

Luke Parsons Dissertation

by Luke James Parsons

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Honda CR500R Study

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Motorcycle Engineering BEng

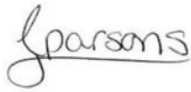
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Declaration of Authenticity

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed:

A handwritten signature in black ink, appearing to read 'J. Parsons', written over a horizontal line.

Date: 18/04/2019

Abstract

This report will explore two chosen areas in which the Honda CR500R can be modified to improve performance for use in several motorcycle disciplines. The first section will cover the design of a pair of CNC machined billet aluminium crank cases which can be used as a direct replacement for the OEM parts. This section will highlight the changes made to the design to improve performance, longevity and make the part suitable for manufacture. The second section will study the exhaust system and how it can be designed to change the characteristics of the engine. A modified system will be created mathematically, manufactured and then tested to allow the real-world data to be compared to the calculated data.

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Nomenclature

Symbol	Name	SI Unit
t	Time	s
L _t	Tuned Length of Exhaust	m
L _D	Length from Piston to Beginning of Baffle Cone	m
L _d	Length from Piston to End of Baffle Cone	m
V _s	Speed of Sound in Exhaust	ms ⁻¹
V ₄₅₀	Speed of Sound in Exhaust at 450°C	ms ⁻¹
V ₂₀	Speed of Sound in Exhaust at 20°C	ms ⁻¹
Θ _o	Exhaust Open Duration	Degrees
D _{port}	Effective Exhaust Port Diameter	mm
A	Mitre Angle (Bend Angle)	Degrees
d	Pipe Diameter	mm
R	Radius of Bend (if segments follow an arc, this is the radius of arc)	mm
N	Number of Equal Segments	

Abbreviations

OEM - Original Equipment Manufacturer.

CNC - Computer Numerical Control.

FIM - Fédération Internationale de Motocyclisme.

RPM – Revolutions per Minute.

BMEP – Brake Mean Effective Pressure (Bar).

CAD – Computer Aided Design.

CoE – Coefficient of Expansion.

1. Introduction

This report will study three areas of the Honda CR500R which can be optimised to improve performance, appearance and longevity. This report will be broken down into two main sections looking at the Crank Cases and Exhaust System on the chosen machine.

1.1 Motocross and the Honda CR500R

Motocross as a sport was first recognised in the 1920s. Road going motorcycles would have the lights, number plates and other unnecessary parts removed. Riders would then fit “Knobbly” tyres, mudguards and number boards and then compete in “scramble” events at weekends.



Figure 1 – 1961 BSA Victor Mettise Scrambler. (Trials and Motocross News, 2019)

Manufacturers such as BSA, Greeves and Triumph quickly released production motocross machines which were vastly superior to home-built conversions, this led to the sport becoming increasingly competitive. Manufacturers from around the world quickly followed suit and produced purpose-built motocross machines; No country did this better than the Japanese. Suzuki and Yamaha both released purpose-built bike in the mid-1960s however in 1973 Honda released the CR250 Elsinore (CR250M).

The CR250M was a huge step forward in motocross technology. It was the lightest of its class by far due to its magnesium alloy engine cases, covers and wheel hubs (White, 2018). When the FIM became the governing body for world championship motocross in 1957, the machines were split into three groups; 500cc open, 250cc and 125cc. This has since been changed to incorporate modern “friendly” 4-stroke engines. However, the bike studied in this report is a machine from the golden era of 500cc 2-strokes. The 1989 Honda CR500R is widely considered to be the best motocross bike ever created and to this day is still the most powerful production motocross bike made.



Figure 2 – 1989 Honda CR500R. (Dirt Bike Magazine, 2019)

1.2 Crank Cases

The role of the Crank Case is to house and position the rotating and reciprocating components of the engine. They must also be sealed to retain the lubricating oil used in the gearbox, clutch and other rotating internals. The cases on the CR500R are high pressure die cast magnesium alloy with a vertical split. They are bolted together using fourteen 6mm bolts. The engine is fixed in place at the rear by the swing arm pivot bolt and at the front by two 10mm bolts which attach to tabs on the frame. It is a common sight to see cracks, splits and sections snapping off. Crashes, impact from large rocks and harsh use all contribute to the damage seen on these engines. Unfortunately, as this bike is no longer in production, parts are discontinued making it almost impossible to purchase new cases. This report

will cover the analysis of a cracked set of crank cases as well as the design and manufacture of a replacement pair.

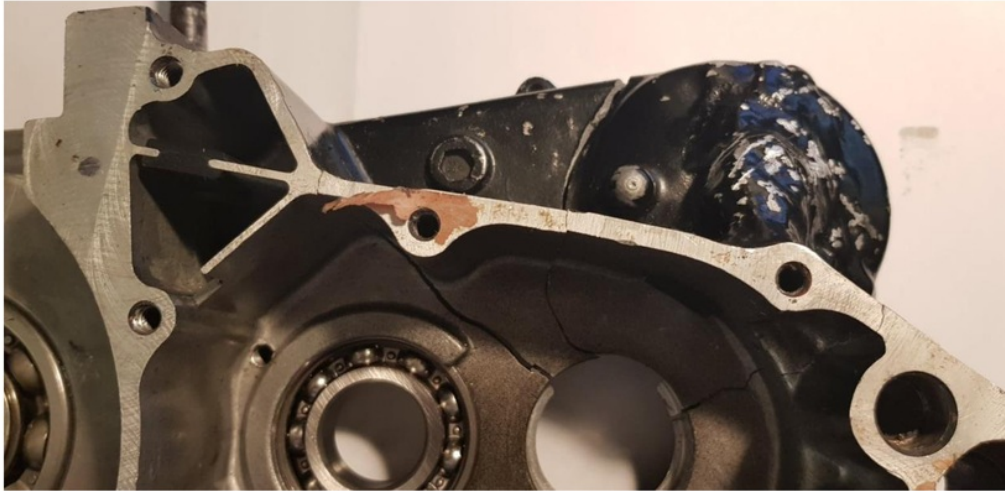


Figure 3 – Right-Hand Crank Case with split around kickstart assembly and output shaft. (Parsons, authors own)

1.3 Exhaust System

The exhaust system on any 2-stroke engine is an important component of critical design. In the early days of 2-stroke engines the function of the exhaust was simply to channel the burnt exhaust gasses away from the engine and behind the rider. However, it was then realised that the careful design of an expansion chamber would have profound effects on power output. This report will look at the design of the DOMA system commonly fitted to the CR500R and one designed specifically to change the characteristics of the engine and to test the formula widely used to design and build expansion chambers. These exhausts will be tested on a standard Honda CR500R in SuperMoto trim using a MAHA motorcycle rolling road allowing the result to be compared and the data for the manufactured exhaust to be compared to the predictions from the design process to validate the equations.

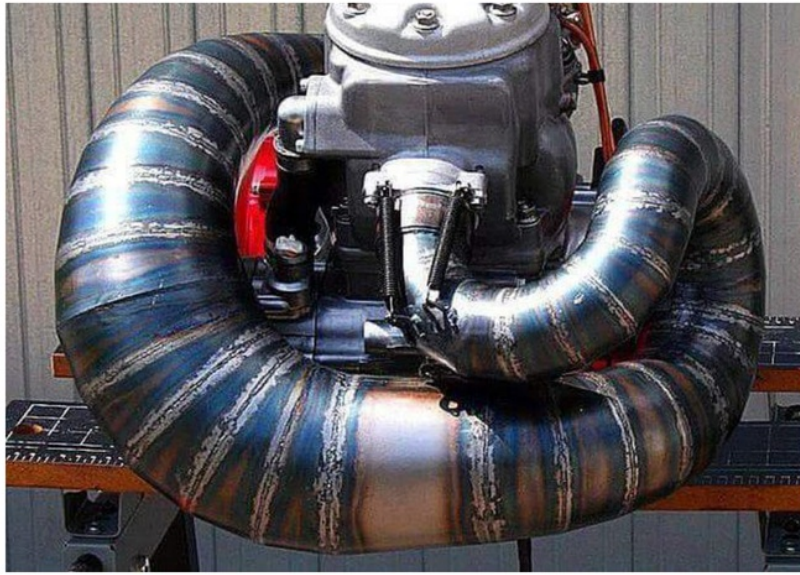


Figure 4 – Handmade Expansion Chamber for Honda CR500R. (Dirt Bike Magazine, 2019)

2. Crank Cases

2.1 Literature Review

2.1.1 Manufacturing Methods

As described earlier, the OEM crankcases are high pressure die cast components. This a method of casting is only used in mass production. This is due to the large investment needed to purchase or manufacture the large cast iron tooling required as described by (Clark & Roth, 1999). There are numerous other manufacturing techniques available which are much more suited to low volume manufacturing. Sand casting using 3D printed sand moulds is a relatively cheap alternative when compared to high pressure die casting. However, the moulds are single use only and are still reasonably costly. 3D printed moulds are a cost-efficient method for one off investment casting as described by (Ruud, 1995) and rapidly advancing technology means that one off prototyping and manufacture will become gradually cheaper. Without doubt however, the best method for rapid prototyping is additive manufacturing using the 3D printer itself. Components can be created using a variety of materials such as PLA, ABS, Aluminium and Titanium. The final method of manufacturing components considered in this report is CNC machining. This can be a costly method of producing one-off prototypes, however, if the component is being redesigned to have improved strength; CNC machining a component from billet is a wise choice. For example, the UTS of die cast Aluminium is around 270 N/mm^2 (Dynacast, 2019) compared to the UTS of billet aluminium plate which is around 340 N/mm^2 .

2.1.2 Bearing Fit

Bearing fit is an incredibly important aspect to consider when designing a set of engine cases. The main bearings, clutch and gearbox bearings are all radial roller ball type. These are pressed into the cases and are intended to have an interference fit. This is to ensure that as the crank cases expand with heat during use, the bearings maintain a tight fit. It is highly problematic if a bearing begins to spin in the crank cases. There are several classes of bearing fit as described in the (Schaeffler, 2014) technical handbook. These range from loose fit to interference fit.

2.2 Crank Case Modelling

2.2.1 Aims

The aim for this section of the project is to design and manufacture a pair of billet aluminium crank cases for the Honda CR500R. They are to be a direct replacement with the exception of the addition of the hydraulic clutch. The OEM crank cases will be studied to assess why the failure occurred, redesigned using a CAD package, prototyped using Ultimaker 3D printers and finally manufactured.

2.2.2 Why Did the Failure Occur?

It is a common sight to see CR500R crank cases that have had repairs on the right-hand side around the kick start. This area is prone to cracking and due to age and an engine that requires large kicking forces to start. The sharp corners (fillets) around the kickstart boss are small. These areas are stress concentrators and will be prone to failure under tensile stress. Unfortunately, these parts are now discontinued and becoming more difficult to find. It is also common to see small area of the cases degrading and crumbling away with age, for example, the extruded hole that retains the left-hand crank shaft seal. It is safe to say that this motorcycle was designed to last a reasonable service life and then be retired. However, the cult following that this motorcycle has gained over the years has introduced the problem of age-related deterioration. With EVO classes growing ever popular the need for improved replacement parts is increasing.



Figure 5 – Right-hand crankcase with crack around kickstart boss. This crank case has been repaired previously. (Parsons, authors own)

2.2.3 Scanning

To allow the accurate modelling of the crank cases, they first had to be laser scanned. These scans create “point cloud” data which can be imported into several different computer packages to be analysed.

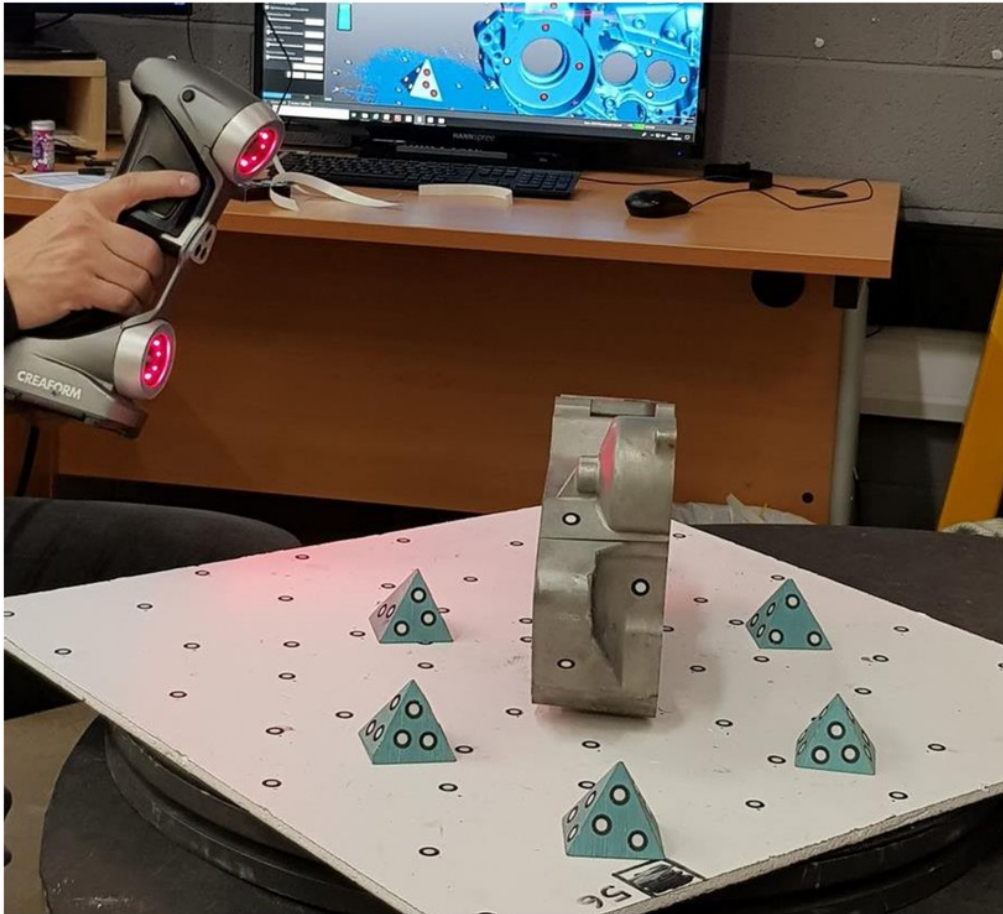


Figure 6 – Photograph of the right-hand crank case being laser scanned. (Parsons, authors own)

The white reflective dots provide a reference allowing the scanner to be moved around the case to capture detail from every angle.

Once completed, the data was opened in a piece of software called GOM inspect. It transforms the point cloud data into a solid body enabling detailed measurements to be made. It has exceptional tools such as auto cylinder which recognises cylindrical holes and creates them as a feature. The most effective way this programme is used is to create sections. This allows the user to create two-dimensional sketches straight from the point cloud data.

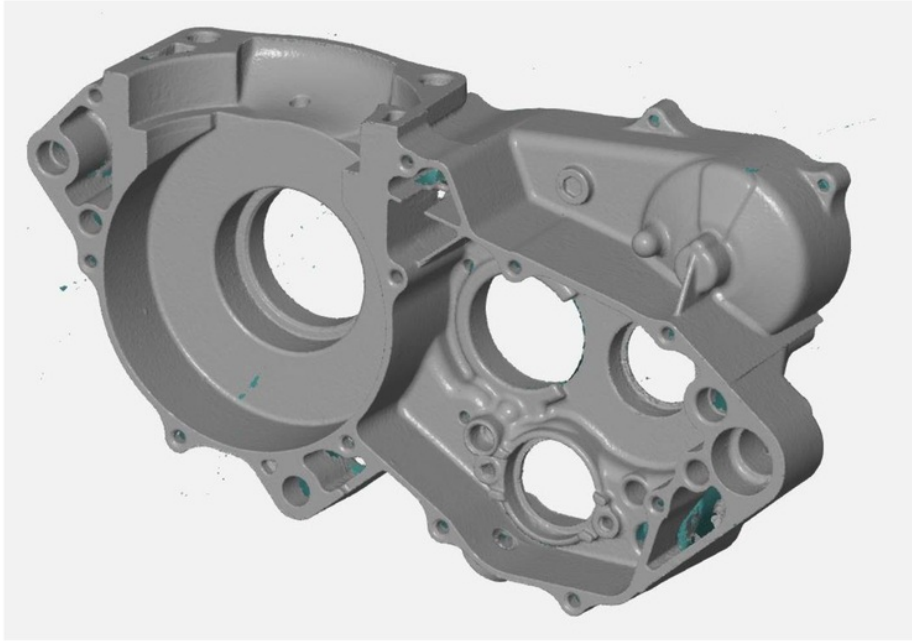


Figure 7 – Right-hand crank case imported into GOM Inspect. (Parsons, authors own)

By using the three gearbox bearing holes along with the main bearing holes the sections can be referenced. This ensures that the holes are the correct distance apart and that they are in the correct location with respect to the outer walls of the case. The sketches created in GOM can be copied directly into Solidworks allowing the creation of features.

2.2.4 Solidworks Model

The Solidworks model of the crankcases was an extremely time thirsty job however the scans significantly shortened this time. The first step taken to create these components was to model a direct copy of the OEM crank cases. The removal of the features associated with the casting process must also be removed. For example, the draft angles all needed to be fixed, small holes and radii had to be removed or modified to make the component suitable for manufacture. The right-hand crank case was modified to remove the small radii around the kickstart boss and other failure prone areas. The rear of the case around the kick start was thickened and ribs were added to give extra support and strength where it is really needed.

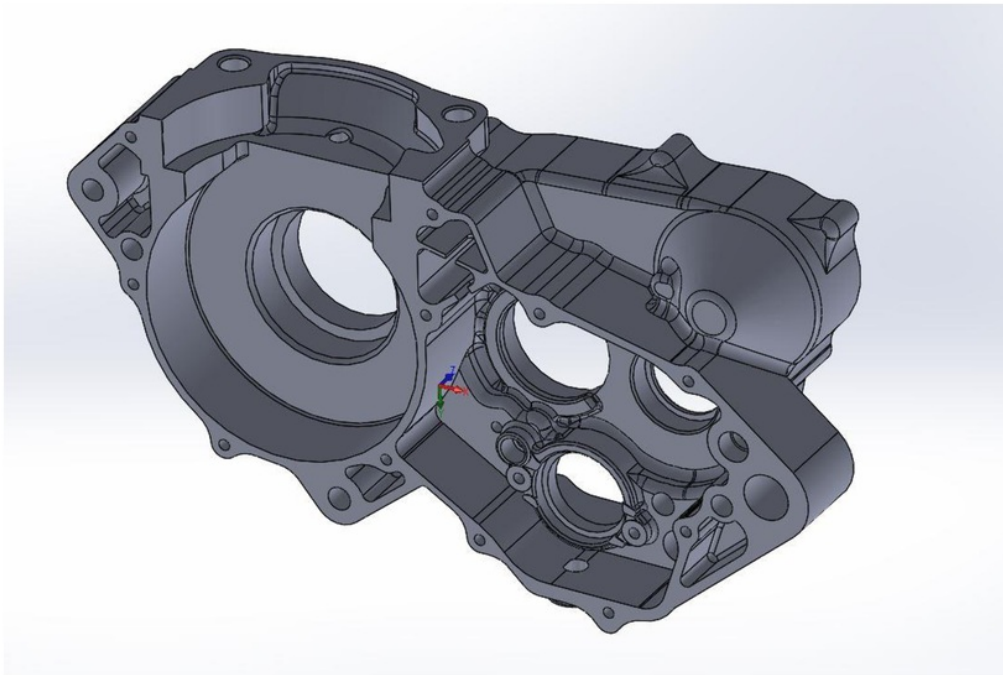


Figure 8 – Solidworks model of the right-hand crankcase showing the area of the kickstart boss that has been strengthened to improve the resistance to failure. (Parsons, authors own)

The left-hand crank case was modelled in exactly the same way. Sketches were created from the GOM Inspect model and transferred into Solidworks. A direct copy of the OEM case was created. The draft angles and small radii were removed to ensure suitability for CNC manufacture. The original design encompasses a clutch arm. This arm is a lever transferring the operation of the clutch lever to the clutch pressure plate though a steel rod. This would create another operation with respect to

machining. The case alone will require three operations to complete; the addition of another just to add in the clutch actuator would be extremely costly as this would require the manufacture of specialist jiggling to hold the component in the milling machine for the operation. The clutch on a CR500R is also notoriously heavy which can be rectified with the addition of a clutch slave cylinder. Aftermarket options are available which use the standard set up but replace the cable. However, the correct way to introduce this system is to mount a slave cylinder in-line with the clutch pushrod at the end of the gearbox input shaft. This will push directly onto the rod and pressure plate without the need for levers and bearings. This will drastically improve the clutch feel and protect the rider from tiring during a race due to having to use a heavy clutch. To allow the fitment of this new equipment the generator side of the crank case has had to be modified. The housing that contains the flywheel, stator plate and pick up coil has had to be reshaped to allow the fitment of the clutch slave cylinder coincident to the gearbox bearing. The smallest available slave cylinder was from a KTM Duke 640. This will, however, restrict the size of the front sprocket somewhat.

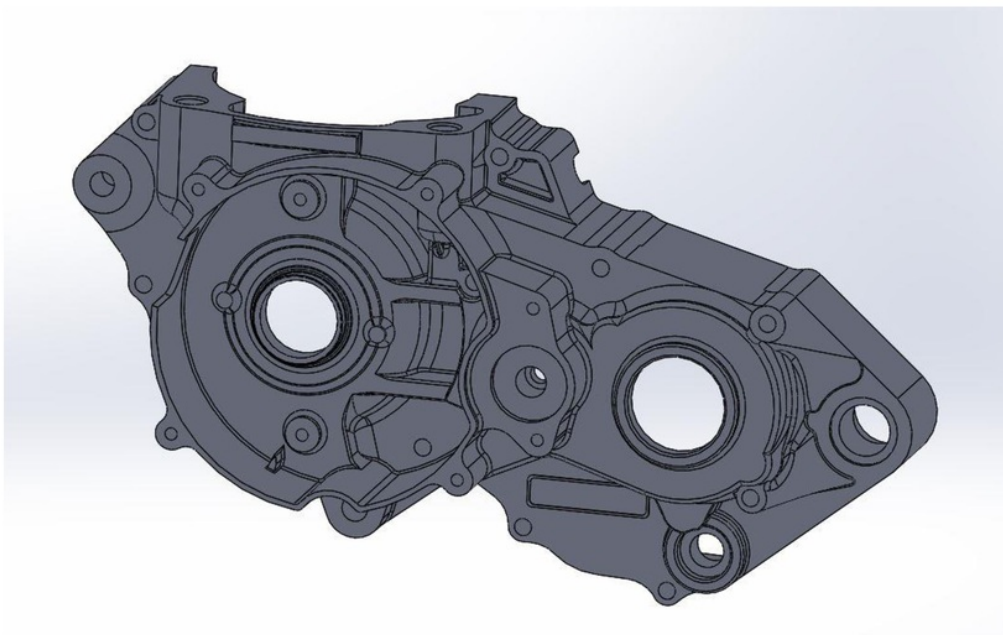


Figure 9 – Left-hand crank case with the addition of the clutch slave cylinder mounting. (Parsons, authors own)

The addition of this mount, causing the generator housing to change shape has introduced the need for a new generator cover. The OEM cover equipped on this motorcycle is plastic or aluminium. A sketch taken from the outer face of the generator housing allowed the creation of a new generator cover.

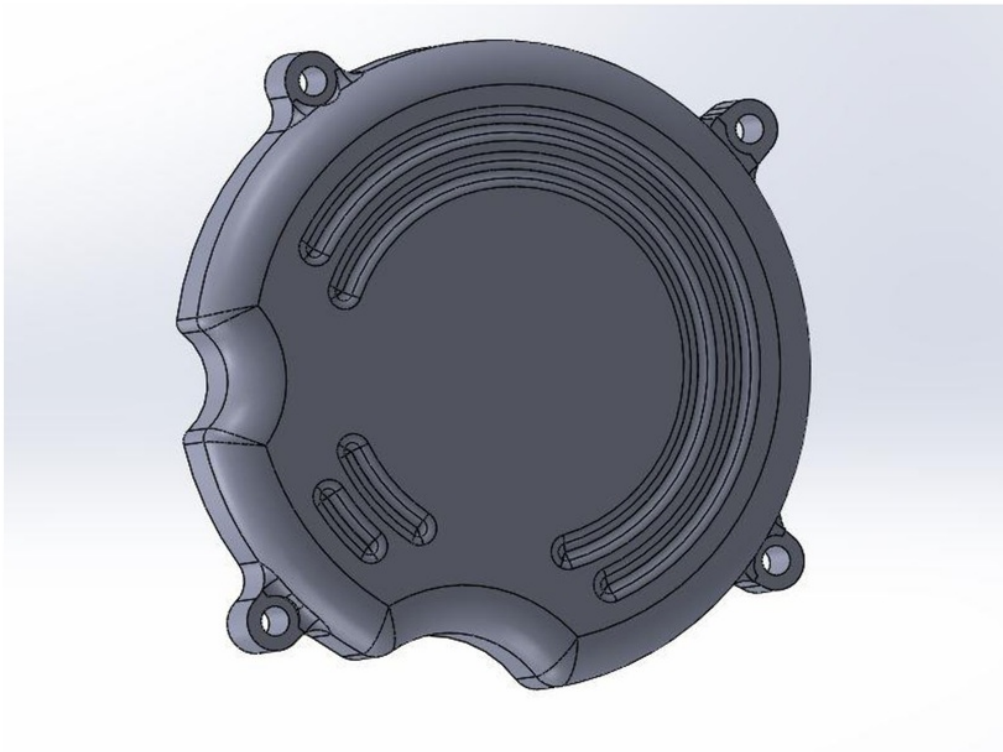


Figure 10 – CAD model of the new design generator cover. (Parsons, authors own)

2.3 Bearing Fit

As discussed previously, bearing fit is an extremely important consideration when designing crank cases. Firstly, heat from engine use is going to cause the materials to expand; they will expand at different rates as the cases are manufactured from aluminium and the bearings from high speed steel. The bearings should be fitted with a certain amount of interference to protect them against coming loose and spinning. The crank cases get hot due to engine use but is unclear exactly how hot these areas of the crank cases get. These bearings must be fitted while the crank case is hot. Assuming the crank case is at 140°C then the size in which the hole needs to be machined at room temperature (20°) can be calculated.

$$\text{CoE Diametral Aluminium} = 0.000025$$

$$\text{CoE Diametral Steel} = 0.000012$$

$$\text{Difference in CoE} = 0.000013$$

To allow the fitment of the bearing the crank case is heated by 120°C.

Therefore, the interference can be calculated.

$$68 \times 120 \times 0.000013 = 0.106 \text{ mm}$$

When cold the hole size needed to create this fit is,

$$68 - 0.106 = 67.894 \text{ mm}$$

Assuming the crankcases reach a maximum of 100°C the interference can be calculated.

$$68 \times 80 \times 0.000013 = 0.071 \text{ mm}$$

The pressure pushing out on the crank case bearing walls can then be calculated assuming all of the give is in the crankcase.

$$\text{Hoop Stress} = E \times 0.071 \times 10^{-6}$$

So, using $E = 2 \times 10^5$,

$$\text{Hoop Stress} = 0.0142 \text{ N/mm}^2$$

$$\text{Hoop Force} = 0.0142 \times \text{Bearing Cross Sectional Area}$$

So,

$$\text{Hoop Force} = 0.0142 \times 18 \times 50 \text{ (measured)}$$

Therefore,

$$\text{Hoop Force} = 12.78$$

$$P \times \text{Bearing housing area} = 2 \times F$$

So,

$$P = \frac{25.56}{18 \times 68}$$

Therefore,

$$P = 0.02 \text{ N/mm}^2$$

The other bearing hole sizes can all be calculated using the equations just used. A chamfer is added on the entry of the holes to help guide the bearings into their place. Bearing sizes need to be tolerated carefully. The 68mm diameter of the main bearing is the maximum possible size. it can be smaller within the given tolerance, but not larger. This must be considered when adding tolerances to engineering drawings.

2.3 Rapid Prototyping (3D Printing)

Once the CAD models were completed, they could then be transferred into the CURA software that works with the Ultimaker printers. Due to the size of the build plate the models have had to be split in half to fit. The addition of dowel pins on the split allow the pieces to be joined together after printing. Each quarter section of the engine case takes around four or five days to print. The material chosen was PLA. This choice was made as it is reasonably cheap and is relatively impact resistant. It allows the tapping of threads as well as drilling if needed. It can be printed at 100% density producing a component made from solid plastic. The density chosen for this engine model is 20%. This allows one half of the engine casing to be produced per roll of 3D printing filament. Once printed the bearings and seals can be pressed in, bearing in mind in the modelling stage that the plastic shrinks as it cools. Allowing 1mm of clearance on all bearings provides the assurance that the bearings will fit.



Figure 11 - 3D printed generator cover. (Parsons, authors own)



*Figure 12 – Left-hand crank case fitted with all bearings, seals, stator plate and clutch slave cylinder.
(Parsons, authors own)*

2.5 Engineering Drawings

To ready the crank cases for manufacture, engineering drawings must be created. The bulk of information will be given to the machinist with the CAD drawing. However, specific details should be pointed out on this drawing. Bearing sizes and tolerances are two important details that are necessary to include. Thread sizes should also be included to ensure that the correct taps are used when creating threads. Any extra information such as surface finish should also be added. The engineering drawings are extremely useful when machining as it shows a clear image of the finished product, allowing the machinist to know exactly what they are looking for. The left-hand crank case requires three engineering drawings to allow ample space to include all necessary detail.

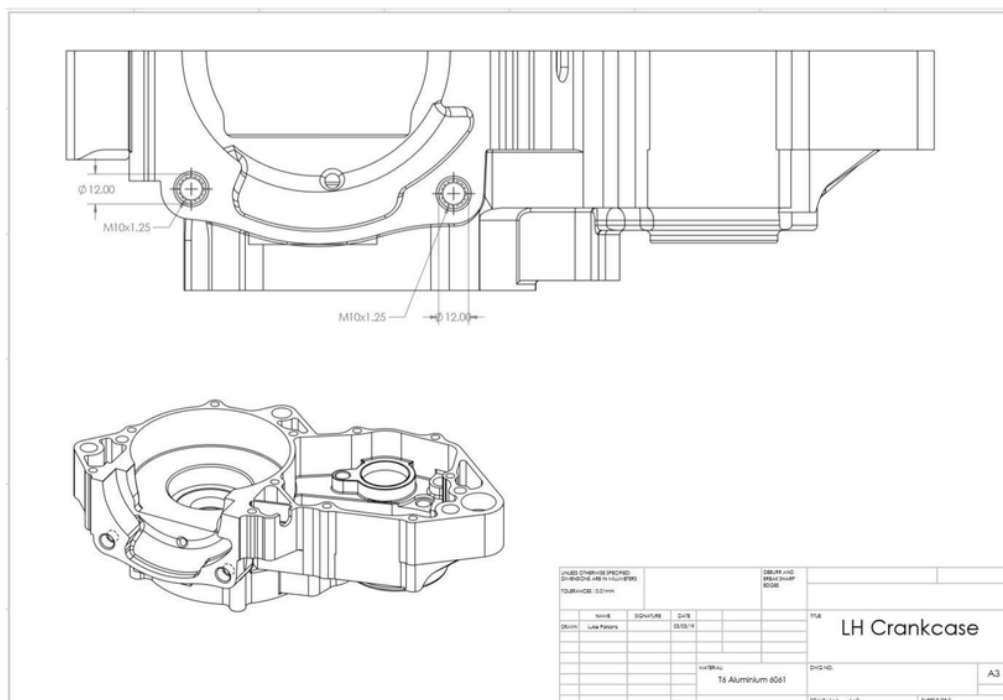


Figure 13 – Engineering drawing to be sent with left-hand crank case on manufacture. (Parsons, authors own)

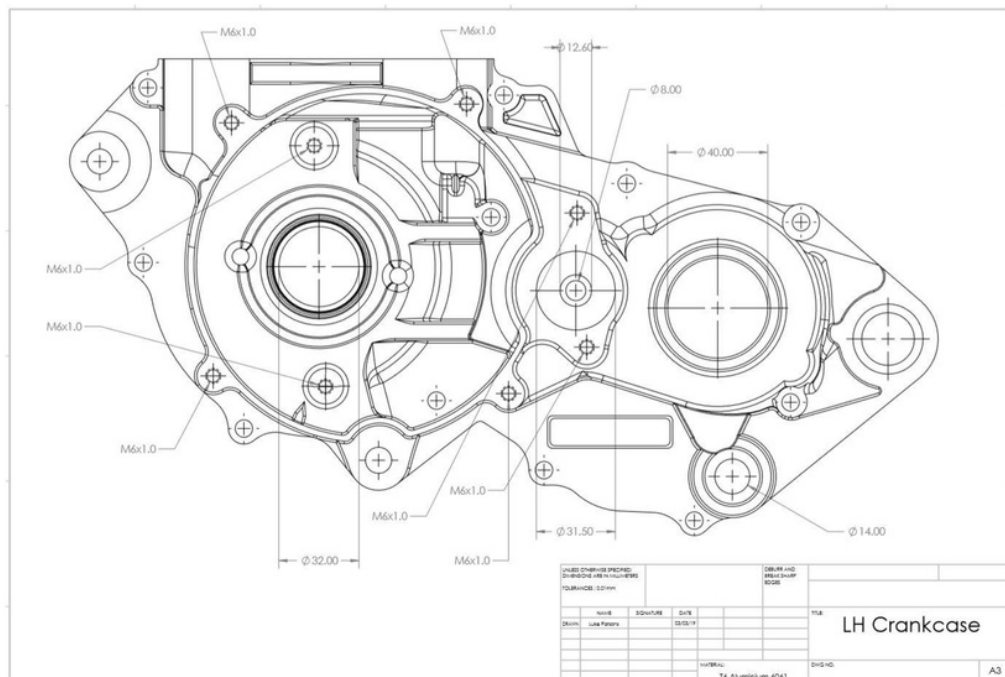


Figure 14 – Front view of the left-hand crank case. (Parsons, authors own)

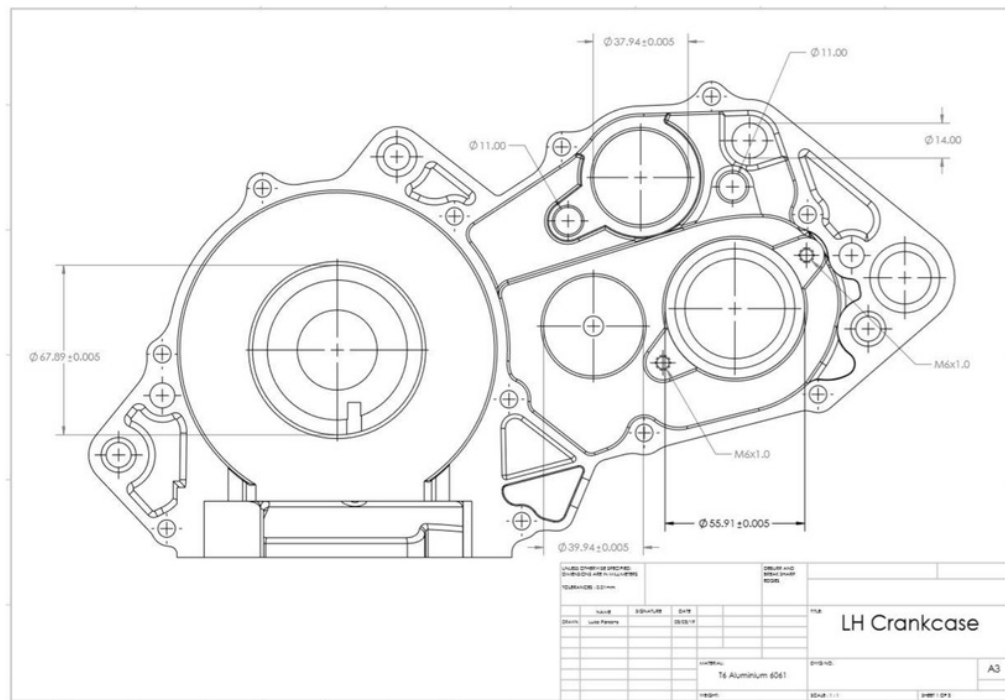


Figure 15 – Rear view of the left-hand crank case. (Parsons, authors own)

2.4 Conclusion

It is clear that the reproduction and improvement of the Honda CR500R crank cases is completely achievable. The addition of the hydraulic clutch will hugely aid the rider and help prevent arm pump and cramping. The use of 3D printers massively aided the progression of this project allowing mistakes and problems to be clearly visible. Whereas, on the screen in the Solidworks package they were easily missed. Upon completion of the manufacturing of the crank cases further conclusions can then be made.

2.5 Evaluation

The creation of reproduction crank cases is realistically a project more suited to being spread over two years. The time needed to complete the modelling and prototyping stages was vastly more than anticipated. The difficulty in machining these crank cases comes with some of the depths of bearing holes. Many specialist tools will be needed to reach the lowest sections of the crankcases making it difficult to manufacture in house. Quotes from large engineering companies have been received and currently being negotiated. The completed prototype will be presented in the final Viva and will consist of a pair of 3D printed, latest generation, crank cases fully assembled with the crankshaft assembly, gearbox and shifting mechanism, barrel, head, manifold and carburettor.

2.6 Further Work

The next step in completing this project is to continue with the manufacture of the crank cases. Once completed the testing stage can begin. Several seasons of competition will ensure reliability or highlight areas that require attention. The manufacture of a CNC machined inner clutch cover would also be desirable as these are often damaged beyond repair when the right-hand casing cracks. The modelling and prototyping stages will begin shortly after term ends.

3. Exhaust System

3.1 Literature Review

The exhaust systems seen on 2-stroke motorcycles has drastically changed through the last century. Early systems consisted of a pipe of near constant diameter which had the sole purpose of channelling the exhaust gasses away from the cylinder to the rear of the motorcycle. The exhaust gasses could then be released into the atmosphere leaving a trail of 2-stroke smoke. It was realised that by tuning the length of this pipe it was possible to increase the power output of the engine.

3.1.1 The Megaphone

The megaphone as described in “The High-Performance 2-Stroke Engine” (Dixon, 2005) was the first improvement over the standard constant diameter pipe used previously. Although it was noted that changing the length of the exhaust gave a pulse tuning effect it was then noted that the introduction of a divergent cone at the end of the exhaust increased the efficiency of the reflection pulses. Increasing the length of the diverging cone section has the effect of spreading out the pulses that are reflected back towards the exhaust port; this effectively widens the power band. This exhaust design is an improvement over the simple tuned pipe. However, the problem is that the addition of the cone improved the efficiency of sound energy production (Hirake, Kobayashi, & Tsai, 1969). Megaphone type exhausts are famously known to be offensively loud.



Figure 16 – Moto Parilla Racing Motorcycle with Megaphone Style Exhaust. (Smith, 2011)

3.1.2 The Closed Megaphone

The closed megaphone type exhaust is as the name suggests; The same system as before with the addition of a rear blanking plate and bleed pipe. This closed end reflects the positive returning pulse with increased efficiency over the previous design. This pulse must travel the length of the pipe and return in the time between the exhaust port opening and closing. The following formula can be used to calculate the tuned length of an exhaust.

$$L_t = \frac{\theta_o \times V_s}{12 \times RPM} \text{ (Dixon, 2005)}$$

(Note this distance is measured from the back of the piston to the reflection point which in this case is the rear blanking plate itself)

This equation has been created by equating the time taken for the pressure wave to travel the length of the exhaust and return to the time in seconds the exhaust port is open.

The time the exhaust port is open can be written as,

$$t = \frac{\theta_o}{360} \times \frac{60}{RPM}$$

The time taken for the pulse to travel the length of the pipe and return can be written as,

$$t = \frac{2 \times L_t}{V_s}$$

Therefore,

$$L_t = \frac{V_s \times \theta_o \times 60}{360 \times 2 \times RPM}$$

Which can be simplified to,

$$L_t = \frac{V_s \times \theta_o}{12 \times RPM}$$

The addition of the rear blanking plate seems to have created the “perfect” exhaust design. The previous problem of noise amplification has been rectified due to the large amount of positive pulses being reflected back towards the cylinder; this leaves just a small amount of pulse leakage through the bleed pipe. Unfortunately, this design is not without its flaws. The reflection of pulses is so concentrated due to the blanking plate being flat, the power band will be very narrow and aggressive.

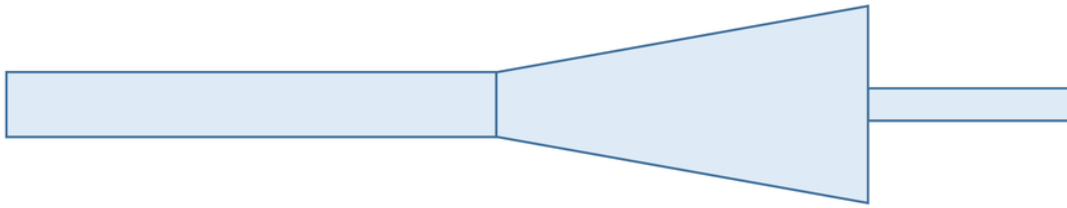


Figure 17 – Closed Megaphone Type Exhaust. (Parsons, authors own)

3.1.3 The Conventional Double-Cone Expansion Chamber

The conventional double-cone expansion chamber is the design which resembles that used today. The simple expansion chamber consists of a header section (often called the lead-in pipe), a diffuser cone (diverging section), a baffle cone (converging section) and a tail pipe (often called a stinger). This type of exhaust was first seen in 1952 on a DKW road racing machine.

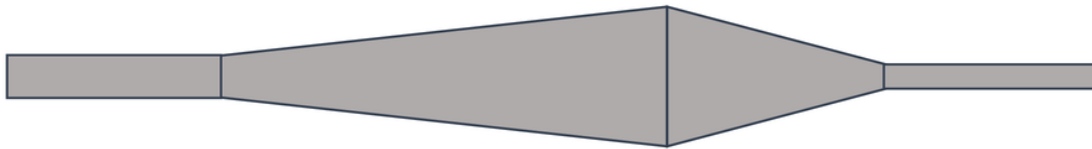


Figure 18 – Double-Cone Expansion Chamber. (Parsons, authors own)

The replacement of the blanking plate with a converging cone had the effect of spreading out the positive pressure waves, increasing the power band width. The addition of the stinger allowed the regulation of exhaust gas exit resistance, allowing the pressure within the expansion chamber to be controlled. By varying the length and diameter of this section the pressure within the exhaust is changed. This has the effect of changing the average internal exhaust gas temperature. By decreasing this temperature, the speed of sound decreases. As the pressure pulses move through the expansion chamber at the speed of sound the slower moving pressure pulses will take a greater time to travel the length of the exhaust effectively lowering the powerband RPM. The geometry of the expansion chamber is fixed which only allows the tuning of the engine for a single RPM. However, the introduction of water into the mid-section of the exhaust allows the average temperature to be varied. As described by (Fleck, 1993), This varying temperature allows the control of the speed in which pressure waves travel in the exhaust. This varying pulse speed means that it is possible to have an

extremely wide powerband as the speed of the pulse can be tuned to reach the exhaust port at the same crank angle with varying RPM. The formula for calculating the tuned length of the exhaust is the same used in the previous section.

$$L_t = \frac{V_s \times \theta_o}{12 \times RPM}$$

3.1.4 The "Blair" Pipe

The Blair type expansion chamber; often referred to as the Di-Con system (Blair, 1996), is an adaptation of the double-cone system. It introduces a mid-section of constant diameter between the two conical sections; This is known as the belly section which size is determined using formula created from empirical data. The second adaptation of this exhaust system was to split both converging and diverging cones in half to create two twin-stage cones. This has the effect of removing sudden changes in shape, thus reducing turbulent flow, aiding cooling. Furthermore, according to (Dixon, 2005) these twin stage cones help to separate the pulses, preventing inefficient overlap. This adaptation is extremely effective however, the most common design seen is the simple Blair exhaust system with single stage cones. The formula for tuned length is again the same as before however, the calculations for diameters and section lengths of the exhaust are still debated. They differ slightly depending on the author however, the most commonly accepted formulae can be found in the Gordon Jennings book "Two-Stroke Tuners Handbook" and will follow shortly.

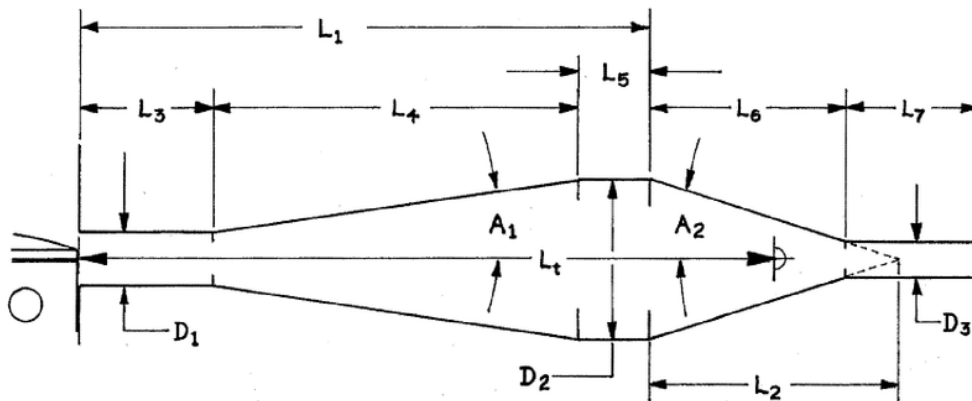


Figure 19 – Blair style expansion chamber. (Jennings, 1973)

The calculation for tuned length of the exhaust has been covered earlier on in this section however, the speed of sound in the exhaust is an unknown value which has to be calculated or measured. Looking at several books and reports there are several suggested values, for example, 1700 ft/sec (520 ms⁻¹) by (Jennings, 1973), 500 ms⁻¹ as suggested by (Dixon, 2005) and 550 ms⁻¹ by (Blair, 1996). These sonic wave speeds are approximations which have been calculated using empirical data. However, it is simple to calculate the speed of sound in the exhaust gas as long as the temperature is known. It is notoriously difficult to accurately measure the average internal temperature of an expansion chamber. This is due to the increases and decreases in cross sectional area throughout the length of the pipe. The average exhaust gas temperature can be estimated using a table from (Davies & Dwyer, 1976) which cross references engine size against BMEP. An estimated average exhaust gas temperature for the CR500R is 450°C. This temperature can now be used in the following equation to calculate the new speed of sound in the exhaust.

$$V_{450} = V_{20} \times \sqrt{\frac{450+273}{20+273}} \text{ (McDonald, 2017)}$$

So,

$$V_{450} = 345 \times \sqrt{\frac{450 + 273}{20 + 273}}$$

Which makes,

$$V_{450} = 542 \text{ ms}^{-1}$$

This value for the speed of sound in the exhaust now allows the calculation of the tuned length. The following formulae for length are all based on this length. Diameters are calculated from the port geometry and empirical data.

$$L_t = \frac{V_s \times \theta_o}{12 \times RPM}$$

$$L_1 = L_t - \frac{L_2}{2}$$

$$L_2 = \frac{D_2}{2} \times \cot(A_2)$$

$$L_3 = 6 \times D_1$$

$$L_4 = \frac{D_2 - D_1}{2} \times \cot(A_1)$$

$$L_5 = L_1 - (L_3 + L_4)$$

$$L_6 = \frac{D_2 - D_3}{2} \times \cot(A_2)$$

$$L_7 = 12 \times D_3$$

$$D_1 = 1.1 \times D_{port}$$

$$D_2 = \sqrt{6.25 \times D_1^2}$$

$$D_3 = D_1 \times 0.67$$

A_1 = Half the diffusers angle of divergence.

A_2 = Half the baffle cones angle of convergence.

These formulae as written by (Jennings, 1973) allow the design of a Blair type expansion chamber. It must be stressed that the tuned length is measured from the back of the piston to the mean point of reflection in the exhaust. The mean point of reflection is an imaginary point part way along the baffle cone. It is found by continuing the converging lines until they meet. Halving the distance from this point and the beginning of the baffle cone will be the mean point of reflection.

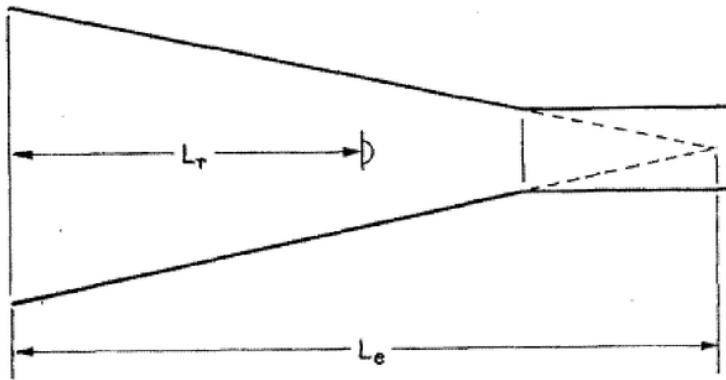


Figure 20 – The mean point of reflection (L_r). (Jennings, 1973)

The formula written by (Jennings, 1973) uses angles of divergence and convergence to define the geometry of the exhaust. These are values to be chosen by the exhaust manufacturer or home tuner. The recommended values as agreed by (Blair, 1996) for the diverging (baffle) cone range between 10 and 20 degrees. As discussed before the use of a conical section after the diverging cone spreads out

the positive pulses with the effect of widening the power band. Thus, the longer and shallower the diverging cone is made, the wider the power band is made. The negative effect being the more spread out the pressure pulses are made the smaller the plugging effect at the port is. This in turn reduces the "kick" of the power band. This can be used to the designer's advantage. In certain types of motorcycle racing it is desirable to have a very broad gentle power band: motocross for example. A road racing machine would call for a much shorter cone with a much steeper angle. This will have the effect of narrowing the power band but increasing the effect of pulse tuning. In effect the trade off is power band width against peak power.

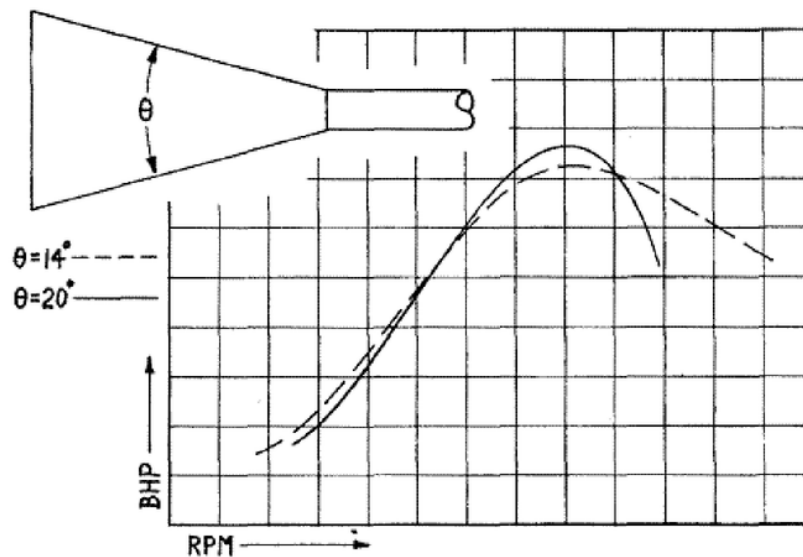


Figure 21 – Graph showing the trade-off between power band width and peak power. (Jennings, 1973)

It can then be assumed that the power band width can be calculated by equating the time in which the exhaust port is open to the distances to the beginning and end of the baffle cone. These two distances represent the extremities of the baffle cone and should represent the amount in which the pulses have been spread out. The exhaust produced in this report will test this theory. The recommendation by (Blair, 1996) and (Jennings, 1973) for the angle of divergence for the diffuser cone is half the angle of convergence of the baffle cone.

3.1.5 Power Valves and Variable Exhausts

Throughout the 1980s and 1990s many different systems were trialled on motocross engines to try and either improve peak power or rideability. The idea of a varying length exhaust sounds brilliant and the length can be actively increased or decreased with changing rpm and load. Yet, this is not as easily achievable as a variable length inlet. Most modern sports bikes are fitted with variable length velocity stacks. These are easily adjustable due to their small size and the absence of extreme temperatures. However, fitting a similar system to the exhaust of a motorcycle is obviously not an option. Water injection is one way of effectively changing the exhaust length as discussed before. However, this system adds weight and complexity; not something that is desirable on any racing machine. In 1984 Honda fitted the ATAC (Automatically Controlled Torque Amplification Chamber) system to their 125cc and 250cc motocross machines.



Figure 22 – Honda ATAC system fitted on a 1985 CR125. (Dirt Bike Magazine, 2019)

This system contains a rotary valve which, when turned forces the exhaust gases through the chamber before entering the exhaust, thus, increasing the total length. By effectively making the exhaust longer, the pressure pulse has a greater distance to travel lowering the peak power RPM. This valve is mechanically controlled by a weighted cam and lever system on the end of the crankshaft. At high RPM the weighted cam forces the lever to lift which closes the valve leading into the ATAC chamber. This allows the exhaust gases to flow straight into the expansion chamber. At low RPM the lever is at the lower position which opens the valve. This forces the gasses to flow through the ATAC chamber

first. By tuning when this valve opens through the use of different springs and weights, it is possible to have two effective power bands. Firstly, this will increase the engines performance at low RPMs but will also reduce the effect of a huge spike in power at high RPMs making the bike much more rideable. The second method adopted by Honda was the HPP (Honda Power Port) system. This, unlike the previous system varies the exhaust port timing through the use of blades. These blades cover and uncover the top of the exhaust port, which controls the duration in which the port is open. Lowering the exhaust port improves performance at low RPM and using the same mechanical method as described before the blades can be retracted effectively raising the top of the exhaust port to improve top end performance. This type of system for changing the effective tuned length of the exhaust is still widely used by all motocross bike manufacturers. A system will not be added to the CR500R in the scope of this project due to time restrictions however, the addition of a power valve is an area that will be pursued in the future.

3.2 Exhaust Design

3.2.1 Aims

There are several aims for this section of the project. The first being to design and manufacture an exhaust system that will lower the peak power RPM and broaden the power band. The second being to test the manufactured exhaust to validate the calculations used to design the exhaust. Reducing peak power RPM is not something usually considered when designing components for a racing machine. However, the aggressive nature of this particular motorcycle has given it a reputation for being very difficult to ride quickly. This is due to the more than ample amount of power but more significantly the narrow, aggressive power band. This bike has history at grand prix level of being hugely successful but taming the engine slightly would make the bike more suited to a “normal” rider.

3.2.2 DOMA Expansion Chamber

The DOMA system is the most common aftermarket replacement for the OEM exhaust. Its geometry is reasonably similar to the OEM pipe and thus performs similarly. The main attractions of the DOMA pipes are the variety of available finishes and the comparatively small price to replace after a race season by which time they are dented and often leaking.



Figure 23 – DOMA “Factory Finish” Exhaust Pipe. (VMX Unlimited, 2019)

The DOMA system is manufactured in plate sections rather than a collection of conical sections making it difficult to accurately measure the individual diameters and section lengths. The tuned length, however, has been measured at 1.1m. By rearranging the formula used earlier and using the calculated sonic wave speed, the tuned RPM can be calculated.

$$RPM = \frac{V_s \times \theta_o}{12 \times L_t}$$
$$RPM = \frac{542 \times 182 \text{ (Measured)}}{12 \times 1.1}$$
$$RPM = 7473$$

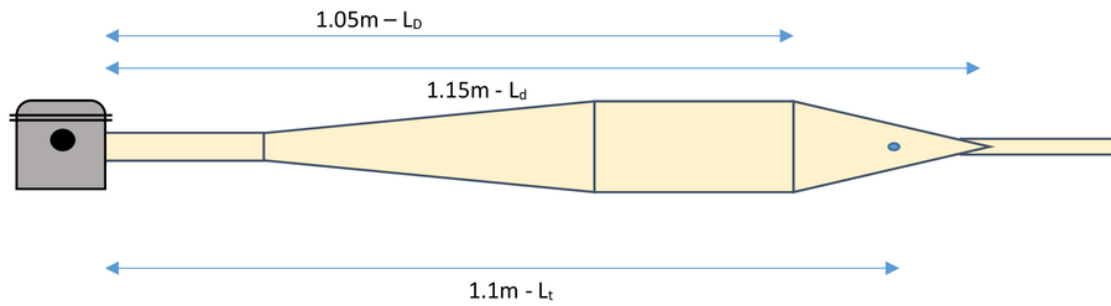


Figure 24 – L_t shown on DOMA exhaust with the lengths from the piston to either end of the baffle cone.
(Parsons, authors own)

values is the power band width.

$$Upper\ RPM = \frac{V_s \times \theta_o}{12 \times L_D}$$

So,

$$Upper\ RPM = \frac{542 \times 182}{12 \times 1.05}$$

Therefore,

$$Upper\ RPM = 7800$$

$$Lower\ RPM = \frac{V_s \times \theta_o}{12 \times L_d}$$

Subsequently,

$$Lower\ RPM = \frac{542 \times 182}{12 \times 1.15}$$

Which makes,

$$Lower\ RPM = 7150$$

$$\text{Power Band Width} = \text{Upper RPM} - \text{Lower RPM}$$

Then,

$$\text{Power Band Width} = 7800 - 7150$$

So,

$$\text{Power Band Width} = 650 \text{ RPM}$$

This exhaust design shares dimensions with other popular aftermarket systems such as FMF's "gold series" and Pro Circuit's "factory sound". The desire for maximum peak power a little below the red line is desirable on most racing machines and the loss of bottom end "grunt" is often sacrificed. A powerband of 650 RPM is somewhat more suited however to a road racing machine. Perhaps, some 125cc motocross machines must be fitted with exhausts providing this engine characteristic. This is to allow a small capacity engine the chance to lock horns and match the performance of other larger capacity bikes. The talented rider will be able to manipulate the gears and clutch to keep the engine within this range allowing the bike to work at its maximum efficiency. Fortunately, the large capacity of this motorcycle means that even at RPM's below the power band there is ample power. For pure riding ease and pleasure the larger capacity motorcycle fitted with a well-designed exhaust is always the preferred option. Unlike the DOMA and other systems the full potential of the expansion chamber has not been utilised. This is usually down to packaging. The design providing the most efficient pulse tuning effect is often a rather large and bulky shape. This is often difficult to fit around the architecture of the motorcycle so a compromise between performance and fitting has to be made, as put by (Kaaden, 1972). "You'll know when you have the design right, because the exhaust will then be impossible to fit to the motorcycle without dragging on the ground or burning the rider's leg." The large belly section of the DOMA system has a major diameter of 95mm. The equation used in the previous section to calculate the belly diameter for maximum pulse efficiency is,

$$D_2 = \sqrt{6.25 \times D_1^2}$$

This dimension is driven by the lead-in pipe diameter D_1 which on the CR500R is 52mm.

$$D_2 = \sqrt{6.25 \times 52^2}$$

Therefore,

$$D_2 = 130mm$$

The major diameter of the DOMA system is 37% undersized to that of a system designed for maximum pulse efficiency. The design of a system lowering the peak power RPM and widening the power band width but also ensuring the sizes need for maximum efficiency is the logical next step. Fitment onto the bike is a problem which has been overlooked in the scope of this project for two reasons. The time needed to manufacture a cone pipe fitted around the frame and engine is too great. The second reason is such an exhaust system would more than likely require the relocation or redesign of several components on the machine to allow suitable space for fitment.

3.2.3 Modified Exhaust Design

The design of an exhaust system suitable for this motorcycle and application requires the desired engine characteristics first being decided. The required characteristics chosen for this design are a lower peak power RPM around 6500 RPM with a power band width of 2000 RPM. The creation of an expansion chamber calculator in Microsoft Excel using the formula as written by (Jennings, 1973) allows the rapid design and redesign of the exhaust system. The use of the rearranged formula to calculate upper and lower RPM's alongside up and down arrows allows the rapid change of cone angles to give the desired powerband width. The following screenshot of the calculator and data are the values used in the manufacture of the exhaust system.

2 STROKE EXPANSION CHAMBER DESIGN

INPUT DATA	
Average Exhaust Gas Temperature (°C)	452
Exhaust Port Open Duration (θ)	182
Tuned RPM	6500
Exhaust Exit Diameter (mm)	52
Exhaust Port Length (mm)	80
Silencer Input Diameter (mm)	35
Angle of Convergence (°)	16
Angle of Divergence (°)	8
Speed of Sound in Exhaust (m/s)	544.266
Upper Powerband RPM	7947.11
Lower Powerband RPM	5996.07
Powerband RPM Width	1951
TUNED LENGTH (mm)	1270

Exhaust Section Dimensions (mm)	
L1	1038.70
L2	462.50
L3 (lead in including Port)	312.00
L4 (Diffuser Cone)	557.73
L5 (belly)	168.98
L6 (Baffle Cone)	337.98
L7 (stinger)	420.00
D1 (Lead in Diameter)	52.00
D2 (Belly Diameter)	130.00
D3 (Stinger Diameter)	35.00

A1	4.00
A2	8.00
Cotangent A1	14.30
Cotangent A2	7.17

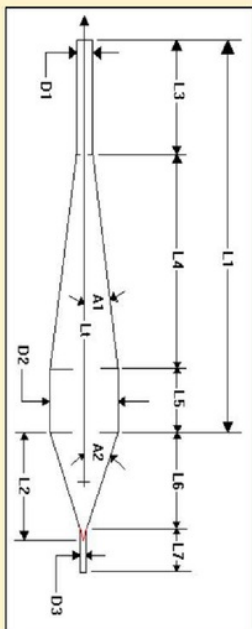


Figure 25 – Screenshot of Expansion Chamber Calculator. (Parsons, authors own)

The choice of routing this 1.27 m long exhaust system was difficult. The ideal design being the design which easiest to manufacture and in this case means the fewest bends possible. With an exhaust port that faces towards the front of the bike and is also at an angle of 45° to the ground there was one design that seemed the best. The expansion chamber coming straight out the barrel, bending upwards slightly and following the curve of the front wheel between the front forks. This decision allowed several points on the frame in which to mount the exhaust and the birth of a new style of motorcycle exhaust that is sure to be followed.



Figure 26 – Side on photograph of the CR500R with suggested exhaust routing shown in yellow.

(Parsons, authors own)

3.3 Exhaust Manufacture

3.3.1 Splitting into Sections

The manufacture of this expansion chamber called for each section to be split into sub-sections. This allowed the sheet steel to be easily handled and folded by hand. The first section of the exhaust to be split was the lead-in pipe. This is the part of the exhaust with the largest number of bends so therefore, needed to be split into the smallest sections. Imagining the expansion chamber as a two-dimensional shape with a centreline allows angles to be drawn at each section of the bend.

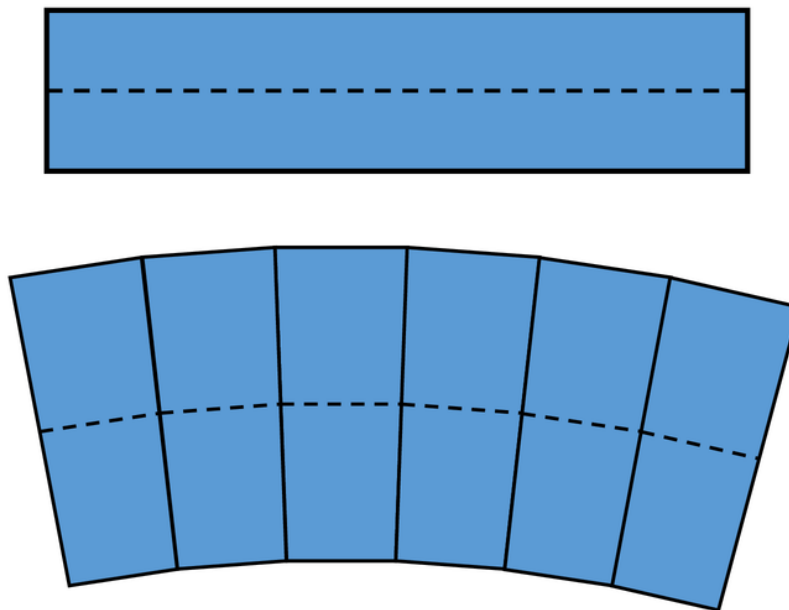


Figure 27 – Lead-In pipe shown split into sections. (Parsons, authors own)

This method of creating a curved pipe using welded together, multiple sections is called “Lobster Backing”. It is the most aesthetically pleasing method of creating an expansion chamber. Each section of the expansion chamber has been split however, certain sections that do not include bends have only been split in half. This is to reduce the number of welds needed; improving the chances of a sealed pipe.

3.3.2 Drawing Lead-In Pipe Sections

The lead-in pipe is the first section of the expansion chamber. It is a pipe of constant diameter which often sees the most changes in direction. There are three common methods used to create these sections. The simplest method is to create this section straight and then use the pie-cut technique. This is by far the quickest way of manufacturing this section but is rather unsightly due to the multiple welds needed after a pie section is cut out of one side and welded back in on the other.

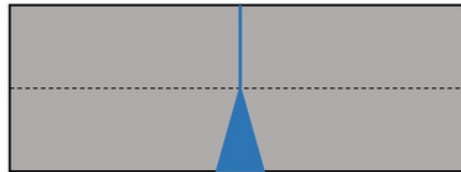


Figure 28 – Pie-Cut method of creating the Lead-In Pipe. (Parsons, authors own)

The second method is the preferred method used to create these pipes as they use one weld per section. By joining sections of equal length, the welds are equidistant from each other. This method is graphically drawing the shapes on paper or in a CAD package. The first step is to draw half of the section to scale. Below, a half circle is drawn and split into eight equal segments. Lines are drawn vertically upwards to intersect with the top of the segment. The distances from the bottom to the top of the section are then transferred onto a line of equal length to the circumference of the pipe. These lines can then be connected with a spline to complete the shape. Once complete this can then be mirrored to create the final template which, once folded will create a mitred pipe as shown in figure 16.

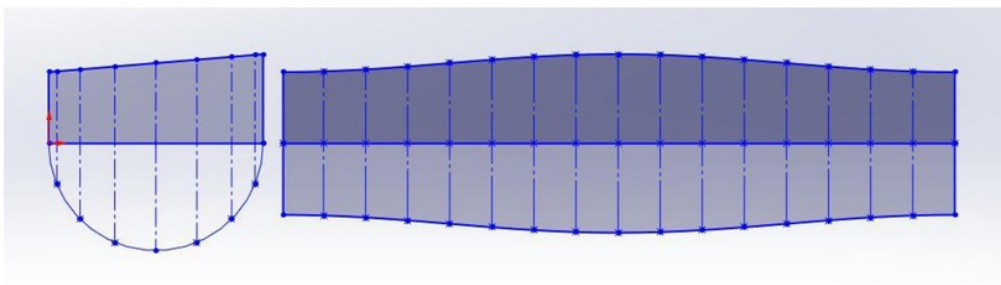


Figure 29 – Graphical Drawing of a laid out mitred pipe as used in the Lead-In section.

The third method is the same as the previous one however, rather than drawing out the cone and half circle, the product can be drawn straight away using numerical calculations.

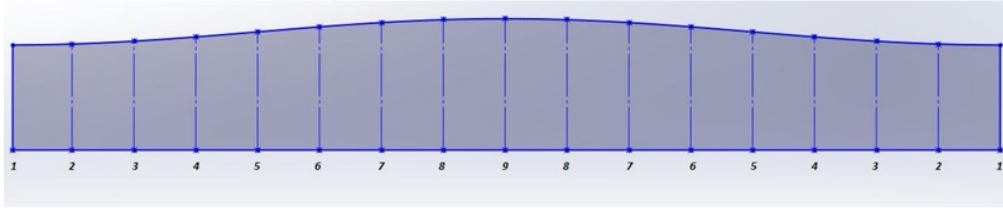


Figure 30 – Numerical method of creating the sections of lead-in pipe. (Parsons, authors own)

The following calculations are used to find the length of each of the numbered vertical lines. The horizontal line is the circumference of the circle as before.

$$\alpha = \frac{360}{N}$$

$$|1| = \left(\left(R + \frac{d}{2} \right) \times \cos 8 \alpha \right) \times \tan A$$

$$|2| = \left(\left(R + \frac{d}{2} \right) \times \cos 7 \alpha \right) \times \tan A$$

$$|3| = \left(\left(R + \frac{d}{2} \right) \times \cos 6 \alpha \right) \times \tan A$$

$$|4| = \left(\left(R + \frac{d}{2} \right) \times \cos 5 \alpha \right) \times \tan A$$

$$|5| = \left(\left(R + \frac{d}{2} \right) \times \cos 4 \alpha \right) \times \tan A$$

$$|6| = \left(\left(R + \frac{d}{2} \right) \times \cos 3 \alpha \right) \times \tan A$$

$$|7| = \left(\left(R + \frac{d}{2} \right) \times \cos 2 \alpha \right) \times \tan A$$

$$|8| = \left(\left(R + \frac{d}{2} \right) \times \cos \alpha \right) \times \tan A$$

$$|9| = \left(R + \frac{d}{2} \right) \times \tan A$$

Once these templates are created, they are able to be used to cut the sheet metal. They can be used as stencils or CAD drawings that can be cut out on a water jet printer; the latter is a much nicer option.



Figure 31 – Photograph of a Lead-In pipe segment. (Parsons, authors own)

3.3.3 Drawing Truncated Cone with Angles

This report will not cover the numerical or graphical method of drawing a simple truncated cone as this can be found easily online and is extremely simple. As before these sections are cut out, folded and welded.



Figure 32 – Truncated cone section used in straight sections where there is an increase in diameter but no change in direction. (Parsons, authors own)

The truncated cone with an angled top uses a method similar to that of the bent sections of the lead-in pipe. The differences are that the half circle is only split into six equal segments and rather than a straight line of equal length to the circumference the cone section is drawn from a centre point. This point is created by extending the two sides of the cones until they intersect. Lines are then drawn from this point down to each of the seven points on the half circle. As before the length of the lines inside the cone are transferred onto the cone layout.

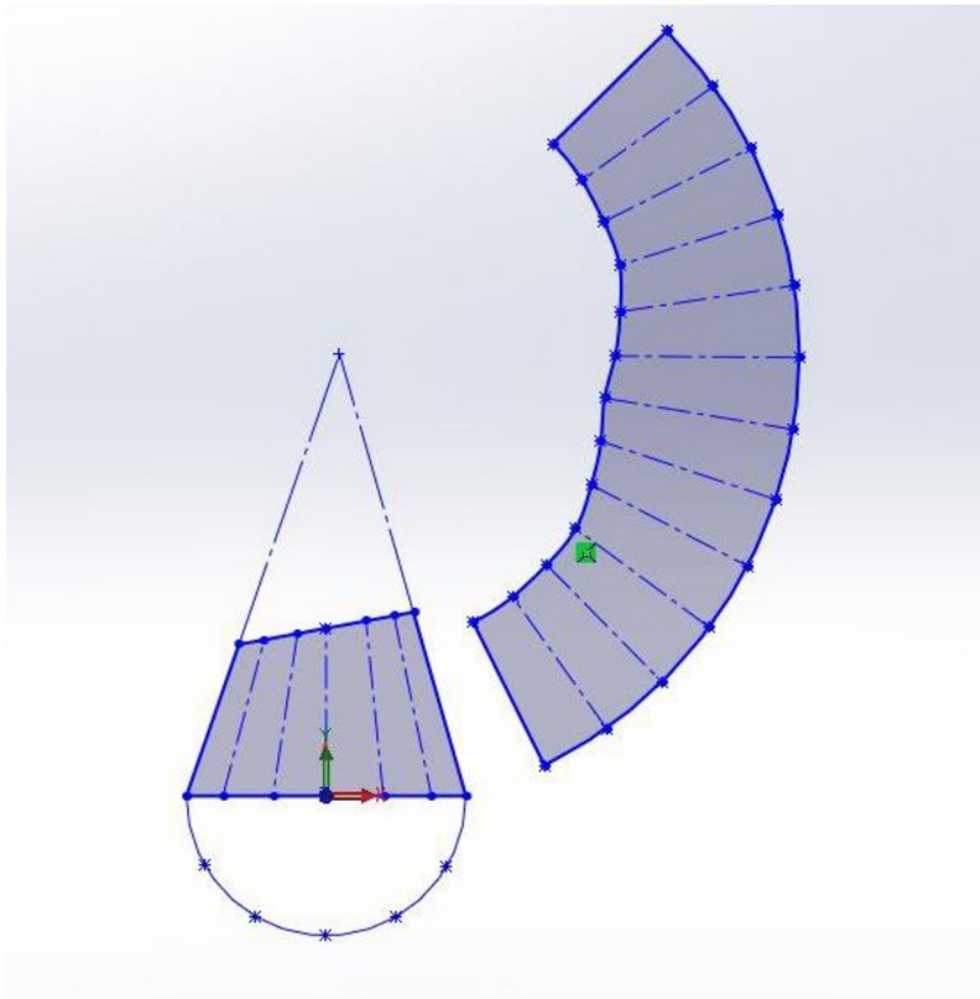


Figure 33 – Truncated cone with angled top. Used in sections with a bend and change in diameter.

(Parsons, own)



Figure 34 – Truncated Cone with angled top, waterjet cut from mild steel sheet. (Parsons, authors own)

3.3.4 Bending, Welding and Fitting

The fabrication of each section of exhaust had to be hand rolled. The absence of a sheet metal roller meant that 0.9mm thick mild steel sheet was chosen. Although this made welding difficult, it allowed the sections to be hand rolled around scaffold tubing secured in a vice. Days spent lovingly bending the material and using a panel beating hammer to beat the sections into the correct shape, allowed them to be welded into individual segments of exhaust that once seam welded together created the expansion chamber as designed. Ideally the sections are gas welded together to leave an almost smooth weld. However, to speed up the prototyping process and to allow for the very thin material a MIG welder was used. Offering the exhaust up to the bike allowed various bracketry to be fabricated to secure the exhaust in place. Mounts were made to connect the exhaust to the lower radiator mounting brackets and another to the bottom yolk. Tabs were then welded onto the lead-in pipe which allowed the fitting of exhaust springs. These pull the front of the exhaust over the sealing ring against the exhaust flange. This is never a complete seal and caused large problems with the smoke alarm in the dyno cell. However, in a field at a motocross meeting a small leakage of smoke is to be expected.



Figure 35 – Manufactured exhaust fitted to CR500R ready for dyno testing. (Parsons, authors own)

3.4 Results (Dynamometer Testing)

The CR500R was run on the MAHA motorcycle dynamometer with the DOMA system and the new manufactured system. The test was carried out in fourth gear between 2500 and 7500 RPM. The tests were completed back-to-back on the same day using the same fuel (Shell V-Power) mixed 32:1 with Silkoline Pro-2 oil.

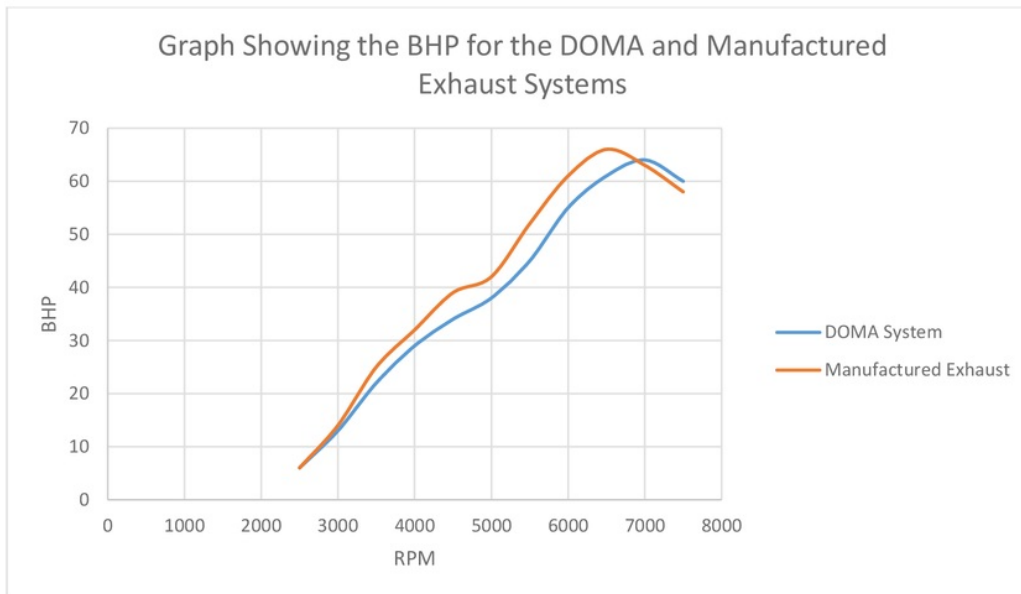


Figure 36 - Graph Showing the BHP for the DOMA and Manufactured Exhaust Systems. (Parsons, authors own)

3.5 Conclusion

In conclusion it is clear that the designed expansion chamber did as expected. The longer tuned length lowered the peak power RPM by the desired amount; validating the formula provided in the (Jennings, 1973) tuning handbook. The power band width is a value which is difficult to put an exact figure on when looking at the graph or even riding along looking at a rev counter. Looking at the graph the powerband appears to be wider than that of the DOMA system, which was the desired effect however, the exact width is difficult to read from the dyno graphs. Surprisingly, the designed expansion chamber produced 2 more BHP peak than the DOMA system. Although this is at a lower RPM it is due to the increased diameter of the belly section. This, as described by (Blair, 1996), is the most efficient design for the positive pressure pulses returning to the exhaust port.

3.6 Evaluation

Overall, the design and manufacture of the exhaust was relatively straightforward. There were slight problems with certain aspects; The thickness of the sheet steel was an issue. Thicker gauge steel would have been preferable had there been access to a sheet metal roller. This would have made the welding much easier and neater; gas welding would have been possible making the finished product much more polished. The largest problem was the collection of the results. The huge amount of smoke produced caused constant problems with the fire alarms. The only way to get the bike to meet the health and safety requirements was to use a heavy-duty exhaust paste and several extra exhaust springs. The motorcycle was strapped down onto the dyno and warmed up with the doors open and every fan active to try and rid the room of as much smoke as possible. Once the bike was ready to complete a power run the doors had to be quickly closed. As soon as the run was complete the doors had to be re-opened to again remove the smoke. This made it particularly difficult to complete back-to-back runs.

3.7 Further Work

Given more time the next step in the project would be to create an exhaust with the ability to have the length adjusted in-situ. This was trialled during the practical section of this project. However, this requires a machined sliding joint on the belly and lead-in sections. The logical follow up to the results gained in this project would be to design several more exhaust systems, each with a different desired engine characteristic. This would allow further verification and potential recommendations to the formula created by (Jennings, 1973). Once a design has been manufactured and tested it would then be necessary to re-manufacture it to fit around the frame like a conventional exhaust system. This may be more work than expected due to the already compact engine/frame section.

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