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Optimisation of Hydraulic Brake Caliper In Scope of All-Terrain Vehicle

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Abstract — The following paper is presented with an objective to design a hydraulic brake caliper for All Terrain Vehicle Racing competitions. The hydraulic brake caliper system being complex in design the study is exhaustive and the subject matter is covered with adequate images and illustrations for easy and quick understanding. The primary focus being the designing and fabrication of hydraulic brake caliper. The proposed design is modelled in Creo Parametric 2.0 environment and analysis is performed in ANSYS. The outcome of this project is an optimized hydraulic brake caliper being light in weight providing adequate braking torque for efficient braking of the vehicle in hostile racing environment. Hydraulic Disc Braking system is most suitable for such hostile racing conditions.

Index terms - CAD modelling, FEM analysis, Seal Geometry, Brake caliper, Dynamic weight transfer,Design methodology, Components

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1. INTRODUCTION

A vehicle is adhered to the roadway by the normal and traction forces produced by the tires. Braking, steering, or accelerating forces must be generated by the small tire tread area contacting the ground. Only forces equal to or less than the product of tire normal force and tire-road coefficient of friction can be applied by the vehicle over the ground through the tire contact patch. If the applied force by the tire exceeds this product of normal reaction and tire coefficient of friction the wheels tend to slip or loose traction. Even the ideal braking and stability control system cannot utilize more traction than provided by the tires and road.

The safe operation of a motor vehicle requires continuous adjustment of its speed to changing traffic conditions. The brakes and tires along with the steering system are the most safety-critical subsystems of a motor vehicle. Brakes must perform safely under all reasonably foresee able operating conditions, including slippery, wet, and dry roads; with a lightly or fully laden vehicle; when braking straight or while turning; with new or worn brakes; when applied by the novice or experienced driver; on smooth or rough roads; or when pulling a trailer.

These basic functions of a brake system must be provided under foresee able circumstances, at reasonable cost and brake wear life, while providing directional stability and acceptable tire-road friction utilization. The braking system must comply with all applicable safety standards. In most conditions, safety standards are considered minimum performance requirements. In today's growing automotive market, the competition for better performance vehicle is growing enormously. The racing fans involved will surely know the importance of a good brake system not only for safety but also for staying competitive. As we are aware of the fact that races are won over split of a second therefore the capacity of the brake system to slow down quickly at turns or corners is very important.

2. COMPONENTS OF BRAKE CALPER

2.1 Caliper Housing

The housing of the brake caliper serves the function of holding all the components of caliper viz. the piston, seals, brake pads, and bleeding screw in position and allowing relative motion between them for effective working of the braking system. The caliper housing should be sufficiently strong to sustain the hydraulic pressure generated in the circuit during actuation of brakes. Tremendous amount of heat is generated during braking action. This heat is transferred to the housing through the brake pads.

Figure1:Exploded view of caliper

2.2 Piston Seal and Seal Groove Assembly

Design of the seal groove assembly in the brake caliper greatly influences the braking performance. The rubber seal performs the dual function of sealing the piston bore and retracting the caliper piston after a brake apply. However, the seal function is affected by the configuration of the seal groove, as well as the friction at the piston / seal and groove / seal interfaces.[1] The material properties of the rubber seal are also important design parameters. Fluid displacement, piston retraction, piston sliding force, and brake drag are some of the critical brake performance parameters that must be considered in every caliper seal-groove design.

[8] A seal groove assembly has three main components - rubber seal, piston and caliper groove. The characteristic features of the groove configuration include seal groove diameter, front angle, bottom angle, corner break, and groove width. These features coupled with the piston diameter and seal dimensions uniquely define the seal groove assembly. By design, the seal outer diameter is larger than the groove outer diameter.

2.3 Brake Pads

For conversion of kinetic energy of the car to thermal energy brake pads are essential. Conversion takes place with the of friction phenomenon.[1]When the brakes are hydraulically applied, the caliper clamps or squeezes the two pads together into the spinning rotor to slow/stop the vehicle. When a brake pad is heated by contact with a rotor, it transfers small amounts of friction material to the disc, turning it dull gray.

2.4 Bleeding screw

Bleeding is the procedure performed on hydraulic brake systems whereby the brake lines (the pipes and hoses containing the brake fluid) are purged of any air bubbles. This is necessary because, while the brake fluid is an incompressible liquid, air bubbles are compressible gas and their presence in the brake system greatly reduces the hydraulic pressure that can be developed within the system. The same methods used for bleeding are also used for purging, where the old fluid is replaced with new fluid, which is necessary maintenance.

3. DESIGN/ANALYTICAL WORK

The design of the caliper begins with the calculation of the required braking force. [3]The required braking force to retard the vehicle from its top speed to complete stop depends on various factors like gross weight, speed, coefficient of friction between tire and road, weight distribution during static condition, dynamic weight transfer, dynamic front axle and rear axle weight of the vehicle.

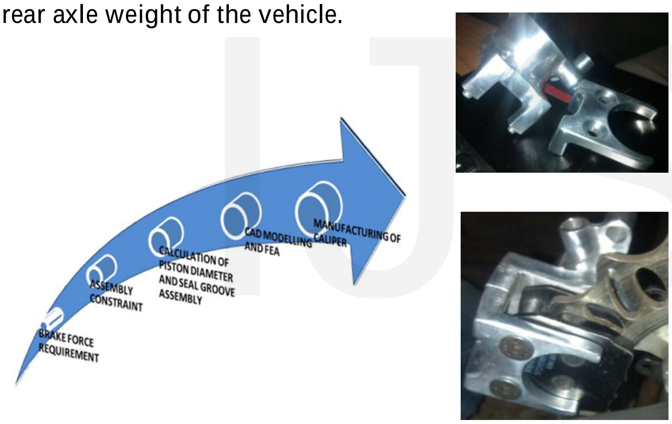

Figure2. Design Methodology

For designing the brake caliper following specifications were considered of a Single seater All-Terrain Vehicle.

- Weight – 160 kg (without driver)
- Driver weight -75 kg
- C.G Height – 20 inches
- Tyre diameter - 23 inches
- Weight distribution-35% -65% (Front to Rear)
- Wheel Base -56 inches
- Coefficient of friction - 0.8
- Gross Weight -235kg

Notations used:

RF_{ZF} –Reaction Force At Front Axle
RF_{ZR} –Reaction Force At Rear Axle
BF_{xf} –Braking Force At Front Axle
BF_{xr} –Braking Force At Rear Axle
T_{xf} –Braking Torque At Front Wheel
T_{xr} –Braking Torque At Rear Wheel
DF_{zf} –Dynamic weight transfer at front axle
DF_{zr} –Dynamic weight transfer at rear axle
LF – Distance of front wheel center from C.G in side view
LR – Distance of rear wheel center from C.G. in side view
L – Wheel Base
W – Gross weight
H – C.G. height
Vmax – maximum velocity
a – Acceleration
μ – Coefficient of friction
Δdyn – Dynamic Weight transfer

Taking the static weight distribution into consideration as 35% and 65% for front and rear we get the static front and rear axle loads as follows-

RF_{ZF} - 82.25 kg
RF_{ZR} - 152.75 kg

From the below figure taking moments about front axle we get,

$$LF = (RF_{ZF}*L)/W = 36.4 \text{ inches}$$
$$LR = L - LF = 19.6 \text{ inches}$$

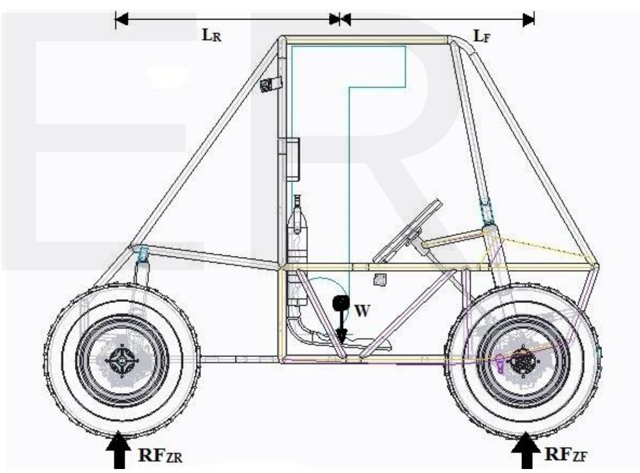

Figure3 Force Diagram

The ratio of static rear axle weight to gross weight of the vehicle is given by,

$$\Psi = (RF_{ZR}/W) = 0.65$$

When the vehicle retards from a certain velocity, due to deceleration there occurs a weight transfer which tends to increase the front axle load and at the same time decrease the rear axle load as compared to static condition. Thus the dynamic axle load is given by the following expression,

$$DF_{zf}, dyn = (1 - \Psi + xa)\, W$$

Where,

$x = H / L = 0.3571$
$\mu = 0.8$

Considering a vehicle top speed of 60 kmph,
Thus,

V_{max} = 60 kmph

We get deceleration of vehicle as,

a = 0.8…..(acceleration in terms of g)

Dynamic weight transfer = XaW

= (h / L) *a*W

= 67.14 kg

$DF_{zf} = (1-\Psi+Xa)\ W$

DF_{zf} = 149.39 kg

DF_{zr} = 85.61 kg

Now,

Braking force required at the front axle,

$BF_{xf} = \mu * FZf$

Where,

μ = coefficient of friction between the tyre and road surface

Thus,

BF_{xf} = 1172.41 N

Similarly,

Braking force required at the rear axle

$BF_{xr} = \mu * F_{Zr}$

BF_{xr} = 671.86 N

Now,

We can get the required braking torque from the braking force and tire diameter by following relationship,

$T_x = BF_x * R$

Where,

R = Radius of the tyre,

Thus,

Braking torque required at the front wheel is

$T_{xf} = BF_{xf} * R$

= (1172.41 * 11.5 * 25.4) / 1000

T_{xf} = 342 .46 Nm

This is the braking torque required for both the front wheels. Thus, braking torque required for each of the front wheels is calculated as,

Braking torque on one front wheel

= $(T_{xf})/2$

= 171.23 Nm

Similarly,

Braking torque at the rear wheels is

$T_{xr} = BF_{xr}*R$

= (671.86 * 11.5 * 25.4) / 1000

= 196.25 Nm

Braking torque on one rear wheel,

= 98.12 Nm

With the actual required braking torque for each of the front and rear wheels we can now proceed with the iterations for calculations of bore diameter of the brake calipers.

Final iteration:

Data,

Master Cylinder Diameter = 19.05 mm.
Front Caliper Diameter = 32 mm.
Rear Caliper Diameter = 32 mm.
Pedal Ratio = 5.3:1
Pedal Force = 250N
Radius of Front Disc (Rf) = 85mm
Radius of Rear Disc (Rr) = 65mm
Coefficient of friction between pads & disc (μpads)=0.4

Calculation,

Area of Caliper (Ac) $= \frac{\pi * 32^2}{4}$

= 804.24 mm2

Area of master cylinder (Amc) $= \frac{\pi * 19.05^2}{4}$

= 2.85*10-4m2

F_{mc} = P.R*P.F

= 5.3*250

= 1325 N.

$P_{mc} = F_{mc}\ /\ A_{mc}$ $\frac{F_{mc}}{A_{mc}}$

= 46.49 bar.

$F_{caliperFront} = P_{mc} * A_c$

= 3738.91 N.

$F_{caliperRear} = P_{mc} * A_c$

= 3738.91 N.

Force on Disc = 2 * μpads * $F_{caliper}$

= 2991.128 N.

Torque generated,

Front = $F_{caliperfront}$ * Rf

= 175.87 Nm.

Rear = Fcaliper* Rr

= 117.24 Nm.

Thus, the braking torque generated on front and rear disc is sufficient enough to lock all the four wheels of the vehicle. Also, the generated force is not much large than required force thus giving an optimum design.

3.3 Material Selection

The material to be used for housing of the caliper must be rigid enough to sustain all the forces that would occur on the caliper housing. [6]The materials commonly used for housing of caliper are aluminium, cast iron and steel. As the objective of the design is to keep the weight of the caliper minimum, choice of material is done with strength to weight ratio. Aluminium serves this condition to be lightest among other materials. To maintain the required strength in the component Aluminium 7075 T6 was selected for the housing. Tough the cost of Aluminium 7075 is higher than Aluminium 6061 which is more commonly used aluminium alloy. Aluminium 7075 was preferred for its strength.

Sr No.	Parameter	Value
1	Density	2870 kg / m3
2	Modulus of Elasticity	71.1 GPa
3	Tensile Strength	572 MPa
4	Yield Strength	503 MPa
5	Thermal Conductivity	130 W / mK
6	Cost to Weight Ratio	1250 Rs / kg

[2]Table 1: Properties of Aluminium 7075 T6

Sr No.	Parameter	Value
1	Density	2870 kg / m3
2	Modulus of Elasticity	68.9GPa
3	Tensile Strength	310Mpa
4	Yield Strength	276 MPa
5	Thermal Conductivity	167 W / mK
6	Cost to Weight Ratio	360Rs / kg

[2]Table 2: Properties of Aluminium 6061 T6

4. MODELLING OF BRAKE CALIPER

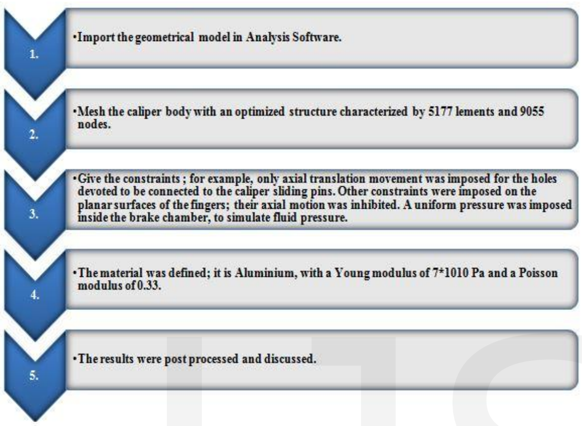

Chart 1: Analysis Procedure

Figure5 : View of Caliper

4.1 FEA of Caliper

This model was analysed by applying the forces and pressure. Static structural analysis of the CAD model was carried out in ANSYS 15.0.

[7]A Structural analysis calculates deformations, stresses, and strains on model in response to specified constraints. Analysis provides the information about model. For instance, a static analysis gives us if the material in our model will stand stress and if the part will break (stress analysis), where the part will break (strain analysis), and how much the shape of the model changes (deformation analysis).After the numerical calculations, all the parameters such as bore diameter, seal groove, mounting, etc. are decided and then the CAD modelling of the caliper was done using Creo Parametric 2.0.

Following material parameters were considered.

Sr No.	Parameter	Value
1	Density	2700 kg / m3
2	Young's Modulus	72 GPa
3	Ultimate Tensile Strength	590 MPa
4	Yield Tensile Strength	503 MPa

Table 3: Properties for analysis

In a first approximation analysis, brake caliper was divided into 11433 elements and 19089 nodes. The other components gave origin only to external constraints and stiffness's, but they were not modeled from a FEM point of view. An axial force F was imposed on the piston, a force –F was imposed on the caliper model. Results were very near to the experimental tests, from the point of view of volume displacement of the whole caliper (including also the pads), as will be shown in the next paragraph.

Von Mises equivalent stresses on the fingers appeared to be too high in comparison to the past experience and what published in literature. As a consequence, to evaluate in detail the stresses inside the wheel caliper, ANSYS 15.0 (they are more sophisticated software's than visualNastran®) models were built. The purpose was to model only the caliper body and simulate a volume displacement test on it, supposing brake pads as infinitely stiff.

4.1.1. Meshing

The different mesh parameters like aspect ratio, skewness were considered too improve the mesh quality. Out of the different element types like hex dominant, sweep etc. tetra elements were considered as they capture the curvatures more accurately than in any other method. Proximity and curvature was used in order to ensure finer mesh along the curved regions and varying cross sections.

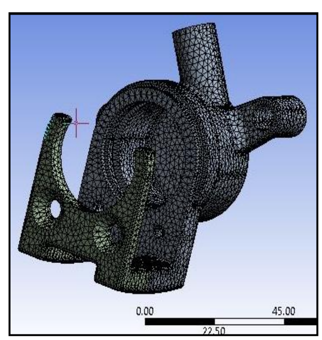

Figure6: Meshed Model of caliper in ANSYS 15.0

Following loads that takes by Caliper Body:

1. Hydraulic pressure applied on piston
2. Reaction on the caliper body due to clamping force

3. Forces on friction pad mounts that transferred form pad friction patch.

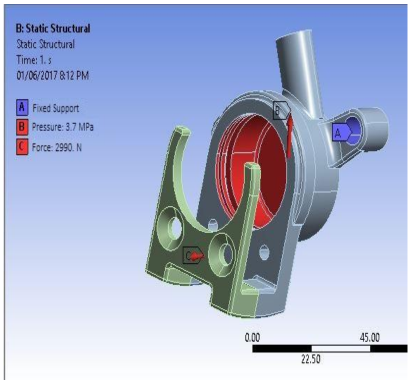

Figure7: Load Cases considered during analysis

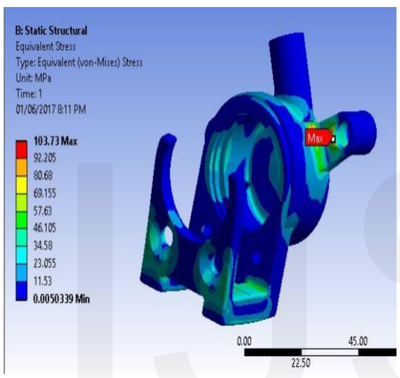

Figure8: Equivalent stress (von-misses) of caliper

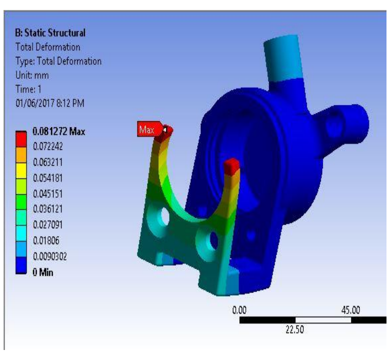

Figure9: Total deformation of a brake caliper

5. RESULTS

After design and analysis of the brake caliper following results were obtained

- Weight of designed caliper: 228gms
- Maximum Von Misses stress acting on the caliper: 103.73 N / mm2
- Maximum deformation of the caliper during working conditions: 0.081 mm.
- Available Factor of Safety: 4.8
- Braking torque generated by caliper in front :175.87 Nm.
- Braking torque generated by caliper in rear :117.24 Nm.

6. CONCLUSION

The proposed design of the brake caliper produces braking torque of 175.87 Nm at front and 117.24 Nm at rear which is greater than required braking torque. Thus, ensuring effective working of the braking system.

The weight of the proposed hydraulic brake caliper is 228gms which is much less than commercially available brake calipers which weigh around 550gms.

Also, FEA is carried out over the proposed design to ensure safe operation without failure. With the use of high grade material, the caliper is optimized without compromising the strength. Thus, with a factor of safety of 4.8 the design is safe enough to handle the forces acting on it. Thereby also ensuring a good fatigue life.

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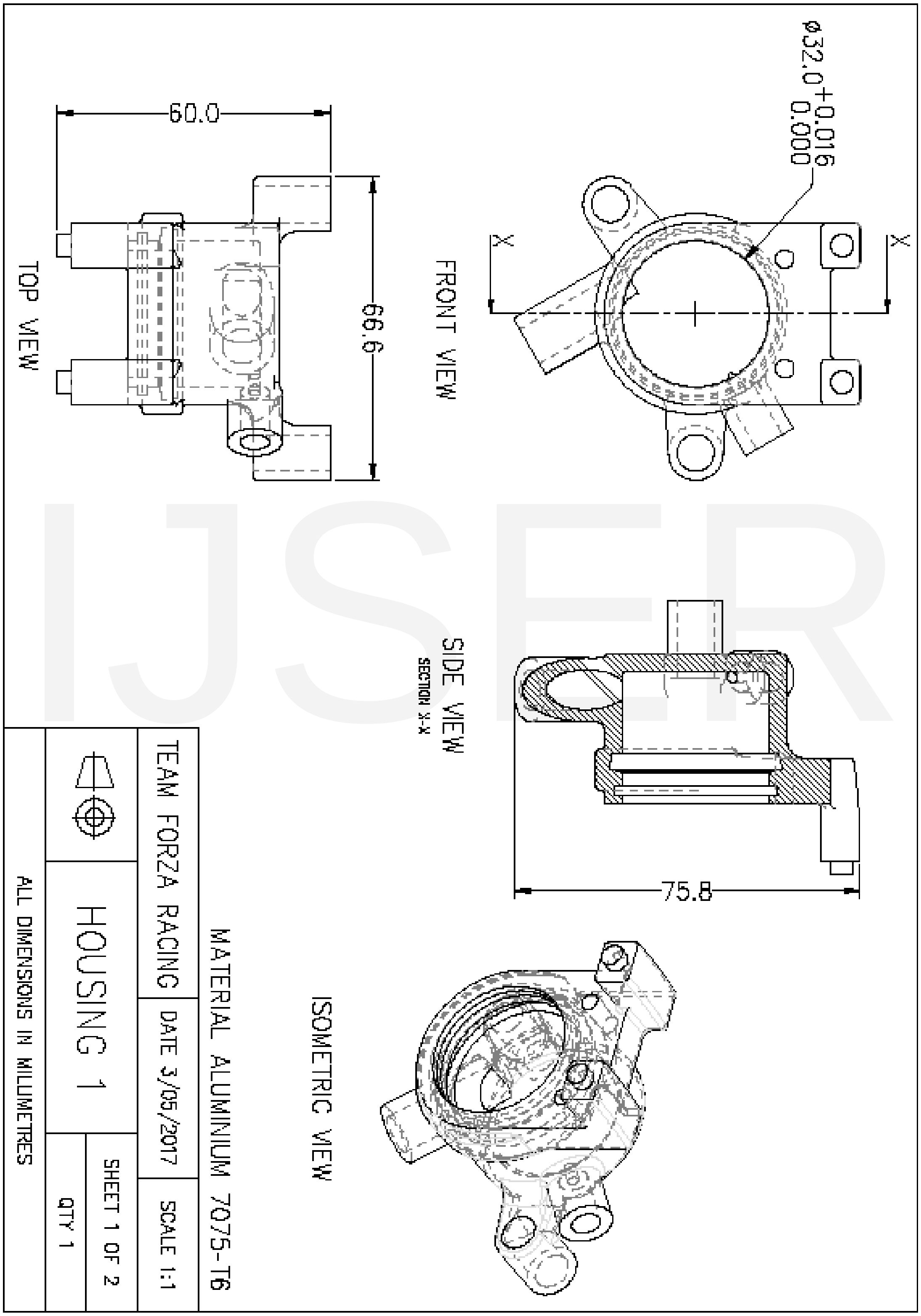
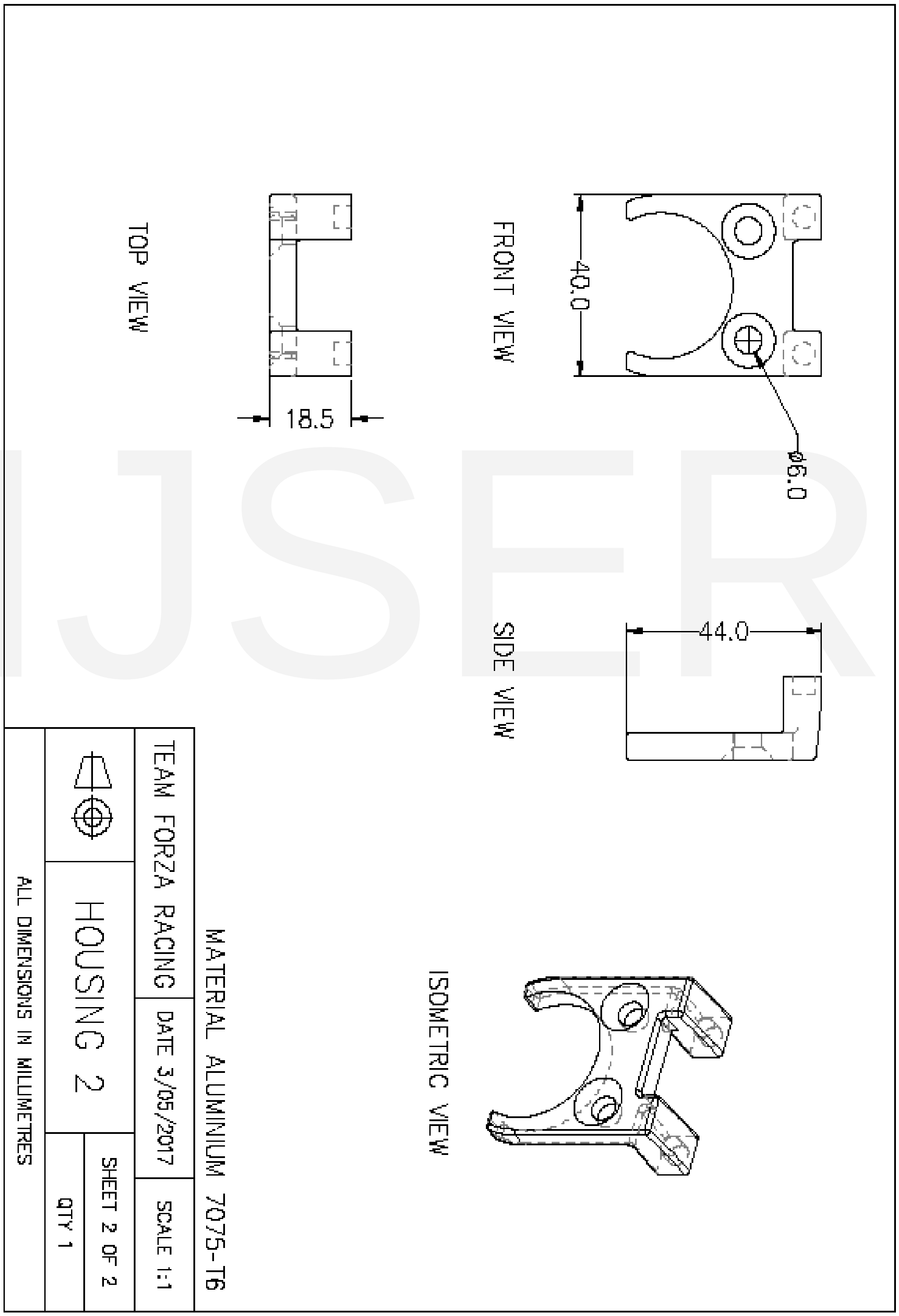
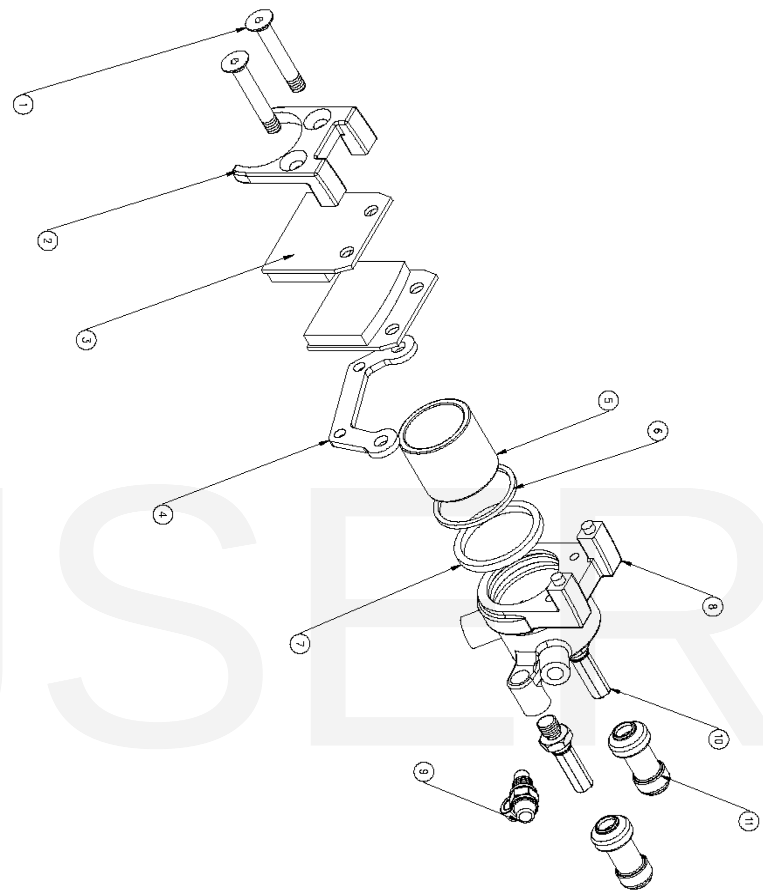
ANNEXURE A

Manufacturing Drawing




TOP VIEW
FRONT VIEW
40.0
18.5
ø6.0
SIDE VIEW
44.0
ISOMETRIC VIEW
MATERIAL ALUMINIUM 7075-T6
TEAM FORZA RACING
DATE 3/05/2017
SCALE 1:1
HOUSING 2
SHEET 2 OF 2
QTY 1
ALL DIMENSIONS IN MILLIMETRES



SR NO.	PART NAME	QTY	MATERIAL
1	M6x1 ALLEN BOLT	2	-
2	CALIPER HOUSING PRT 2	1	AL7075-T6
3	BRAKE PAD	2	-
4	MOUNTING CLIP	1	M.S
5	PISTON	1	M.S
6	DUST SEAL	1	-
7	PISTON SEAL	1	-
8	CALIPER HOUSING PRT 1	1	AL7075-T6
9	BLEEDING SCREW	1	-
10	GUIDE PIN	2	-
11	GUIDE PIN BUSHES	2	-

TEAM FORZA RACING	DATE 3/05/2017	SCALE 1:1
ASSEMBLY		SHEET 3 OF 3
		QTY 1

ALL DIMENSIONS IN MILLIMETRES