the working conditions in service.
- The cost of the material.

The material selected for the construction/ molding of the portable barbecue machine is stainless steel since it surpasses all other materials in corrosive environments. The type of stainless steel used is S30400.Type 304 is a variation of the basic 18-8 grade, Type 302, with a higher chromium and lower carbon content. Lower carbon minimizes chromium carbide precipitation due to welding and its susceptibility to inter-granular corrosion (Askeland *eta al*, 2010) and (Callister and Rethwisch, 2010). The thickness of the 304 stainless steel plate range from 0.025– 6.35 mm and its width is up to 1219 mm. Type 304 steels have very good drawability. Their combination of low yield strength and high elongation permits successful forming of complex shapes. However, these grades work-harden rapidly. To relieve stresses produced in severe forming or spinning, parts should be fully annealed or stress-relief annealed as soon as possible after forming (Ashby *eta al*, 2007). These steels exhibit excellent resistance to a wide range of atmospheric, chemical, textile, and petroleum and food industry exposures.

Cooking grids (cooking grates) are the surface on which the food is cooked in a grill. Most high end barbecue grills use stainless steel grates, but there is a health benefit to using bare *cast iron grids.* When cast iron is used to cook food containing high level of acidity, such as lentils, tomatoes, lemonade sauces, or marinades with strong vinegar content, there is increased iron dietary intake. Iron and iron deficiency, particularly, is an important issue for pregnant women and young children. The longer and hotter the grilling temperature, the more iron is infused into the food. Hence cast iron is selected for the grid design.

V. Design Specifications

Stainless steel 304 are covered by the following specifications: AMS 5513; ASTM A240; ASTM A666.

The table 1. illustrates the detailed information on the type of stainless steel which is selected for the design.

Table 1 : Mechanical Properties of Stainless Steel Type 304

Composition	%	Physical Properties	Range of Values
Carbon	0.08	Density	8.03 g/cm^3
Manganese	2.00	Electrical Resistivity, μΩ-cm	20 °C -72 659 °C-116
Sulfur	0.030	Thermal Conductivity, W/m.K	100 °C-500 °C 16.2-21.4
Silicon	0.75	Mean Coefficient of Thermal Expansion, μm/m•K	0-100°C-16.9 0-315°C- 17.3 0-538°C-18.4 0-649°C-18.7
Chromium	18.00-20.00	Magnetic Permeability H	200
Nickel	8.00-12.00	Annealed	1.02 max
Nitrogen	0.10	Modulus of Elasticity, MPa	Tension 193 x 103 Torsion 78 x 103
Iron	Balance	Melting Range, °C	1399 - 1454
Mechanical Properties	**Value**	**Oxidation Resistance**	(816 – 899)°C
UTS	621 MPa	Heat Treatments	Annealing (1038 1121)°C Stress Relief Annealing (399°C)
0.2% YS	290 MPa		
Elongation% in 50.8mm	55		
Hardness Rockwell	B82		

VI. Fuel Selection

The source of fuel selected to power the machine is the liquefied petroleum gas (LPG). LPG is a flammable mixture of hydrocarbon gases used as a fuel. The varieties of LPG bought and sold include mixtures that are primarily, propane (C_3H_8) and butane (C_4H_{10}) considered as natural gas liquids (NGLs) (Smith, 2010). LPG is selected as the source of energy over charcoal. Below are some of these reasons:

- LPG is environmentally friendly
- It burns cleanly with no soot
- Provides complete burning
- Poses no ground or water pollution hazards
- A regulator ensures the possibility of controlling the heat energy
- Heat energy is uniform
- Prevents deforestation
- Serves as a source of refrigerant to replace chlorofluorocarbons in an effort to reduce the depletion of the ozone layer
- Provides high heating value to save time and energy cost

VII. Modeling and Construction

As a design ethic, every machine or structure must be assembled as a unit before it can function well. The medium of joining machine components in this design is by welding and fasteners (Storer and Haynes, 1994) and (Khurmi and Gupta, 2005). AutoCAD software was used for modeling purposes (Omura, 2010). Dimensioning and mechanical component specifications are tabulated in table 2.

VIII. Mechanical Component Specifications

The table 2. displays the design specifications of materials and the number of components used in this design.

Table 2 : Mechanical Component Specifications of the Design

Dimensions	Portable Gas Burner
Length	64cm
Depth	44cm
Height	100cm
Assembled Dimensions	64cm×44cm×100cm
Gas Cylinder Description	23cm×27cm
Cooking Area	61cm×41cm
Materials	**Description**
Hinge Material	Stainless Steel
Burner Material	Stainless Steel
Cover Material (side and top lid)	Stainless steel

Features	Material Description
Fuel	LPG
Recommended Gas Type	LPG
Regulator Included	Yes
Cooking Grate	Cast iron (Austenitic Iron)

IX. Results and Discussion

The design specifications, complete design of the gas barbecue machine, its operation and the necessary recommendations are addressed.

a) Proposed Design

The proposed design comprises the gas cylinder and its components, the various machine components and the complete design with the assembled parts.

b) Gas Cylinder

This is the recommended gas cylinder and the designed burners. There is a regulator incorporated to the connecting pipe which controls the amount of gas in

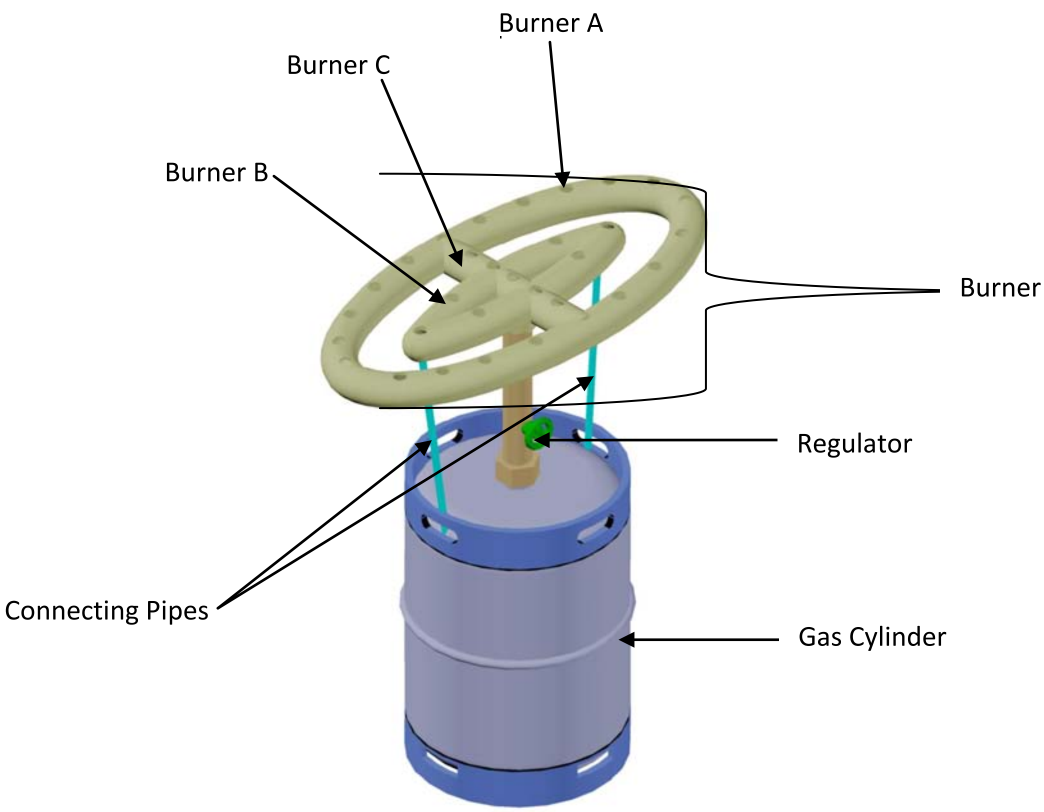

Fig. 31 : Modeled Gas Cylinder and Burner

c) Modeled Diagram of the Portable Gas Barbecue Machine

This diagram shows how the gas cylinder is being supported.

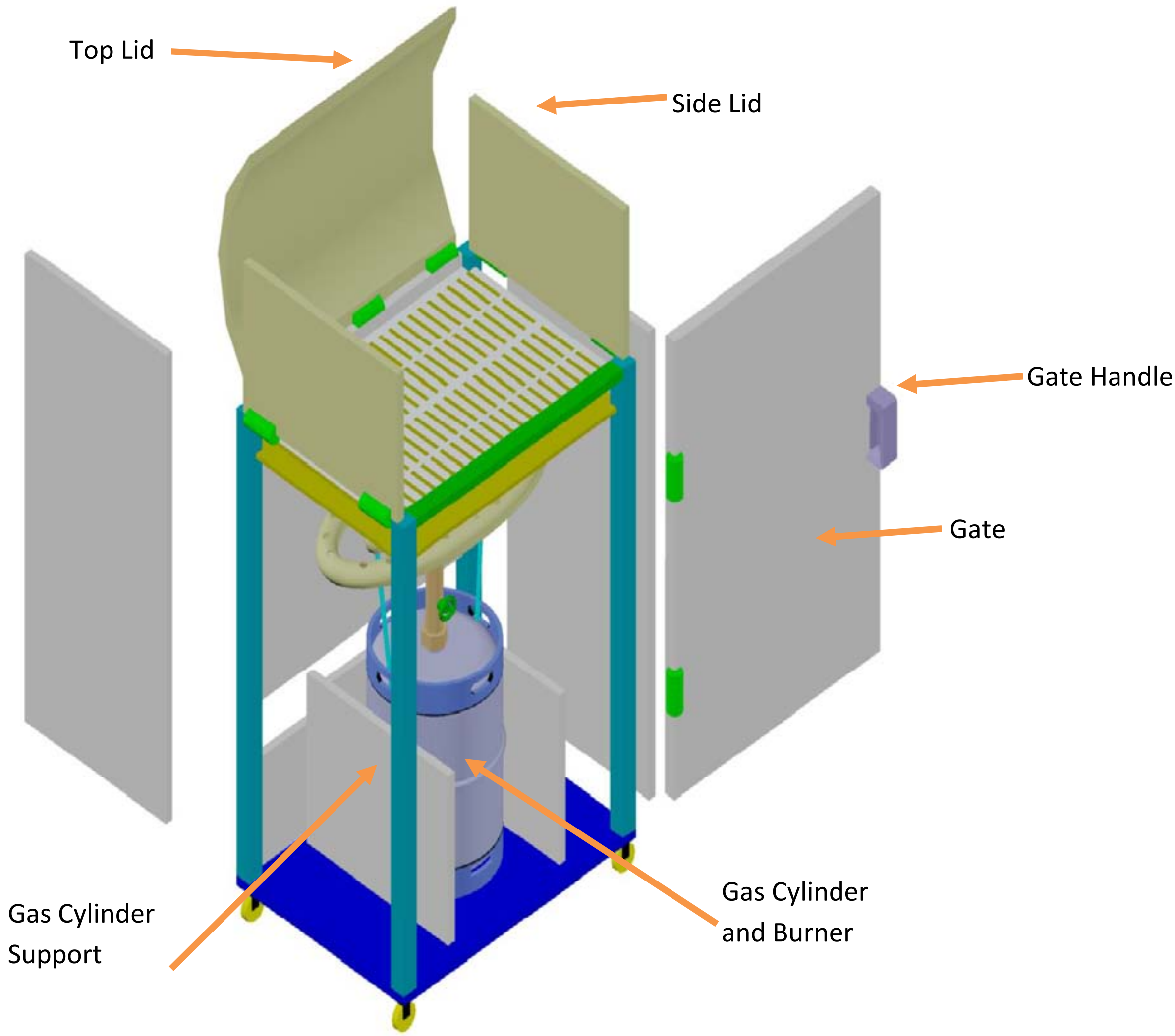

Fig. 3.2 : Cut-Out Design Model

d) Back View of the Gas Barbecue Machine

This view displays how a *vent* has been created at the back side of the barbecue to allow circulation of air.

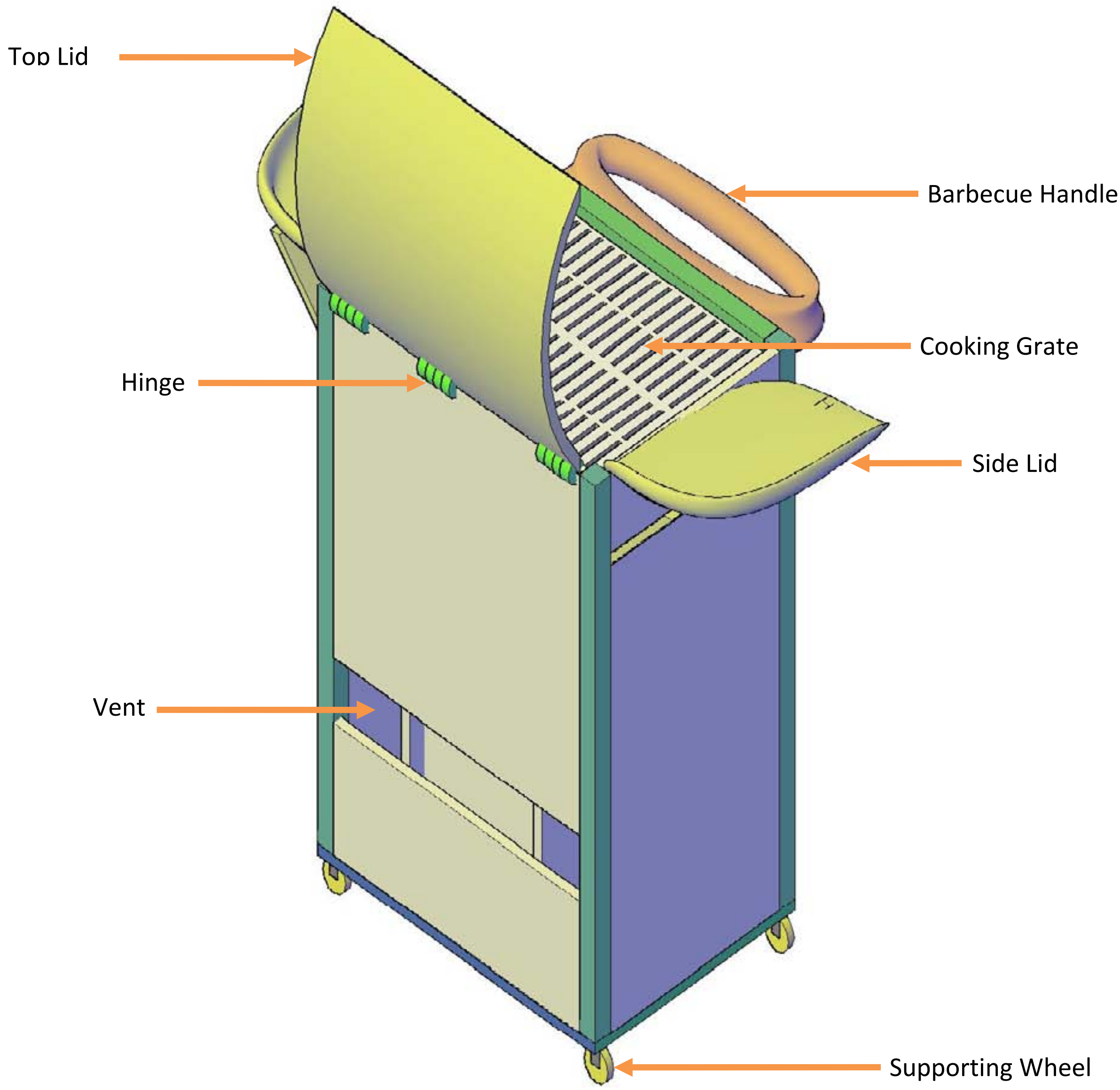

Fig. 33 : Barbecue Machine with a Vent at its Back

e) Gas Barbecue Machine with its Gate Opened

This diagram shows the barbecue machine with its gate opened to display how the gas cylinder has been positioned in the barbecue.

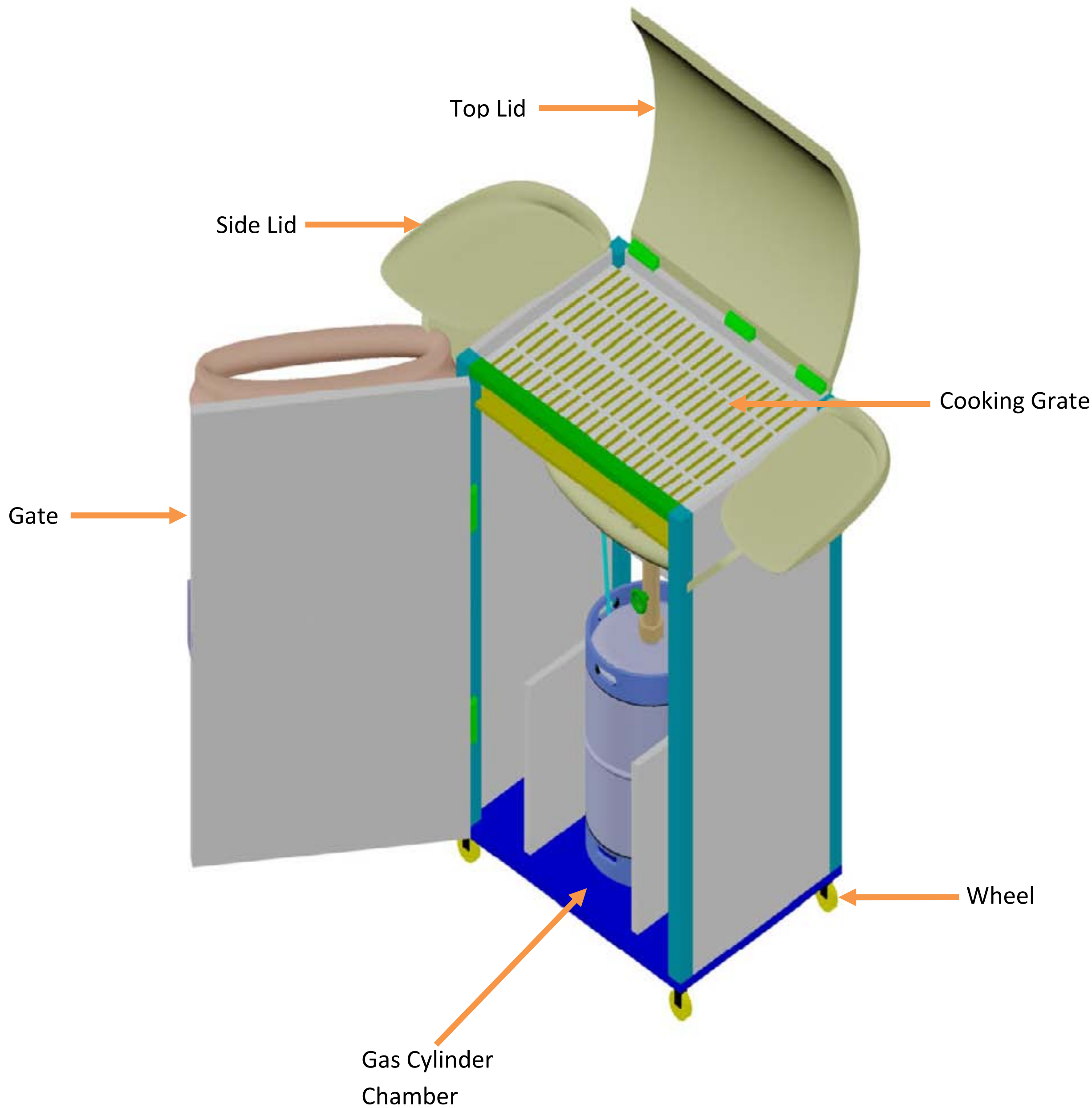

Fig. 3.4 : Position of the Gas Cylinder

f) The Complete Design

This is how the gas barbecue machine is structured after assembling its components.

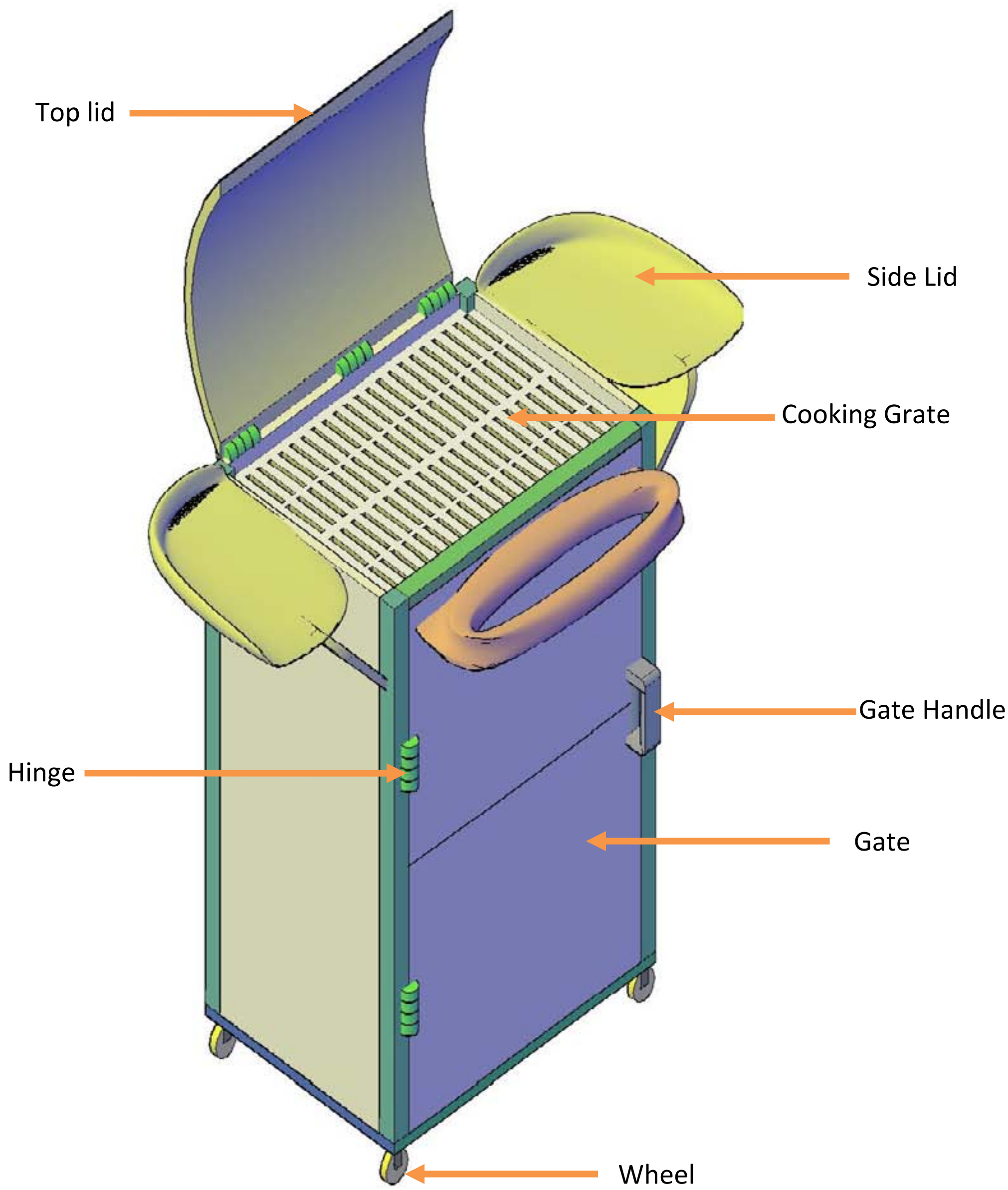

Fig. 3.5 : The Complete Proposed Design

g) Mathematical Modeling

The design calculations are strictly centered on the weights regarding the satay products, the barbecue machine and the gas cylinder. These weights amount to the entire total weight of the completed portable gas skewering machine. The total weight of the machine is then used to design the wheels and stands whose total weight in turn, counteracts that of the machine. The wheels and stands serve as supports to promote balance, movement and stability.

h) Design Specifications

Table 3. provides the design specifications; the sizes and units used in the proposed design.

Table 3 : Complete Dimensions of the various Mechanical Components of the Proposed Model

Component Description	Component Sizes and Units	
Cuboid Dimensions of the Barbecue Machine	in cm	in m
Length of the barbecue, l_b	62	0.62
Width of barbecue, b_b	42	0.42
Height of barbecue, h_b	100	1
Gas Cylinder Dimensions	in cm	in m
Diameter of Gas Cylinder, d_c	23	0.23
Height of Gas Cylinder, h_c	27	0.27
Gas Cylinder Chamber Dimensions	in cm	in m
Length of chamber, l_c	24	0.24
Width of chamber, b_c	24	0.24
height of chamber, h_c	13	0.13
Pipe Dimensions	in cm	in m
Outside Diameter of the Pipe, D_p	2	0.04
Inside Diameter of the Pipe, d_p	2	0.02
Height of the Pipe, h_p	40	0.4
Burner Dimensions	in cm	in m
Outside Diameter of Burner, A, D_1	6	0.06
Inside Diameter of Burner, A, d_1	4	0.04
Outside Diameter of Burner, B, D_2	6	0.06
Inside Diameter of Burner, B, d_2	4	0.04
Outside Diameter of Burner, C, D_3	4	0.04
Inside Diameter of Burner, C, d_3	3	0.03
Diameter of each Burner Hole, d_h	2	0.02
Height of each Burner Hole, h_h	2	0.02
Gas Cylinder Supports	in cm	in m
Length of a and b	24	0.24

Length of c	30	0.3
Height of the supports	13	0.13
Thickness of the supports	3	0.03
Adjustable Lids Dimensions	in cm	in m
Length of Top Lid, l_{tl}	62	0.62
Width of Top Lid, b_{tl}	43	0.43
Thickness of Top Lid	1	0.01
Length Side Lids, l_{sl}	42	0.42
Width of Side Lids, b_{sl}	20	0.2
Thickness of Lids, h	13	0.13
Cooking Grids Dimensions	in cm	in m
Length of the Cooking Grid, l_{cg}	56	0.56
width of the Cooking Grid, b_{cg}	36	0.36
Thickness of the Cooking Grid, x	3	0.03
Cut Out Spaces Dimensions	in cm	in m
Length of Vent, l_v	56	0.56
Width of Vent, b_v	3	0.03
Height of Vent, h_v	12	0.12
Length of space in barbecue, l_s	56	0.56
Width of space in barbecue, b_s	36	0.36
Height of space in barbecue, h_s	90	0.9

i) Total Weight of the Barbecue Machine

These calculations cover the weights of the barbecue machine, the gas cylinder, the top lid and the side lids, the barbecue gate and those of the sate products respectively. According to (Gere and Goodno, 2009), the total weight W_T is given by;

$$W_T = W_1 + W_2 + W_3 + W_4 + W_5 \qquad 1.1$$

Where W_1 comprises the sum of the weights of only the barbecue Machine, the supports for the gas cylinder and the cooking grates.

Thus, $W_1 = W_b + W_{sc} + W_{cg}$ 1.2

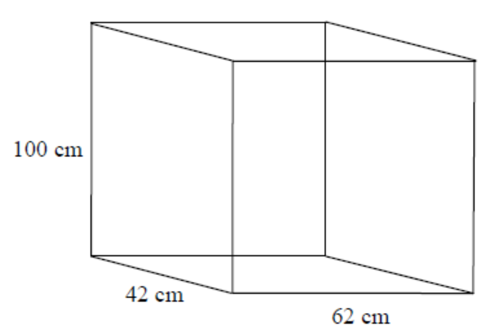

Fig. 4.1 Barbecue Machine Modeled as Cuboid

The vent created at the back of the barbecue machine is also modeled as a cuboid. The volume of the vent is therefore given by; (Craig, 2011),

$$V_v = l_v \times b_v \times h_v \qquad 1.3$$

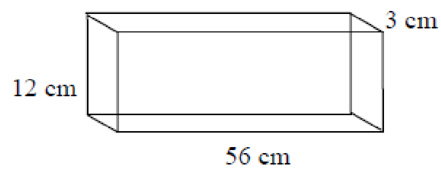

Fig. 4.2. Vent at the Backside of the Barbecue Machine

Hence, the entire inner space of the barbecue machine is shown in Fig. 4.3.

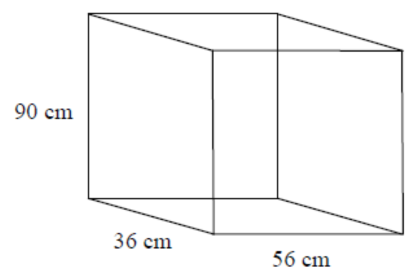

Fig. 4.3. Modelled Inner Space of the Barbecue Machine

Also, the volume of the gas cylinder chamber is modeled as a rectangular prism. Hoop stresses and circumferential stresses would exist in the pressurized state of the gas cylinder. Therefore, the volume of the gas cylinder chamber is given by; (Craig, 2011),

$$V_{gc} = l_{gc} \times b_{gc} \times h_{gc} \qquad 1.4$$

Fig. 4.4. shows a modeled of the supporting systems for the gas cylinder.

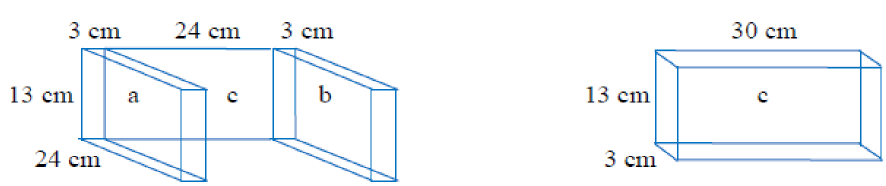

Fig. 4.4. Supports for the Gas Cylinder

Fig. 4.5. and Fig. 4.6. show a modeled of the cooking grate and the gas cylinder. Dimensioning of the parts is included.

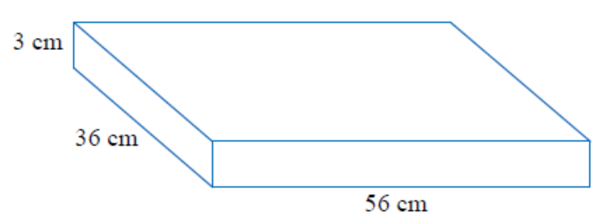

Fig. 4.5. Model of the Cooking Grate

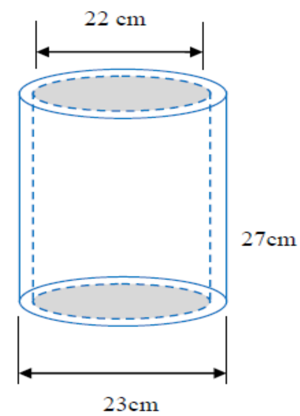

Fig. 4.6. Model of the Gas Cylinder

Fig.4.7. illustrates a model of the pipe connecting the cylinder to the burners (i.e. Connecting pipes).

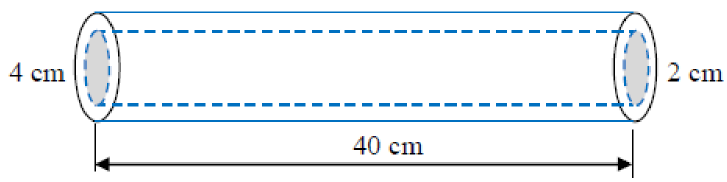

Fig. 4.7. Modelled Connecting Pipe

For burner *A*, the outside and inside diameters are D_A = 2 cm≈ 0.02 m and d_A = 1 cm≈ 0.01 m respectively.

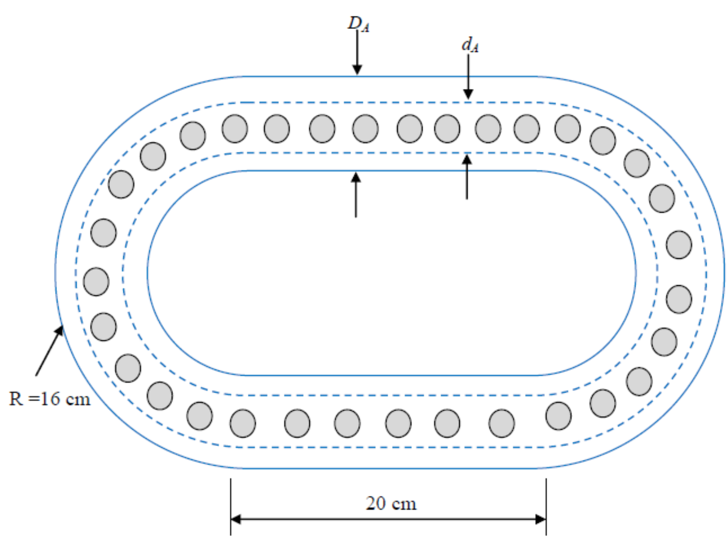

Fig. 4.8a Detail Model of Burner A

The number of holes in burner A, is 34; each hole has a diameter, d_h = 0.3 cm ≈ 0.003 m; and height, h_h = 0.5 cm ≈ 0.005 m.

For burner *B*, the outside and inside diameters are D_b = 2 cm≈ 0.02 m and d_b = 1 cm≈ 0.01 m respectively.

D_B = 12 cm≈ 0.12 m and d_B = 10 cm≈ 0.1 m are the inside and outside diameters of burner *B*, respectively as shown in Fig.4.9.

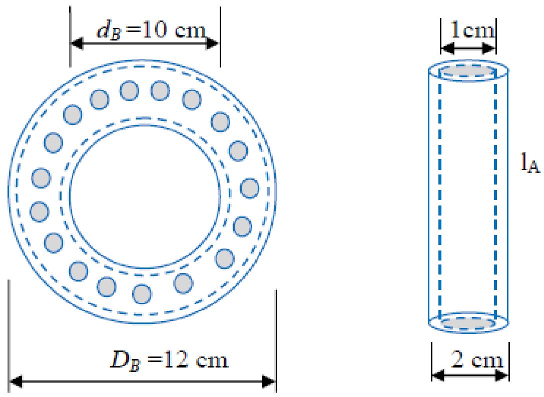

Fig. 4.9. Detailed Model of Burner B

For burner *C*, the outside and inside diameters are D_C = 1.2 cm ≈ 0.012 m and d_C = 0.8 cm≈ 0.008 m respectively.

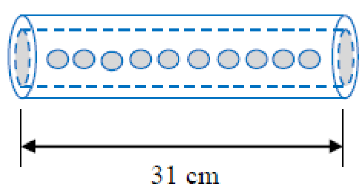

Fig. 4.10. Detail Model of Burner C

The top lid was considered as a cuboid with length, l_{tl} = 62 cm ≈ 0.62 m; width, b_{tl} = 43 cm ≈ 0.43 m and height, h = 2 cm ≈ 0.02 m as shown in Fig. 4.11a.

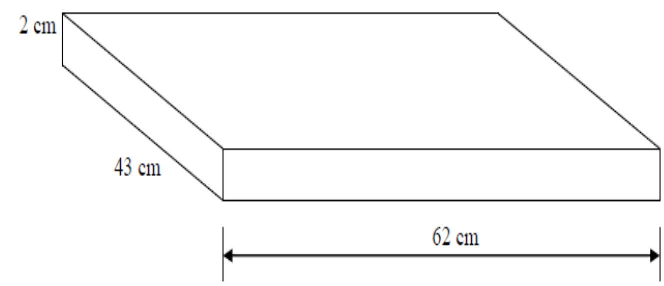

Fig. 4.11a. Detail Model of the Top Lid

The side lids are considered as a rectangular prism with lengths, l_a = 42 cm ≈ 0. 42 m, l_b = 20 cm ≈ 0.2 m, l_c = 41 cm ≈ 0.41 m; widths, b_a = 20 cm ≈ 0.2 m, b_b = 1 cm≈ 0.01 m, b_c = 1 cm≈ 0.01 m; and heights, h_a = 1 cm≈ 0.01 m, h_b = h_c= 13 cm≈ 0.13 m.

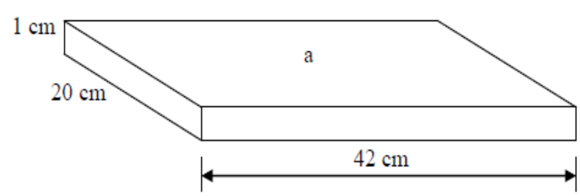

Fig. 4.11b. Side lid

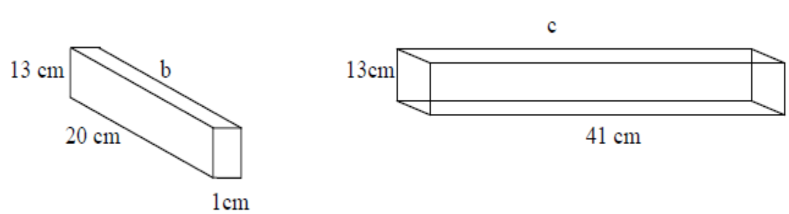

Fig. 4.11c. Detail Model of the Side Lid Parts

Fig. 4.12a and Fig.4.12b illustrate the model of the barbecue gate and the handle respectively. Where the length of the gate, l_{bg} = 56 cm≈ 0.56 m; width of gate, b_{bg} = 1 cm ≈ 0.01 m; and the height of the gate, h_g = 94 cm ≈ 0.94 m.

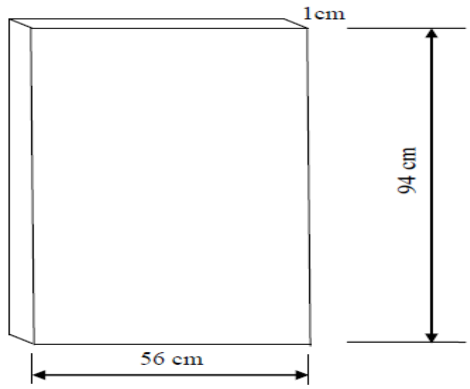

Fig. 4.12a. Model of the Barbecue Gate

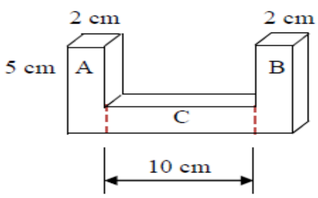

Fig. 4.12b Model of the Handle of the Barbecue Gate

The entire weight of the barbecue machine totally acts on the four wheels which are designed to act as supports. The total weight of the barbecue is therefore, considered to balance on the four wheels. The total weight acting on the wheels is considered as a single force, W_t, acting downwards. Four equal forces acting upwards at the wheels balances the weight of the barbecue machine (Budynas and Nisbett, 2011).

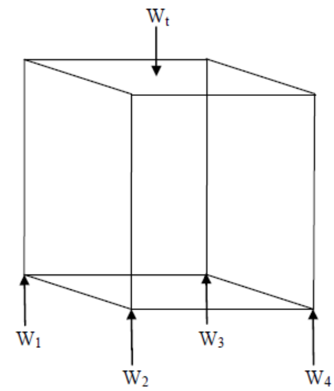

Fig. 4.13. Equilibrium of Forces on the Barbecue Machine

X. Modeling Of The Hinges

The hinges are purchased with regard to their weights or reactions they would offer for supporting the barbecue gate and the lids.

a) Hinges at the Gates

Fig. 4.14a. and Fig.4.15b. illustrate the dimension of the hinges on the barbecue gate and the side lids respectively. Reactions on the hinges are also indicated. Hinges for the top lid mimic that of the barbecue gate hinges.

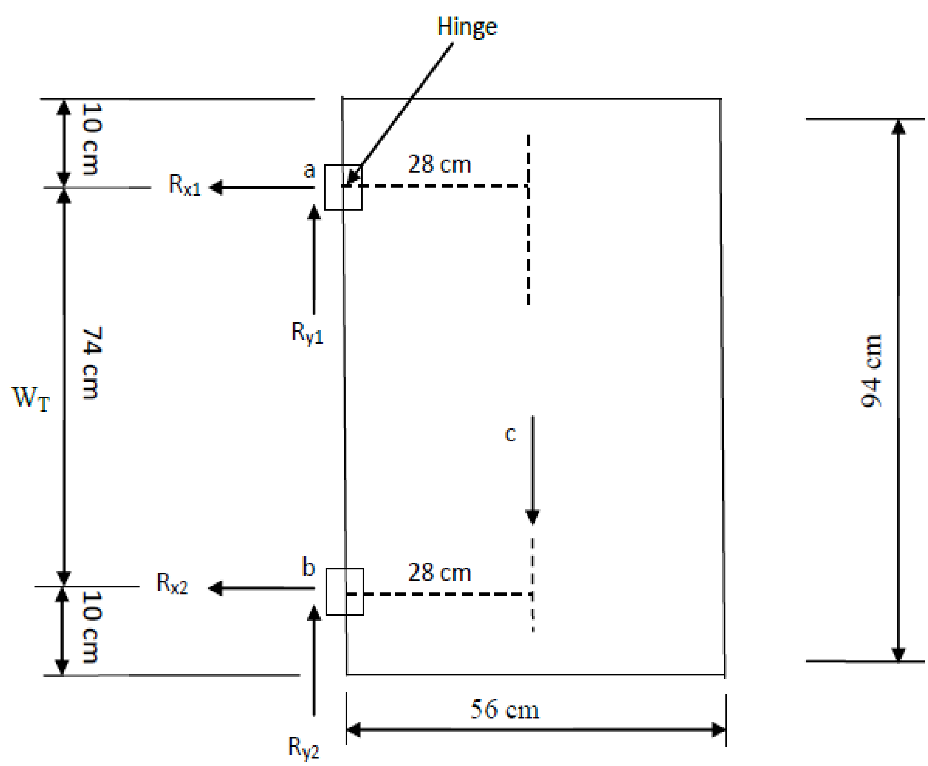

Fig. 4.14a. Barbecue Gate with its Hinges

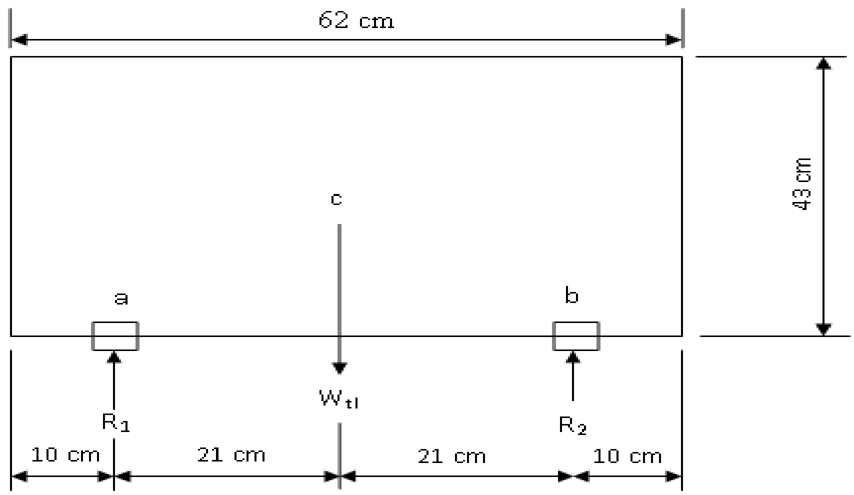

Fig. 4.14b : Top Lid with its Hinges and Dimensions

b) Rate of Heat Flow Analysis

Let a heat flowing at a rate *Q* be applied at a temperature, *T* across the total surface area, *A*, of the *cast iron cooking grid*. The transfer of heat through the grid is by radiation.

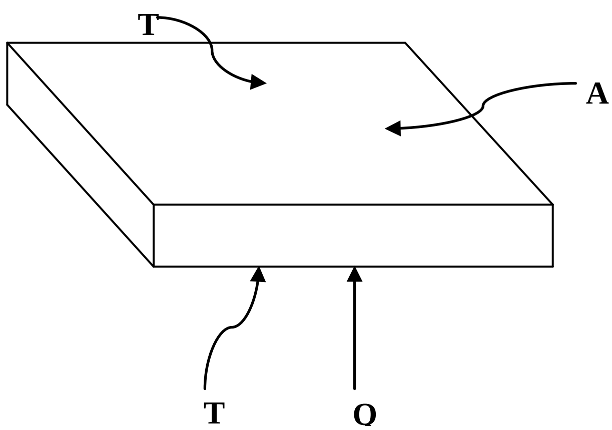

Fig. 4.15 : Cooking Surface

According to (Kreith *eta al*, 2011), the rate of heat flow is given by;

$$Q = \varepsilon \sigma A T^4 \qquad 1.5$$

But σ (Stefan Boltzmann) = 5.67×10^{-8} W/m^{2}K^4; ε (emissivity of the cooking surface) = 0.21.

Radiation heat transfer differs from that by convection and conduction because the driving potential is not the temperature, but the absolute temperature rose to the fourth power. Furthermore, heat can be transported by radiation without an intervening medium. These principles are what the satay products would go through in the barbecue machine.

c) How to Operate the Gas Barbecue Machine

With charcoal, you always had to use starter and wait for the coals to get hot, then you have to wait for the grill to cool before you could clean up that horrible mess left from the coal's ash. For the barbecue machine, you will find is really a great convenience and requires a minimum amount of maintenance to operate. The procedure is as follows;

1. Remove the top lid cover. Position the barbecue so you can easily open the lids completely and have access to every side of the machine.
2. Open the lids of the barbecue machine completely and leave it open.
3. Find the gas cylinder valve (regulator) under the barbecue machine. This circular valve rests just above the gas cylinder. Grasp this valve in your hand and turn it one complete turn clockwise.
4. Gas will flow through the connecting pipe.
5. Light a match close to this burner. It should light with one or two pushes of the button.
6. Grasp the gas cylinder valve in your hand and turn it clockwise or anti-clockwise to control/regulate the fire.
7. Close the lids cover and allow your barbecue to preheat on high for approximately five minutes.
8. Put your food stuffs on the cooking grate and close the lids cover to start grilling process.

XI. Conclusions

After the complete project, the following conclusions can be deduced:

- The portable gas barbecue machine has been designed, which might be more efficient, serviceability, low cost, and better heat radiation controllability when manufactured.
- Safe operation of the gas barbecue machine has been explained.
- Problems associated with the use of the local skewers that make use of charcoal have been eliminated. E.g. Ashes from the charcoal can get into the products to contaminate the satay products which can result in health hazards.

XII. Recommendations

The following are important recommendations concerning this design:

- This design is recommended for use by homes and wayside barbecue users. The gas barbecue is also suitable for use during parties, picnics, anniversaries, and camping. Due to its safe operating conditions, this design is also recommended for both indoor and outdoor usage.
- Manufacturing of a prototype of the gas barbecue machine is recommended.
- Other destructive and non-destructive testing should be conducted on the various components of the barbecue machine before manufacturing.
- A modified version of this design is to introduce more vents of smaller sizes in the design to allow more space for air circulation. These vents must be designed in such a way that the entry of air does not disturb the burning process.
- An automatic gas barbecue machine can also be designed where the amount of gas flow and the rate of heat flow would not be taken manually. The automatic gas barbecue machine would operate in a way such that the cooking operations would be executed depending on the cooking and the warming indicator lights.
- Gas barbecue machine produce a great deal of heat that can melt hoses, knobs and other parts. The number one cause of gas fires is an obstruction in the path of the fuel. This can take place behind, underneath or inside. Thus, the gas grill must regularly be inspected for problems. Bugs and other critters can climb into little places causing gas to flow into wrong spaces. At the first sign of problems, the regulator must be turned off and everything disconnected.
- Repeated paintings over several months or years will make a grill or smoker even more impervious to rust.
- It is important to keep cooking grate clean and keep it oiled in the case of bare cast iron to prevent rusting.

Acknowledgement

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3. Submission of Manuscripts,

4. Manuscript’s Category,

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- What you account in an conceptual must be regular with what you reported in the manuscript
- Exact spelling, clearness of sentences and phrases, and appropriate reporting of quantities (proper units, important statistics) are just as significant in an abstract as they are anywhere else

Introduction:

The **Introduction** should "introduce" the manuscript. The reviewer should be presented with sufficient background information to be capable to comprehend and calculate the purpose of your study without having to submit to other works. The basis for the study should be offered. Give most important references but shun difficult to make a comprehensive appraisal of the topic. In the introduction, describe the problem visibly. If the problem is not acknowledged in a logical, reasonable way, the reviewer will have no attention in your result. Speak in common terms about techniques used to explain the problem, if needed, but do not present any particulars about the protocols here. Following approach can create a valuable beginning:

- Explain the value (significance) of the study
- Shield the model - why did you employ this particular system or method? What is its compensation? You strength remark on its appropriateness from a abstract point of vision as well as point out sensible reasons for using it.
- Present a justification. Status your particular theory (es) or aim(s), and describe the logic that led you to choose them.
- Very for a short time explain the tentative propose and how it skilled the declared objectives.

Approach:

- Use past tense except for when referring to recognized facts. After all, the manuscript will be submitted after the entire job is done.
- Sort out your thoughts; manufacture one key point with every section. If you make the four points listed above, you will need a least of four paragraphs.
- Present surroundings information only as desirable in order hold up a situation. The reviewer does not desire to read the whole thing you know about a topic.
- Shape the theory/purpose specifically - do not take a broad view.
- As always, give awareness to spelling, simplicity and correctness of sentences and phrases.

Procedures (Methods and Materials):

This part is supposed to be the easiest to carve if you have good skills. A sound written Procedures segment allows a capable scientist to replacement your results. Present precise information about your supplies. The suppliers and clarity of reagents can be helpful bits of information. Present methods in sequential order but linked methodologies can be grouped as a segment. Be concise when relating the protocols. Attempt for the least amount of information that would permit another capable scientist to spare your outcome but be cautious that vital information is integrated. The use of subheadings is suggested and ought to be synchronized with the results section. When a technique is used that has been well described in another object, mention the specific item describing a way but draw the basic principle while stating the situation. The purpose is to text all particular resources and broad procedures, so that another person may use some or all of the methods in one more study or referee the scientific value of your work. It is not to be a step by step report of the whole thing you did, nor is a methods section a set of orders.

Materials:

- Explain materials individually only if the study is so complex that it saves liberty this way.
- Embrace particular materials, and any tools or provisions that are not frequently found in laboratories.
- Do not take in frequently found.
- If use of a definite type of tools.
- Materials may be reported in a part section or else they may be recognized along with your measures.

Methods:

- Report the method (not particulars of each process that engaged the same methodology)
- Describe the method entirely
- To be succinct, present methods under headings dedicated to specific dealings or groups of measures
- Simplify - details how procedures were completed not how they were exclusively performed on a particular day.
- If well known procedures were used, account the procedure by name, possibly with reference, and that's all.

Approach:

- It is embarrassed or not possible to use vigorous voice when documenting methods with no using first person, which would focus the reviewer's interest on the researcher rather than the job. As a result when script up the methods most authors use third person passive voice.
- Use standard style in this and in every other part of the paper - avoid familiar lists, and use full sentences.

What to keep away from

- Resources and methods are not a set of information.
- Skip all descriptive information and surroundings - save it for the argument.
- Leave out information that is immaterial to a third party.

Results:

The principle of a results segment is to present and demonstrate your conclusion. Create this part a entirely objective details of the outcome, and save all understanding for the discussion.

The page length of this segment is set by the sum and types of data to be reported. Carry on to be to the point, by means of statistics and tables, if suitable, to present consequences most efficiently.You must obviously differentiate material that would usually be incorporated in a study editorial from any unprocessed data or additional appendix matter that would not be available. In fact, such matter should not be submitted at all except requested by the instructor.

Content

- Sum up your conclusion in text and demonstrate them, if suitable, with figures and tables.
- In manuscript, explain each of your consequences, point the reader to remarks that are most appropriate.
- Present a background, such as by describing the question that was addressed by creation an exacting study.
- Explain results of control experiments and comprise remarks that are not accessible in a prescribed figure or table, if appropriate.
- Examine your data, then prepare the analyzed (transformed) data in the form of a figure (graph), table, or in manuscript form.

What to stay away from

- Do not discuss or infer your outcome, report surroundings information, or try to explain anything.
- Not at all, take in raw data or intermediate calculations in a research manuscript.

- Do not present the similar data more than once.
- Manuscript should complement any figures or tables, not duplicate the identical information.
- Never confuse figures with tables - there is a difference.

Approach

- As forever, use past tense when you submit to your results, and put the whole thing in a reasonable order.
- Put figures and tables, appropriately numbered, in order at the end of the report
- If you desire, you may place your figures and tables properly within the text of your results part.

Figures and tables

- If you put figures and tables at the end of the details, make certain that they are visibly distinguished from any attach appendix materials, such as raw facts
- Despite of position, each figure must be numbered one after the other and complete with subtitle
- In spite of position, each table must be titled, numbered one after the other and complete with heading
- All figure and table must be adequately complete that it could situate on its own, divide from text

Discussion:

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- Make a decision if each premise is supported, discarded, or if you cannot make a conclusion with assurance. Do not just dismiss a study or part of a study as "uncertain."
- Research papers are not acknowledged if the work is imperfect. Draw what conclusions you can based upon the results that you have, and take care of the study as a finished work
- You may propose future guidelines, such as how the experiment might be personalized to accomplish a new idea.
- Give details all of your remarks as much as possible, focus on mechanisms.
- Make a decision if the tentative design sufficiently addressed the theory, and whether or not it was correctly restricted.
- Try to present substitute explanations if sensible alternatives be present.
- One research will not counter an overall question, so maintain the large picture in mind, where do you go next? The best studies unlock new avenues of study. What questions remain?
- Recommendations for detailed papers will offer supplementary suggestions.

Approach:

- When you refer to information, differentiate data generated by your own studies from available information
- Submit to work done by specific persons (including you) in past tense.
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Introduction	Containing all background details with clear goal and appropriate details, flow specification, no grammar and spelling mistake, well organized sentence and paragraph, reference cited	Unclear and confusing data, appropriate format, grammar and spelling errors with unorganized matter	Out of place depth and content, hazy format
Methods and Procedures	Clear and to the point with well arranged paragraph, precision and accuracy of facts and figures, well organized subheads	Difficult to comprehend with embarrassed text, too much explanation but completed	Incorrect and unorganized structure with hazy meaning
Result	Well organized, Clear and specific, Correct units with precision, correct data, well structuring of paragraph, no grammar and spelling mistake	Complete and embarrassed text, difficult to comprehend	Irregular format with wrong facts and figures
Discussion	Well organized, meaningful specification, sound conclusion, logical and concise explanation, highly structured paragraph reference cited	Wordy, unclear conclusion, spurious	Conclusion is not cited, unorganized, difficult to comprehend
References	Complete and correct format, well organized	Beside the point, Incomplete	Wrong format and structuring

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