

# **Additive Manufacturing (3D Printing) - A Potential Future for Tennis Racket Production**

Could 3D Printing / Additive Manufacturing eventually replace the current manufacturing method?

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DEGREE THESIS	
Arcada	
Degree Programme:	Plastics Technology
Identification number:	830209-2596
Author:	Julian Kollataj
Title:	Additive Manufacturing (3D Printing): A Potential Future for Tennis Racket Production
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<p>Currently, tennis racket production is lengthy and labour-intensive, using carbon composite materials, produced mainly in the Far East to keep production costs low, keep companies competitive and profitable.</p> <p>The main objective of this thesis was to establish what production advantages additive manufacturing (AM) could have, if it were to become the new generally-accepted method of racket production.</p> <p>The method involved understanding aspects of innovation, racket production history, 3D printing (3DP) history, types, and solid modelling, to produce a standard tennis racket design process framework, to then produce a standard, full-length, 1:1 scaled, tennis racket prototype – including final assembly parts for the stringing of the racket – made of PA2200 Nylon, within the constraints of a SLS (Selective Laser Sintering) 3DP machine. An aesthetically different variant of the original “basic” model, keeping within the external surface boundaries of the racket’s main body, was produced to highlight the potential of future racket production with 3DP.</p> <p>Theoretically, a standard tennis racket of 685.8 mm, could have been produced as one part, in the then-largest, commercially-accessible SLS 3D printing machine, the EOSINT P760, whose length is 700 mm (according the manufacturer’s (EOS) documentation). However, the key technical challenge, was that the racket length dimension exceeded 650 mm (the limitation set by the service provider, Shapeways) to limit production risk associated with large parts.</p> <p>The solution resulted in a multi-part racket, designed in Dassault Systèmes’ SolidWorks: The main part was set to a length of 650 mm, while one removable “Outer Grip”, which, when produced twice, and added to the final assembly, would create the grip. Once the “Basic” model was created, including grommets and bumpers, the variant, “Hexa”, could be designed and produced, keeping in mind that the Basic’s bumpers, grommets, and grips, could be interchangeable between rackets. By comparing two current production methods, by production activities, the ability to produce custom-designed and -produced 3D printed rackets, production could require less labour, machinery and tools at the production site, while resulting in innovation developing more rapidly, giving focus to creativity, and potentially, the democratization of racket design and production.</p>	
Keywords:	Tennis racket; design; 3D printing; prototype; PA2200; Selective Laser Sintering; SolidWorks; solid modelling
Number of pages:	46 (excluding Appendices); 80 in total
Language:	English
Date of acceptance:	

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# 1. Background

## 1.1 Curiosity and Awareness

Julian Kollataj, a final year Plastics Engineering student from Arcada University of Applied Sciences, worked at Shapeways in Eindhoven, The Netherlands, as an intern, for three months, over the summer of 2012 (Kollataj, 2012).

The author took his tennis rackets with him, as he plays and teaches tennis, and discovered his racket fits into their large 3D printer / SLS (Selective Laser Sintering) machine, which uses Nylon PA2200 plastic, and it begged a question of the author, “Could a full tennis racket be designed and produced with this machine, as a functioning racket, but as a prototype, at the very least? If so, then how close are we to producing sports equipment/working parts, with additive manufacturing, in major industries, as a main production method?”

A year later, in 2013, in the 7<sup>th</sup> Issue of Price Waterhouse Coopers’ Gaining Altitude:

*“An exciting new technology has come on the scene with the potential to revolutionize the way companies manufacture products, including those for aerospace and defense. This technology, known as additive manufacturing or 3D printing, involves building physical objects one layer at a time, using digital models and special material deposition devices. Although they are nowhere near having the capabilities of a science fiction replicator, today’s 3D printing machines have come a long way in a short time and are capable of fabricating complex components out of a variety of materials, including steel, aluminum (sic), titanium, and a variety of plastics. As evidence of its potential, 3D printing is crossing the chasm between interesting concept and legitimate production technology.”*

## 1.2 Objectives

The main objective of this thesis was to establish a baseline tennis racket design process framework, by reverse-engineering a racket owned by the author, to produce a standard, full-length, 1:1 scale, tennis racket prototype, including final assembly parts (grommets and bumper) for the stringing of the racket, made of PA2200 Nylon, within the constraints of a SLS (Selective Laser Sintering) 3D printing (3DP for the rest of the document), also known as Additive Manufacturing machine.

A secondary objective was producing a variant of the original “basic” model, staying within the external surface boundaries of the racket’s main body, to be aesthetically different, to highlight the potential of future racket production with 3DP.

The key technical challenge was that the racket length dimension exceeded limitations of the then-largest, commercially-accessible SLS 3DP machine, the EOSINT P760:

The length of a standard tennis racket is 685.8 mm.

Generally, a tennis racket has an elliptically-shaped “head” for the string bed; a “throat” made up of two tangential (to the face) arced, converging, shafts, becoming one “shaft”; eventually, becoming an octagonally-shaped “handle” (or grip) that flares at its base.

The available machine length is 700 mm (according to the EOSINT’s manufacturer’s documentation).

Theoretically, the racket’s frame could be produced as one part. However, the service provider, Shapeways, limited the dimension to 650 mm, to limit production risk associated with large parts.

The solution resulted in multi-part rackets, designed in Dassault Systèmes Solidworks. This document will contain knowledge gathered from meeting the challenge.

This document will not cover the theoretical and conceptual details of the variant racket.

In the Discussion and Conclusion section, comparisons and advantages between the current production method and 3D Printing will be highlighted, based on Method and

### 1.3 List of Symbols

3DP	3-D Printing
AM	Additive Manufacturing
LMOI	Linear Model of Innovation
SLS	Selective Laser Sintering
$\pi$	Pi, the ratio of the circumference of a circle divided by twice the radius (the diameter)
a	length of semimajor axis of ellipse
b	length of semiminor axis of ellipse
k	length-to-width ratio of a / b for ellipse
mm	measurement in millimetres
$A_{ellipse}$	area of ellipse
$A_{circle}$	area of circle

## 2. Introduction

To consider why and how a new type of tennis racket production method would be welcomed and adopted to replace a current method of a production, such as 3D printing / Additive Manufacturing, it is important to understand these key components:

- *innovation* – the concept, and its influence on technology adoption;
- *factors of production* - the concept, how it influences production output and business viability;
- *the anatomy and internationally-set standards of a racket* – what key components or aspects of a racket are;
- *the history of racket-making* – how the progression of racket design has evolved due to new production methods and materials that have an impact on the strength, power, size, durability, and playability of a racket frame, and therefore, have an impact on the player, and the overall game of tennis; and,
- *how a tennis racket is currently made* – the steps / processes of current racket production.

To design and produce a tennis racket prototype using 3DP, without any previously accessible equipment or racket-making experience, the following aspects have been considered:

- *the history, and present-day availability of 3d printing (also referred to as additive manufacturing)*; and,
- *solid modelling* – history, what it is, and what it is used for.

### 2.1 Innovation

This section will look at understanding innovation in terms of definition, its aspects, where innovation is found (in relation to this thesis), and how innovation is diffused (adopted by others), as it applies to understanding how tennis racket production has progressed.

#### 2.1.1 Definition

Innovation is “*the production or adoption, assimilation, and exploitation of a value-added novelty in economic and social spheres; renewal and enlargement of products, services, and markets; development of new methods of production; and establishment of new management systems. It is both a process and an outcome.*” (Edison, 2013)

Two dimensions of innovation exist (Edison, 2013):

- degree of novelty: this depends on how new the innovation is – to a firm, a market, an industry, and to the world; and,
- type of innovation: a process, product, or service (or a combination of some or all types).

#### 2.1.2 Relevant Source of Innovation:

Linear model of Innovation (LMOI):

The model’s hypothesis is that innovating starts with basic research, adds applied research and development, then ends with production through to diffusion (the distribution among a given population accepting and adopting the innovation):

**Basic research** → **Applied research** → **Development** → **(Production and) Diffusion**  
(Godin, 2005)

This LMOI is considered a 1<sup>st</sup> Generation innovation model, from the 1950s and 1960s, relating to technology push (Buyse, 2012).

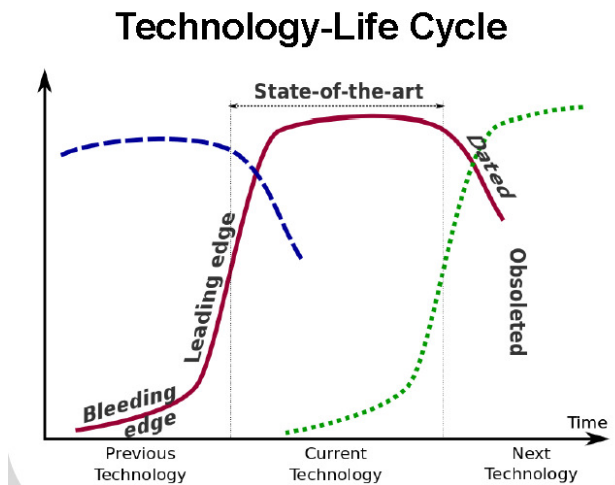


Figure 1: Technology Lifecycle (Industry Tap, 2013)

### 2.1.3 Diffusion of Innovation

Emerging technologies:

The basic tenet is that over time, one s-curve will be replaced by another, while aiming for an upwards growth. In figure 1, it can be seen that a previous technology's relevance and growth in usage subside, and still higher than the new technology, however the new technology is growing initially slow to be adopted but then will start to become ever so widely accepted and used.

To understand Figure 1, the s-curve (diffusion curve) shows growth either in revenue or productivity over time.

1. Initially, bleeding edge technology refers to very new and unreliable forms of technology creation and adoption.
2. As the technology improves steadier reliability, usability, and implementability, such that benefits start exceeding costs of adopting the new technology, the organisations or companies that do it earlier than others, start having the leading edge over the competition, in terms of saving time, effort, and/or money, passing on the novelty on to the rest of society.
3. At the "state-of-the-art" position on the curve, the technology is widely used and adopted by society, while still having space for growth, though not as significant as the leading edge stage.
4. At the downward turning point of the curve, the technology has nowhere to grow, leading towards obsolescence, with no more need to invest in it, as there is a new type of technology on its way, at the bleeding edge stage.

## 2.2 Factors of production

The four factors of production are:

- raw materials – the materials used to produce the object;
- labour – the people involved in the production activities;
- capital goods – referring to machinery and tools used in-house/outsourced, to transform the raw materials into finished products; and,
- land – the location and buildings used to house the production site.

## 2.3 Tennis racket

What defines a generally-accepted tennis racket in the current status of the tennis industry, what's their history of production, and how are they currently produced? The following answers these questions.

### 2.3.1 Basic Anatomy and Terminology:

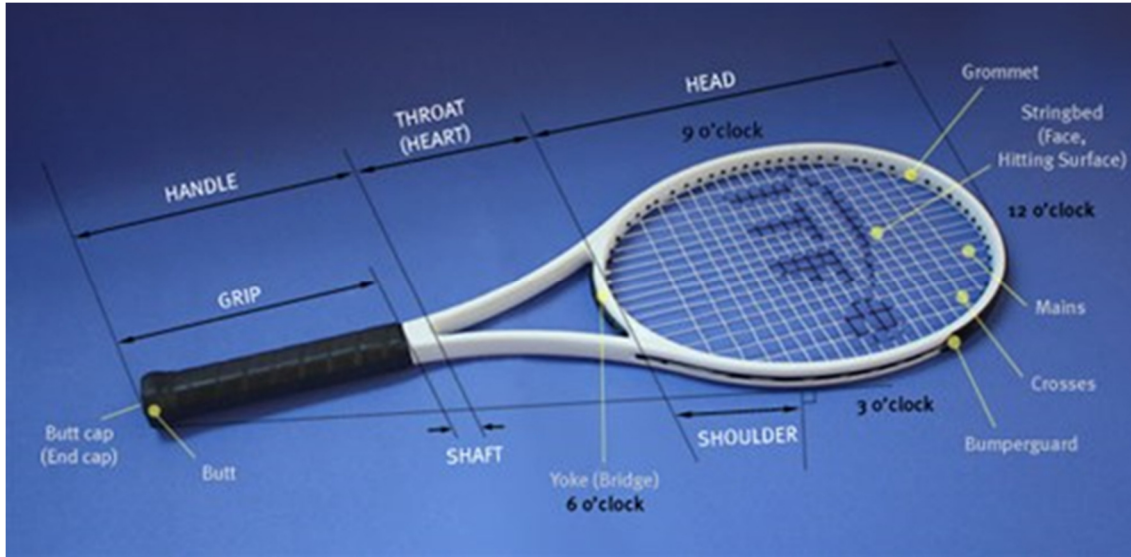


Figure 2: Terminology used for a tennis racket (International Tennis Federation, 2016)

The basic tennis racket consists of, according to the ITF (International Tennis Federation, 2016), “a frame and strings. The frame is composed of a head, throat and handle.

**Head:** The furthestmost (distal) region from the grip, which merges with both shoulders. The edge of the frame that runs around the head is called the rim. The top of the head is called the tip.

**Shoulder:** The region of the frame at the base of the head where a tangent starting at the butt touches the frame.

**Yoke:** The part of the frame at the top of the throat (situated between the shoulders). This is also referred to as the bridge.

**Throat:** The region of the frame between the head and shaft. This is also known as the heart.

**Shaft:** The region of the frame between the throat and grip.

**Grip:** The part of the frame where the player holds the racket. The end of the handle is referred to as the butt.

The strings are contained within the string area, and are typically either main strings (running parallel to the length of the racket) or cross strings (at right angles to the main strings).

**String area:** The area which is limited by the inner boundaries of the head. This is also termed the face, or hitting surface when strung.

**Grommets:** Individual sleeves inserted into holes in the frame in order to protect the strings. Several grommets may be combined to form a grommet strip.

**Bumperguard:** A piece of material fitted onto the head to protect the frame and strings.”

## 2.1.2 Rules and adherence to internationally accepted racket standards (International Tennis Federation, 2015):

“c. The racket shall not exceed 73.7 cm (29.0 inches) in overall length, and 31.7 cm (12.5 inches) in overall width. The hitting surface shall not exceed 39.4 cm (15.5 inches) in overall length, when measured parallel to the longitudinal axis of the handle, and 29.2 cm (11.5 inches) in overall width, when measured perpendicular to the longitudinal axis of the handle.”

A tennis racket has varying shapes found in it, but the most profound are the ellipse, triangle, and square, as they pertain to the head, throat, and handle, respectively. What needs to be understood about them, when relevant to designing a tennis racket? The next section considers the aspects of an ellipse mainly, in preparation for calculations in the design of the racket, using the international racket standards.

## 2.3.2 Geometric Shapes of a tennis racket

### 2.3.2.1 Primitive, Rectilinear, and Curvilinear, Shapes:

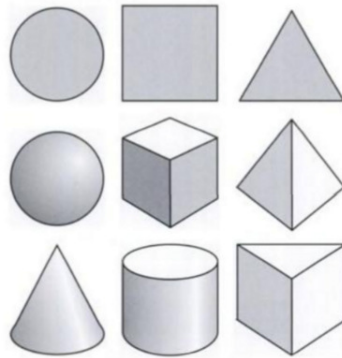


Figure 3: From 2-Dimensional to 3-Dimensional Primitive Shapes (Pipes, 2004)

- Primitive Shapes

2-dimensional geometric shapes are “simple, mechanical shapes, which are defined by mathematical formulae and which can be produced using the implements found in geometry sets. We recognize them as triangles, rectangles, stars, circles, and ovals” (Pipes, 2004, p. 48), and goes on to say later, “these shapes, or planes, have their equivalent forms in three dimensions: in pyramids, cones, rectangular boxes, cylinders, spheres, and prisms. These are termed primitive shapes and forms. In theory, and complex form can be created by merging and/or subtracting the right selection of primitives. In computer graphics, complex shapes are developed using Boolean operations of union, difference, and intersection.”

- Rectilinear Shapes

These shapes are “types of geometric shape, produced using straight lines, usually parallel to the horizontal and vertical” (Pipes, 2004, p. 48).

- Curvilinear Shapes

Curvilinear shapes are “based on the organic shapes found in nature” (Pipes, 2004, p. 50), and goes on to write, “curvilinear shapes can be drawn freehand or by using splines of plywood or piano wire bent into tension and held in place by lead weights. Sets of French curves were also used by draftsmen to produce flowing line. Computer programs use controllable Bézier curves. Three dimensional curvilinear forms are created in the computer using meshes of polygons” (Pipes, 2004).

### 2.3.2.2 Ellipse elements (a key shape of the tennis racket head)

- Source of shape

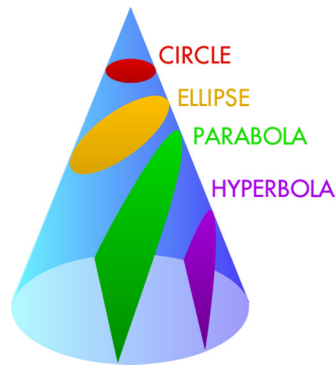


Figure 4: Shapes from conic sections (Mathigon, 2016)

There are four types of shapes that can be created by cutting through a cone at different angles, starting at parallel to the base of the cone, and then by increasing the angle of the cut, an ellipse, parabola, or hyperbola is produced. (Mathigon, 2016)

- Relevant Terminology in an ellipse

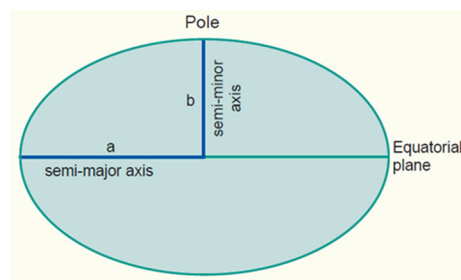


Figure 5: 'a' is the length of the Semi-major Axis, and 'b' is the length of the Semi-minor Axis (International Institute for Geo-Information Science and Earth Observation (ITC), 2009)

A Major Axis is “the longest diameter. It goes from one side of the ellipse, through the center, to the other side, at the widest part of the ellipse”. A Minor Axis is the shorter diameter. (Maths Is Fun, 2015)

In Figure 5, 'a' is the length of the Semi-Major Axis (“half its extent along the longer of the two principal axis” (Wolfram Research, Inc., 2016), and 'b' is the length of the Semi-Minor Axis (“half its extent along the shorter of the two principal axis” (Wolfram Research, Inc., 2016)).



- Equation similarities and differences between a circle and ellipse:

Circle:

$$(x^2 - x_0) + (y^2 - y_0) = a^2 \text{ (Wolfram Research, Inc., 2015) ,}$$

can be reduced to

$$x^2 + y^2 = a^2, \text{ if the circle's centre is at (0,0).}$$

Ellipse:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1, \text{ if the ellipse's centre is at (0,0) (Wolfram Research, Inc., 2015).}$$

- Getting a different perspective on ellipses, using mathematical parametrical representation:

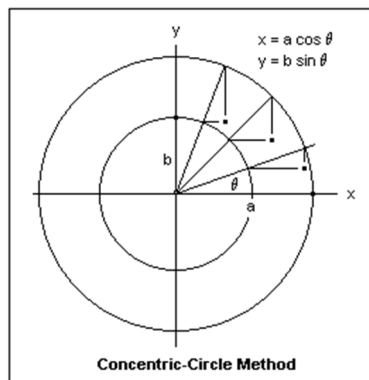


Figure 6: Parametric equation for the ellipse, using the Concentric-Circle Method. (Calvert, 2005)

Parametric equations are “a set of equations that express a set of quantities as explicit functions of a number of independent variables, known as "parameters." ” (Wolfram Research, Inc., 2016)

As can be seen in Figure 6, the parametric form of the curve can be given as:

$$x = a \cos \theta$$

$$y = b \sin \theta$$

- Area of an ellipse

With reference to the semi-axes a and b of Figure 5,  $A_{ellipse}$  , the area of an ellipse is calculated as:

$$A_{ellipse} = \pi ab \text{ (Wolfram Research, Inc., 2015).}$$

The area of a circle,  $A_{circle} = \pi b^2$  (Wolfram Research, Inc., 2016), can be broken down into  $A_{circle} = \pi \cdot b \cdot b$  , indicating that if the ellipse (can also be considered a stretched or squashed circle) has been modified by a scale of a  $\frac{a}{b}$  (such that  $0 < b < a$  ), then

$$A_{ellipse} = \pi \cdot b^2 \cdot \frac{a}{b},$$

resulting in

$$A_{ellipse} = \pi ab .$$

### 2.3.2 History of Tennis Racket Production

The International Tennis Federation provides the history (International Tennis Federation, 2016):

Wood was used from the 1870s to the early 1980s: Rackets were made from ash wood originally due to its strength and malleability properties, made of layers of veneers, glued together with urea-formaldehyde, before metal and composites become more available and widely used.

Metal, such as aluminium-alloys and carbon-steel, was used for making frames from 1950s to 1980s.

Composite frames have been used since the 1970s, using glass fibre, and carbon fibre due its greater strength and stiffness over steel, mainly from laminates of resin pre-impregnated carbon fibre sheets.

Carbon-reinforced thermoplastic injection-moulded rackets (seen further below in Figure 8 with a cross-section cut away view), made by Dunlop, a racket manufacturer, were successfully used in the 1980s, including having been played with at Wimbledon, but came to an end when Dunlop could not compete with the composite frames strength and production costs found in Asia.

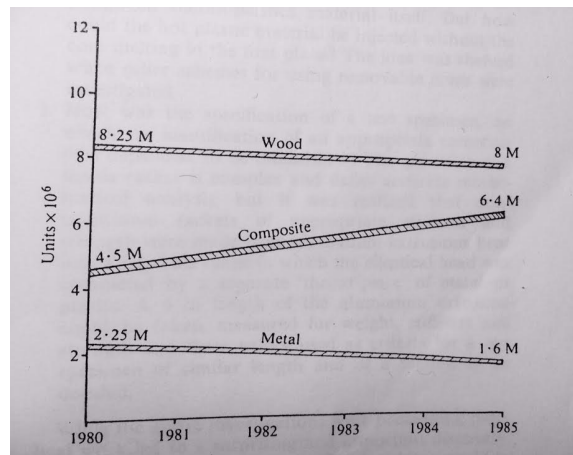


Figure 7: World market: tennis racket types 1980-85 (Haines, et al., 1983)

Looking back, with Figure 7 in mind, with that of racket production in the early 1980s, the graph indicates that the emerging technology / production method of using composite materials was on its way to overtaking the then-current production materials of wood and metal. (Haines, et al., 1983)

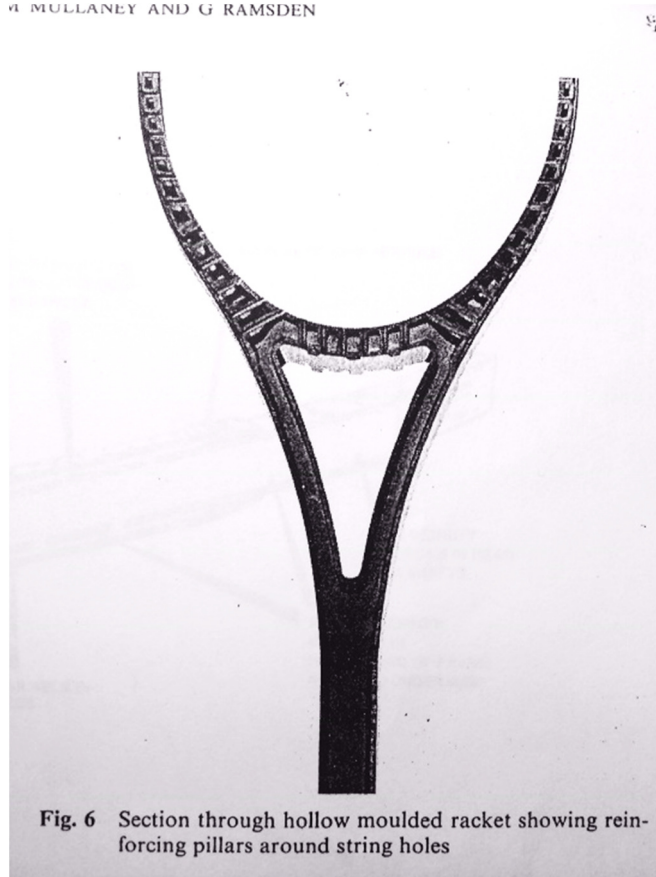


Figure 8: A cut-away section of the 1980s-manufactured racket (Haines, et al., 1983)

To present day, why tennis rackets are made of carbon composites:

Rackets can have a “40% larger head, be 3 times stiffer and 30% lighter than the most highly developed wooden version” (International Tennis Federation, 2016).

### 2.3.3 The Current Production Method

The current production process-chain of a racket is (International Tennis Federation, 2016):

1. Pre-preg



Figure 9: sheets are cut to size and shape for hand lay-up (International Tennis Federation, 2016)

## 2. Mould



*Figure 10: The mould is closed and heated at 150°C for several minutes while the plastic tube is inflated to provide moulding pressure until the resin is cured. (International Tennis Federation, 2016)*

## 3. Drill holes



*Figure 11: Drilling string holes into the raw frame (International Tennis Federation, 2016)*

## 4. Cosmetics



*Figure 12: The frames are then painted with the base colours and graphics (“decals”) are transferred onto the racket (International Tennis Federation, 2016)*

## 5. Fit butt



Figure 13: The butt cap is stapled to the end of the handle, prior to the grip being fitted. A grommet strip and individual grommets are added and the frame is strung to complete the racket. (International Tennis Federation, 2016)

## 2.4 3D Printing / Additive Manufacturing Overview

### 2.4.1 What is the basic concept of 3D Printing?

3D Printing / Additive Manufacturing is a method to produce a physical object, layer by layer, of varying materials ranging from plastics, such as ABS, PLA, and Nylon, to metals like Aluminium, Steel, and Gold, which has been originally designed with 3D modelling / surfacing / CAD (Computer Aided Design) software, or combined and refined with 3D scanning, or other software with recognizable 3D modelling export/import functions, and then 'sliced' in preparation for physical production, and saved as an .STL file, a generally recognizable file format for 3D printers, as can be seen by flow of activity in Figure 14.

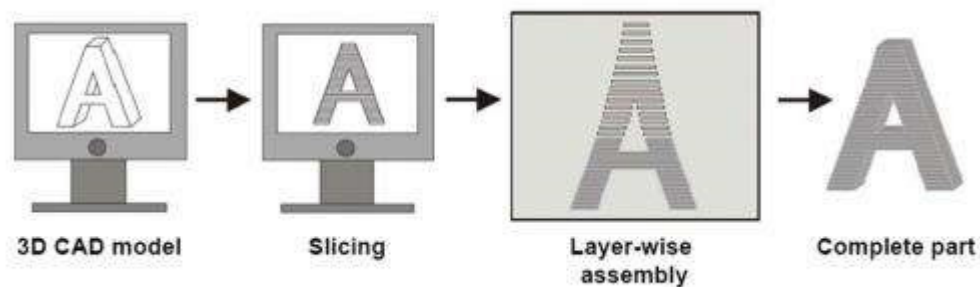


Figure 14: The Additive manufacturing Process (Phys.org, 2014)

### 2.4.2 What is the basic technological process of 3D Printing?

The word 'additive' refers to the process by which an object is built, layer by layer, usually with heat. In contrast, reductive/subtractive manufacturing refers to the process of removing sections through cutting from, grinding away at, or milling away from, a block of material.

The layers, ranging between 0.06mm to 0.4mm thick, are laid down, one by one, until the required height is achieved. The time to produce as well as the quality of an object depends on the layer thickness determined prior to production, as well as the structure, volume, density, of the object, material chosen, as well as type of 3D printing machine/method. 'Support' material (for overhangs or unsupportable angles) may be used, depending on the machine type.

### 2.4.3 History of 3D printing

In 1981, news was published that Hideo Kodama of Nagoya Municipal Industrial Research Institute had created a “functional rapid prototyping system using photopolymers” (Autodesk, 2014). In 1984, Charles Hull invented stereolithography. In 1992, the world’s first stereolithographic apparatus (SLA) machine was produced, while DTM, a company, produced the world’s first selective laser sintering (SLS) machine.

Between 1999 and 2010, organs were started to be 3D-printed, while parts of 3D printers could produce parts for their own machines, accessibility of 3d printing opened up to a larger part of society, and then 3D printers could print with different materials in the same models. (Autodesk, 2014)

From 2011 to present day, companies like Shapeways, a 3DP service-providing company, currently offers “from Metals to Porcelain, Plastics to Sandstone, and everything in-between” (Shapeways, Inc., 2016), referring to metals like silver, gold, aluminium, ceramics, plastics such as PLA, PA2200, ABS, highlighting the range of machine and material manufacturers available to choose from for wide application.

Newer 3DP manufacturers are exposing their developments on the web, relating to composite materials, like Kevlar and Carbon Fibre, such as: Markforged has claimed to have created “the world’s first and only desktop carbon printer” (Markforged, 2016); Impossible Objects has claimed to have developed and is refining “the first composite-based additive manufacturing method (CBAM) using fabrics of Carbon Fiber, Kevlar, Fiberglass” (Impossible Objects, 2016); while Continuous Composites has claimed to have “in August 2012 laid the foundation for 3D printing technology which utilizes a method we call, Continuous Composite Three Dimensional printing” (Continuous Composites, 2016).

### 2.4.4 Types of 3D printing

There are a few types and technologies of 3D printing methods (3D Printing from Scratch, 2016):

- Light Polymerization: Stereolithography (SLA);  
Digital Light Processing (DLP);
- Extrusion: Fused Deposition Modelling (FDM);
- Powder Bed: Selective Laser Sintering (SLS);  
Selective laser melting (SLM);  
Electronic Beam Melting (EBM);
- Lamination: Laminated Object manufacturing (LOM).

## 2.5 Choosing Powder Bed-type, Selective Laser Sintering (SLS):

### 2.5.1 How SLS works

Sintering is a many millennia old process for producing objects made from powders, using atomic diffusion, to create jewellery, porcelain, and bricks (Live Science, 2013). Sintering, by definition,

is to “make (a powdered material) coalesce into a solid or porous mass by heating it (and usually also compressing it) without liquefaction” (Oxford University Press, 2016)

During SLS, fine-powdered plastic, about 40 microns, or then that of ceramic or glass, for example, is fused together, by a laser, creating a solid object.

It was in the 1980s when Carl Deckard and his colleague from the University of Texas developed and then patented the SLS process (Live Science, 2013).

In the schematic of Figure 15 below, the SLS process is described:

1. A laser is fired down at a cross-section of the model at the specific layer, first creating an outline, and then filling it in, fusing the powder together to make a solid form, at sintering temperature (just below melting point).
2. When the layer is complete, about 0.1 mm is moved down, so that a new layer of powder can be spread over the surface (by an arm or roller), for the previous step to take place.
3. Step 1 and 2 are repeated until the model, object or ‘job’ has been completed.
4. The object is left to cool, and then the tray is removed from machine.
5. Post-production processing and cleaning can include pearl blasting and air blasting to remove excess powder, while polishing and colour dyeing, can be performed to improve aesthetics.

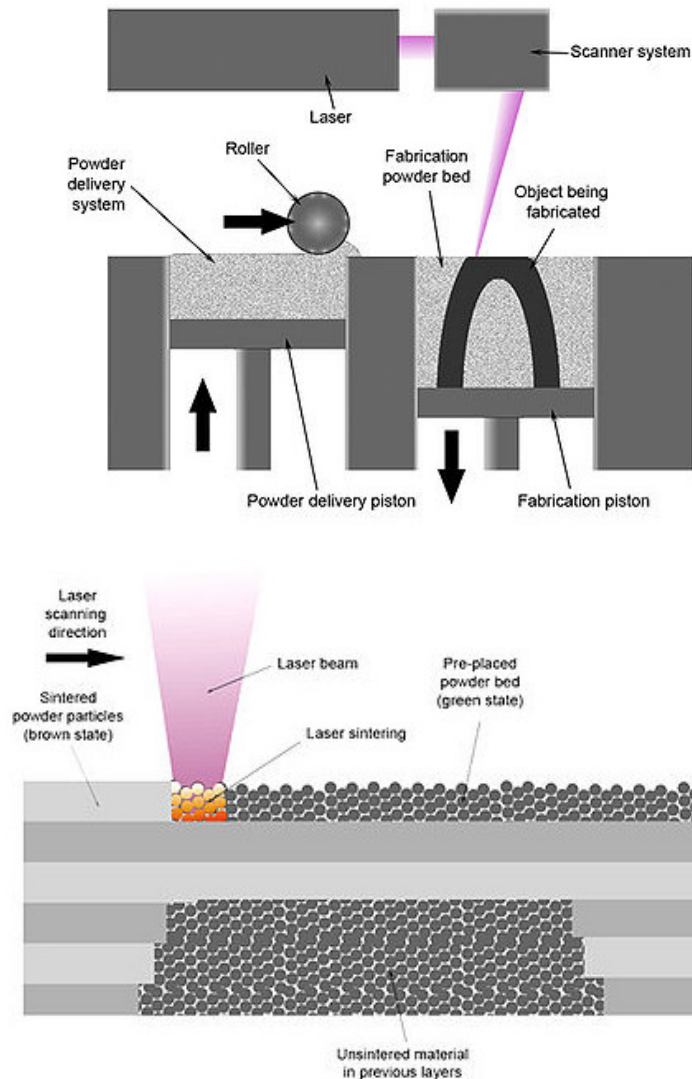


Figure 15: A schematic showing the Selective Laser Sintering system (Live Science, 2013)



Figure 16 below gives a general overview of the design to finished, 3D-printed product process.

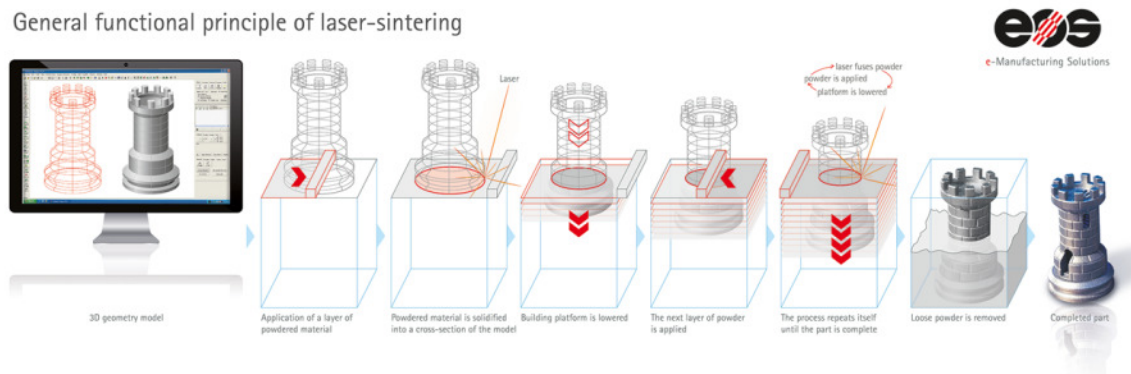


Figure 16: General Functional Principle of Laser-Sintering (in Steps) (EOS GmbH, 2016)

### 2.5.2 SLS Machine – EOSINT P760



Figure 17: EOSINT P 760 (EOS GmbH, n.d.)

Table 1: Basic EOSINT P760 Technical Data (EOS GmbH, 2014)

<b>EOSINT P 760 Technical Data</b>	
Effective building volume	700 mm x 380 mm x 580 mm
Building speed (material-dependent)	up to 32 mm/h
Layer thickness (material-dependent)	0.06 mm - 0.10 mm - 0.12 mm - 0.15 mm - 0.18 mm
Laser type	CO <sub>2</sub> , 2 x 50 W
Precision optics	F-theta-lens
<b>Dimensions (W x D x H)</b>	
System incl. switching cabinet	2,250 mm x 1,155 mm x 2,100 mm
Control terminal	1,045 mm x 850 mm x 1,620 mm
Powder conveying system	1,890 mm x 1,350 mm x 1,550 mm
Unpacking station	1,600 mm x 800 mm x 1,370 mm
Recommended installation space	4.8 m x 4.8 m x 3.0 m
Weight	approx. 2 300 kg



The EOSINT P760 was chosen because the Effective Building Volume was closest to that of a tennis racket, while the machine was accessible through a service, as Arcada University of Applied Sciences does not own one.

### 2.5.3 Material for sintering – PA 2200

PA2200 Material Overview (EOS GmbH, 2016):

“This whitish fine powder PA 2200 on the basis of polyamide 12 serves with its very well-balanced property profile a wide variety of applications. Laser-sintered parts made from PA 2200 possess excellent material properties:

- high strength and stiffness
- good chemical resistance
- excellent long-term constant behaviour
- high selectivity and detail resolution
- various finishing possibilities (e.g. metallisation, stove enamelling, vibratory grinding, tub colouring, bonding, powder coating, flocking)
- biocompatible according to EN ISO 10993-1 and USP/level VI/121 °C

Typical applications of the material are fully functional plastic parts of highest quality. Due to the excellent mechanical properties the material is often used to substitute typical injection moulding plastics. The biocompatibility allows its use e.g. for prostheses, the high abrasion resistance allows e.g. the realisation of movable part connections.”

Table 2: PA2200 – Basic Properties

PA2200 Properties	Value	Unit	Test Standard
Tensile Modulus	1700	MPa	ISO 527-1/-2
Tensile Strength	48	MPa	ISO 527-1/-2
Strain at break	24	%	ISO 527-1/-2
Flexural modulus (23°C)	1500	MPa	ISO 178
Flexural Strength	58	MPa	ISO 178
Melting temperature (20°C/min)	172-180	°C	ISO 11357-1/-3
Density (laser sintered)	930	Kg / m <sup>3</sup>	EOS Method
Average Grain size	56	µm	ISO 13320-11
Ball indentation hardness	78	N / mm <sup>2</sup>	ISO 2039

### 2.5.4 Accessibility and Restrictions

Shapeways, Inc. is a 3D printing services company, possessing an EOSINT P760 at one of its production centres, based in Eindhoven, The Netherlands, geared towards large objects.

When the author worked there in 2012 and discovered the size of that machine, it was the moment of questioning the possibility of 3D printing a tennis racket.

Due to the company’s decision, the maximum production dimension was constrained to 650 mm x 350 mm x 550 mm (Shapeways, Inc., 2015), and the only material available to print for the machine was/is Nylon PA 2200.

## **2.6 Solid Modelling (SM):**

### **2.6.1 SM, Defined**

Solid modelling is a form of computer-aided design for creating, shaping, moving, and manipulating lines, profiles, surfaces, vertices, edges, bodies, and other geometric shapes, with a digital toolset in a computer graphic-based spatial environment, with references to scales, dimensions, material types, and mathematical formulae, to create a graphical representation of a desired, real-world, and producible physical object or part (either stand alone, or for assembly purposes), while being able to add comments or instructions about the part, and animation, for better contextual understanding and feedback when demonstrating.

### **2.6.2 Two Methods of SM**

The two most known methods of SM are Constructive Solid Geometry (CSG) and Boundary Representation (Brep):

CSG uses primitive forms such as prisms, spheres, cylinders, cones, while Boolean operations such as unions, subtractions, and intersections, define the output of the overlapping forms.

Brep methods are based on wireframe profiles, either made of straight lines, curves, or splines. From there, the profile can be extruded, swept, revolved, lofted, or skinned, affecting the model's form. Boolean operations can be used on profiles, and solids can be generated from these profiles. Sewing operations allow for surfaces to be combined, making more intricate shapes.

As each method has its own strengths and weaknesses on their own, most makers of solid modelling software have performed a Boolean operation on these two methods to combine them, to get the best from each method, to enhance the experience of solid modelling for designers and makers. (Marr, 1996)

### **2.6.3 CAD Applications**

Many applications are available, as open-source or commercially. Dassault Systèmes Solidworks 2015 is widely used, which the author had access to.

### 3. Method

The results are a summation of the methods applied from collected information. This is how the results were obtained:

#### 3.1 Prior to racket design

- Through work experience as a Production Planner in 2012 for three months, seen in Figure 18, learning about design rules set by the company to ensure that customers' printed objects were successful:



*Figure 18: From Top Left, Clockwise: Production Planning; cleaning after printing; pearl Blasting to Remove Excess Powder; Air-Blasting cleaning (Julian Kollataj, 2012)*

- Through university courses understanding aspects of strength of materials;
- Learning about the EOSINT P760 machine's production dimensions, the material it uses, as well as reading through design guidelines on EOS's documents;
- Reading articles and literature found on the Internet to understand how 3D printing works, the different types, and the basic premise of how SLS works, and the Internet using search engine notifications relating to 3d printing advancements;
- Understanding a standard tennis racket's dimension range, set by the International Tennis Federation, by reading information on their website;
- Understanding the history of tennis racket production through the International Tennis Federation (ITF) website;
- Traveling to interview the ITF Technical Manager in London, receiving documentation of Dunlop's past efforts to produce carbon-reinforced plastic-molded tennis racket, as well as transcribing relevant parts of the interview (see 8.1 in the Appendix). These are images of the interview:



*Figure 19: Interviewing ITF Technical Manager James Capel-Davies (Julian Kollataj, 2015)*



*Figure 20: Dunlop Injection-moulded racket (Julian Kollataj, 2015)*



*Figure 21: Receiving and inspecting document of 1980s Dunlop racket (Julian Kollataj, 2015)*

- Taking measurements from the author's own tennis racket, and of other rackets;
- Understanding primitive shapes and the ellipse's characteristics through specific Internet pages, documents, and online books;

## 3.2 Designing the rackets – applications / software / services used

1. In Microsoft Excel (Appendices contains data):

Calculations were made of lengths of throat and handle, depending on input measurements for iteration purposes, and on wanted racket face area; calculations of conversion for max and min dimensions – inches to millimeters; string pattern values and calculation

2. Designing the multi-part racket in Dassault Systèmes' Solidworks 2015/16 (the feature trees, dimensions, and calculations can be found in the Appendices):

1. Basic Assembly Design

- i. Main racket frame (“FTIH”)
  1. The Head;
  2. The Throat;
  3. The Shaft;
  4. The Outer grip, to get the Inner Handle/Grip shape
  5. Split Inner Handle/Grip into separate part and file
- ii. The Outer grip(s)
- iii. Bumperguards, then ‘split’ them into two parts
- iv. Side Grommets
- v. Bridge Grommets (split into two parts)
- vi. Saved each part in .SLDPRT format.
- vii. Created assembly file .SLDASM, added all parts, and “mirrored” the non-frame components to complete the assembly.
- viii. Created .STL export file in preparation for file upload to the server of the production service provider, Shapeways, for each .SLDPRT file.

2. “Hexa” Assembly Design

- i. Created the “Basic” negative plate
- ii. Main racket frame (“Hexa FTIH”)
  1. Started with the head;
  2. Then the Throat
  3. The shaft;
- iii. Combined negative plate and Hexa frame, using the plate to remove material from the ‘raw’ Hexa frame
- iv. Imported the Basic Inner Grip/Handle
- v. Combined the parts to create the final Hexa frame
- vi. Save file as .SLDPRT part, then export as .STL file for 3D printing
- vii. Replace Basic frame in Assembly with Hexa frame and create a new assembly file

3. Iso Omena Library

Some initial model designs were printed using Iso Omena Library's 3D printers (Ultimaker) to test part concepts such as the Outer Grip, Handle, and Throat of the ‘Basic’ model



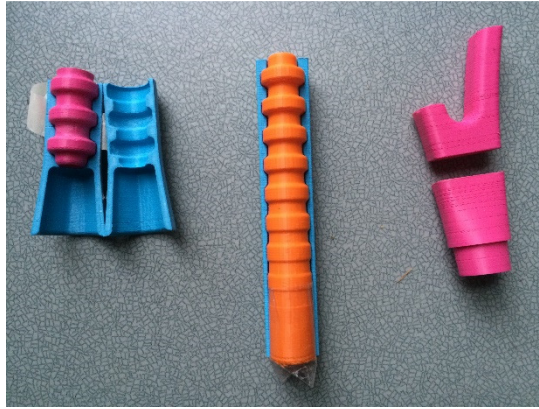


Figure 22: PLA 3D prints of some initial designs, made at Iso Omena's Library, using their Ultimaker 2 (and 2 Extended) printers (Photo: Julian Kollataj)

4. Youtube.com (supporting learning / understanding of software)  
Used to get freely available tutorials on how to use SolidWorks (unfamiliar / not-yet-learned skills)

### 3.3 Summary of Racket Assembly

#### 1. Basic Frame

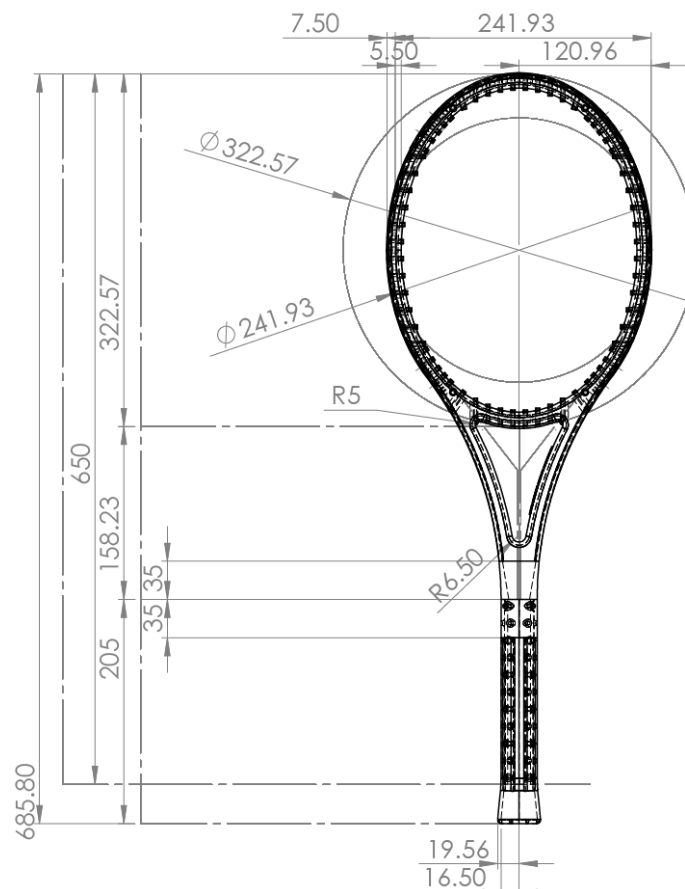


Figure 23: Basic racket dimensions, Top View, using SolidWorks 2015 (Julian Kollataj, 2016)

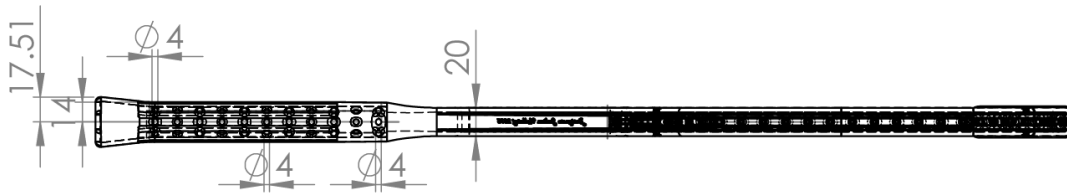


Figure 24: Basic racket dimensions, Right View, using SolidWorks 2015 (Julian Kollataj, 2016)

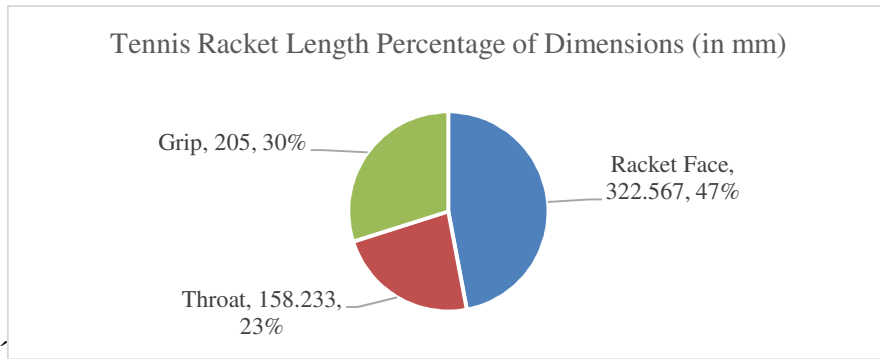


Figure 25: Percentage of sections of a tennis Racket (Julian Kollataj, 2015)

### 3.3.1 Total Racket Length without bumper parts

Standard length of 685.8 mm (27 inches) for the ATP (Association of Tennis Professionals) and WTA (Women’s Tennis Association)



Figure 26: Author’s tennis racket, as a reference for design (Julian Kollataj, 2015)

### 3.3.2 Racket head size (See Appendices - Excel for calculations)

- b (semi-major axis) of 161.284 mm (Outside wall) (322.57 mm tall)
- a (semi-minor axis) of 120.963 mm (Outside wall) (241.93 mm wide)
- Area<sub>Ellipse</sub> = 95 square inches (61290.20 mm<sup>2</sup>) (based on Julian Kollataj’s Yonex RQiS95)
- Length-to-width ratio of ellipse =  $k = \frac{a}{b} = 0.75$

### 3.3.3 Grip Length

$L_{\text{Grip}} = 205 \text{ mm}$ , based on measure grip length of Yonex RQiS95

### 3.3.4 Throat Length (base of Racket head or Ellipse to top of Grip)

$$\begin{aligned} L_{\text{Throat}} &= L_{\text{Total}} - L_{\text{Major Axis}} - L_{\text{Grip}} \\ &= 685.8 \text{ mm} - 322.57 \text{ mm} - 205 \text{ mm} \\ &= 158.233 \text{ mm} \end{aligned}$$

### 3.3.5 Holes for strings

4 mm diameter for the standard holes was measured on currently available rackets, while 5 mm by 4 mm ellipse holes were made for knotting of strings.

1 mm thickness for the grommets was measured.

Average tennis racket strings diameter, on the market, range between 1.1 mm and 1.3 mm.

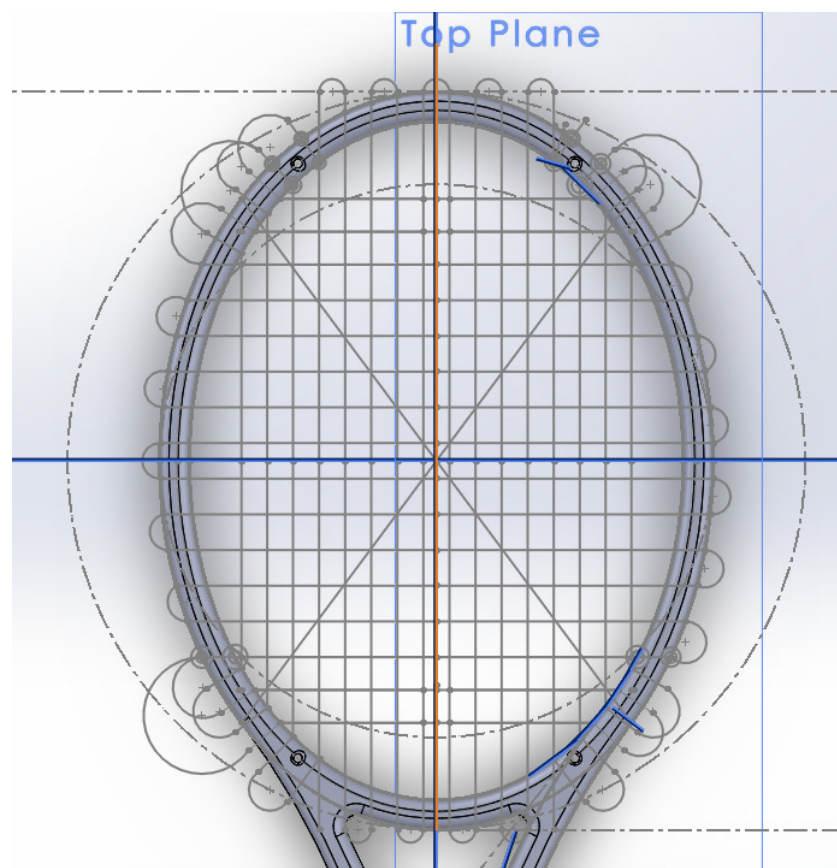


Figure 27: Racket Head with Sketch of string pattern (Top view) (Julian Kollataj)



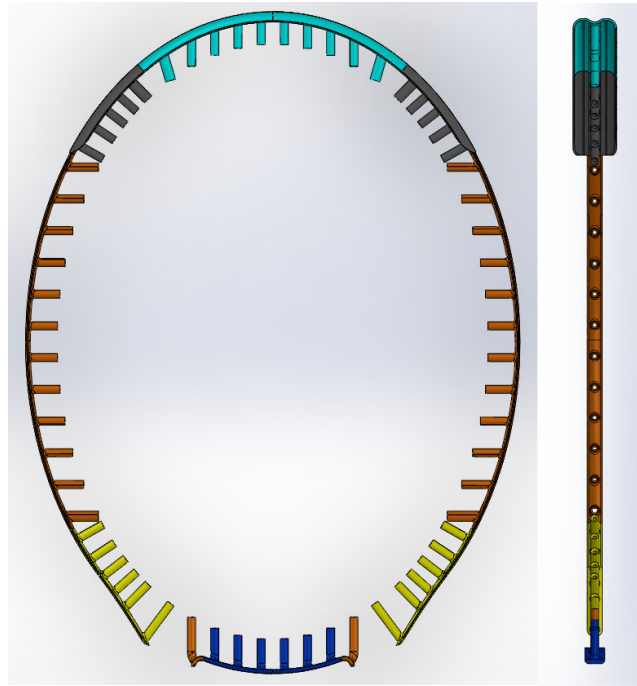


Figure 28: Top and side view of bumperguard, side and bottom grommets (Julian Kollataj, 2015)

### 3.3.6 String pattern of racket

Measurements and calculations in Appendices.

### 3.3.7 3-Dimensional values to consider for racket (Wall thicknesses / heights)

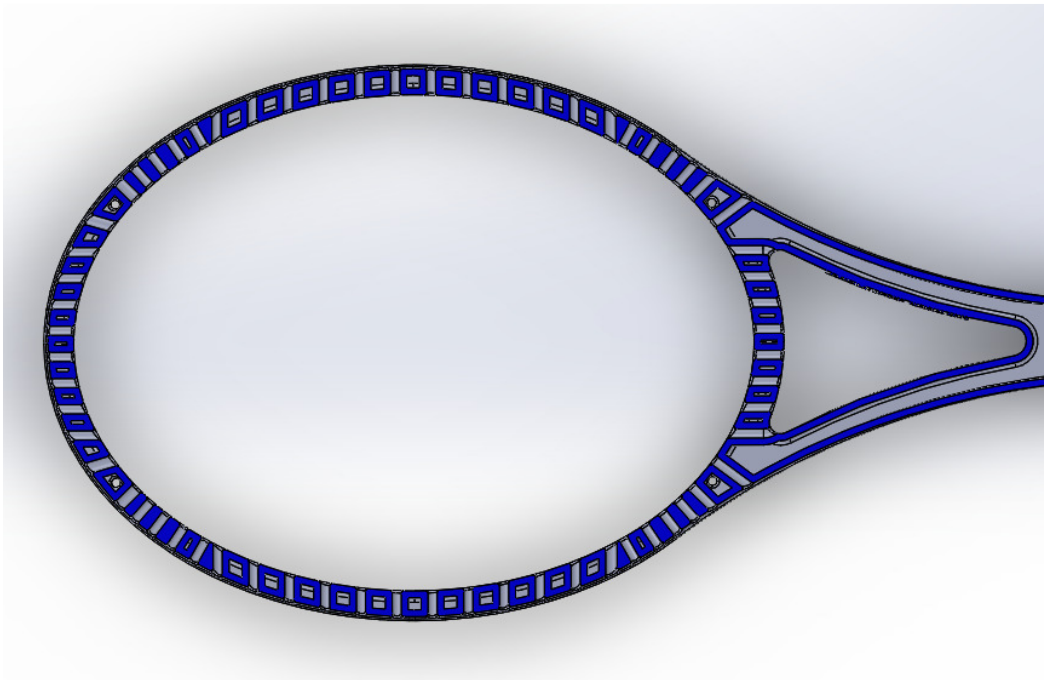


Figure 29: Cross-section view of racket head and throat, Top View, highlighting wall thicknesses of 3mm (SolidWorks file) (Julian Kollataj, 2015)

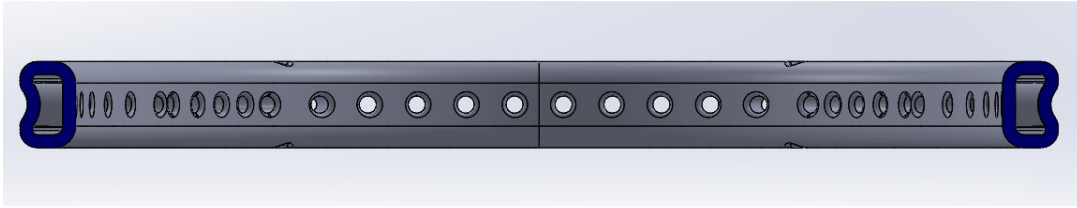


Figure 30: Cross-section view from butt-end, at middle of tennis racket head, highlighting wall thickness of 3mm, and total height of 20mm (Julian Kollataj, 2015)

### 3.3.7.1 Height (depth) of racket

#### Racket Head and Throat

A height of 10 mm was decided, in both directions, therefore totalling a thickness of 20 mm, after having considered the current average heights of rackets on the market.

#### Grip

Maximum thickness at butt-cap: 36 mm (from Yonex RQiS95)

Maximum width at butt-cap: 40 mm (from Yonex RQiS95)

### 3.3.7.2 Wall thickness about the Head and Throat

1 mm, 2 mm, and 3 mm were considered, however 3 mm was decided on, considering what the software (SolidWorks) allowed for, providing warning errors, as well as recommended thicknesses from Shapeways' website (Shapeways, Inc., 2016)

#### Thickness between Inner Handle and Throat

The thickness for the intersection of grip and throat, to also accommodate for profile change, meant that the wall thickness varied between 3 mm and 6 mm.

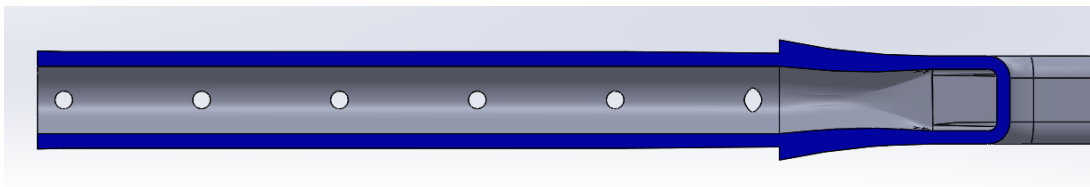


Figure 31: Cross-section view of inner handle and throat intersection, variable thickness of 3 to 6mm (Julian Kollataj, 2015)

### 3.3.7.4 Thickness between Outer Grip and Throat

The thickness for the intersection of grip and throat, to also accommodate for profile change, meant that the wall thickness varied between 3 mm and 6 mm.

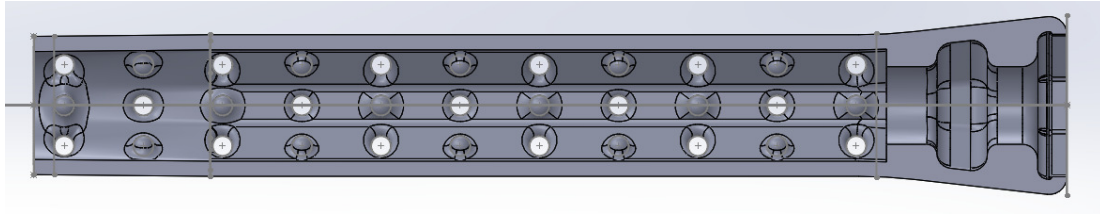


Figure 32: Cross-section view of 205mm long outer grip, variable thickness of 3 to 6mm (Julian Kollataj, 2015)

### 3.3.8 The Final Assembly

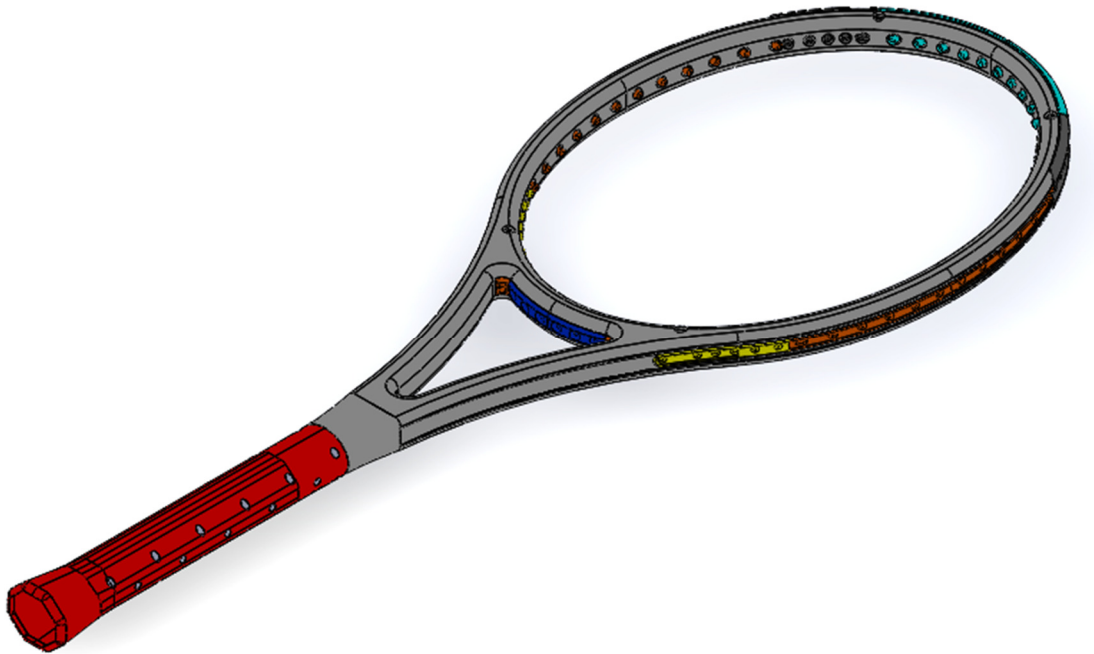


Figure 33: Isometric view of Basic Racket Assembly (Colours for distinguishing parts) (Julian Kollataj, 2015)

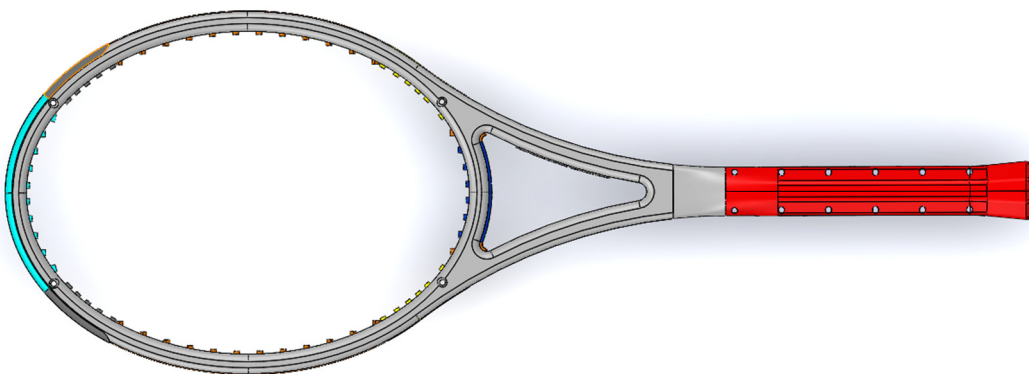


Figure 34: Top view: The final assembly of 13 parts (colours for distinguishing parts) (Julian Kollataj, 2015)

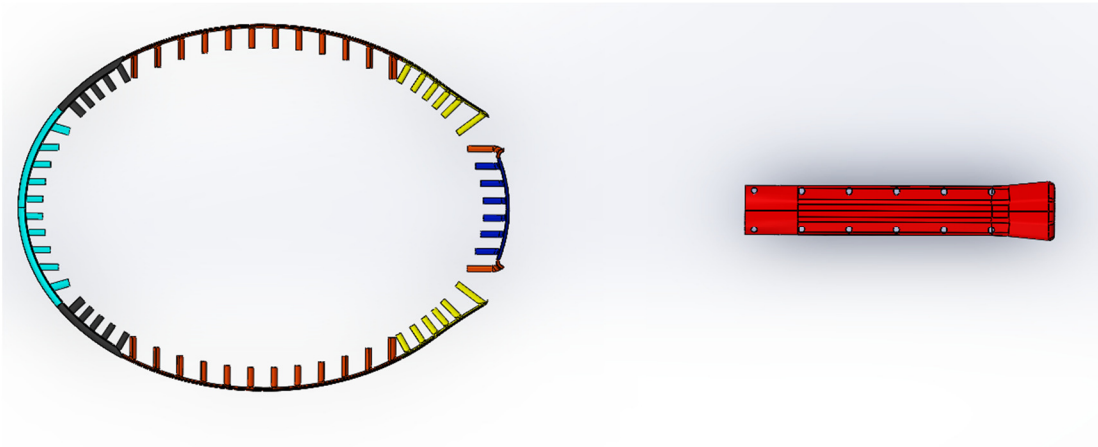


Figure 35: Top view: the final assembly, excluding main part (colours only used to distinguish parts – not actual)  
(Julian Kollataj, 2015)

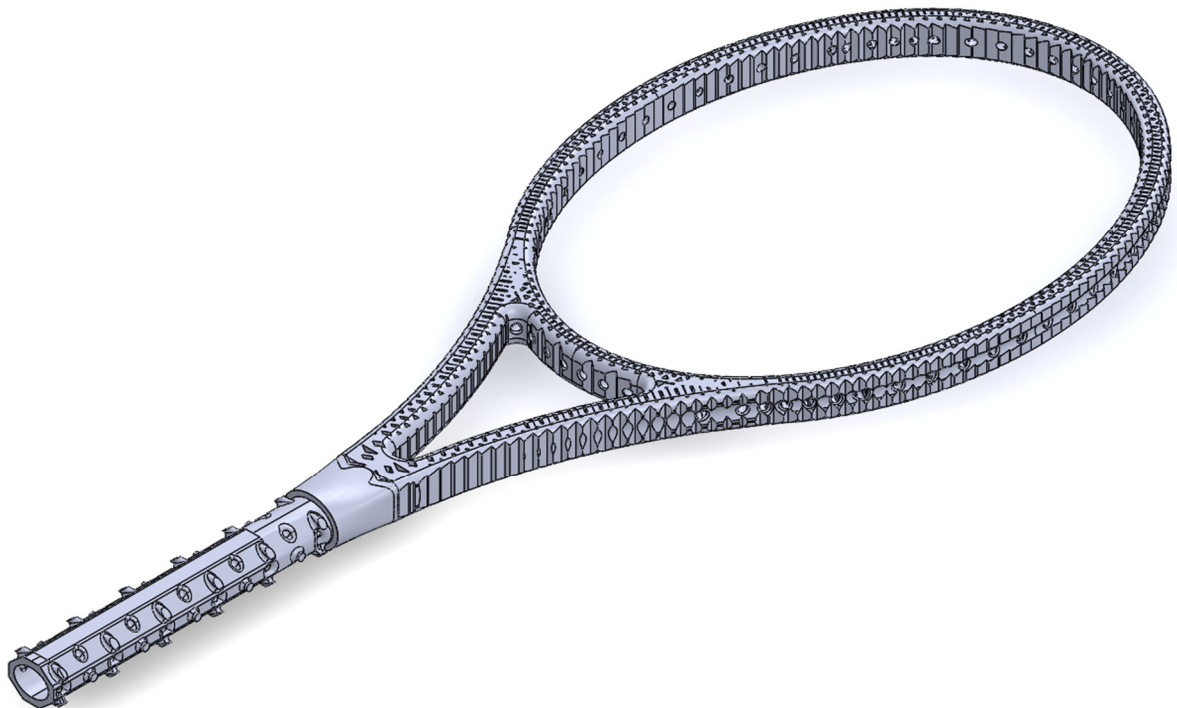
Design note:

In closed objects, “Exit Holes” for non-sintered post-printed powder are required for the powder to be removed when models are cleaned up. In the tennis racket, holes, from the front of the racket through to the back of the racket, were created in this “Basic” model, at positions of 11 and 1, and 5 and 7, o’clock, if the racket is seen upright.

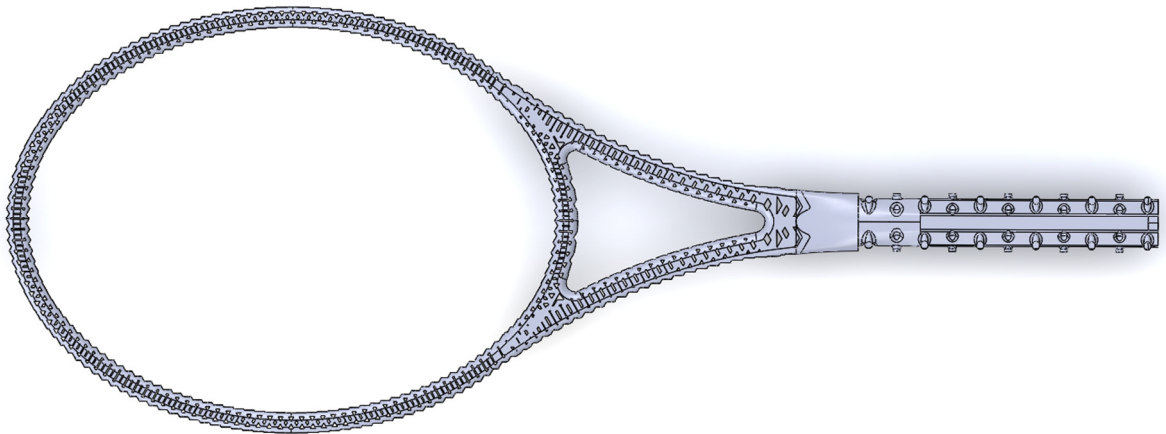
## 2. Hexagon – Model name “Hexa”

Hexagons of 13 mm in diameter, with a walling of 2.25 mm, were placed over-lapping each other, on the racket face curve/ellipse, while along the throat, the diameters and thickness were gradually increased to fit the maximum surface boundaries of the “Basic” model.

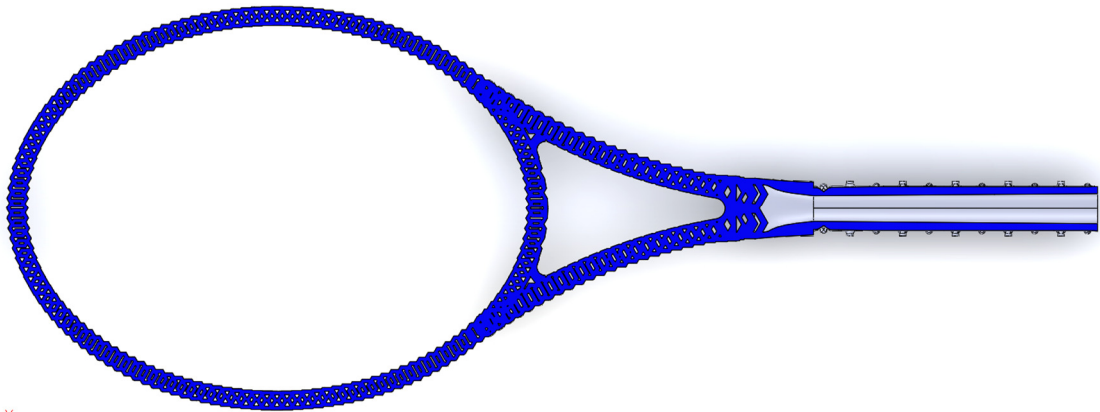
Isometric view



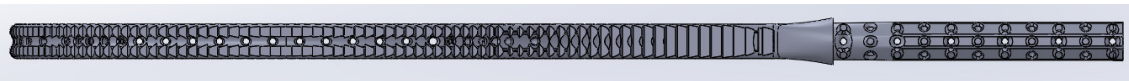
Top view – Overview



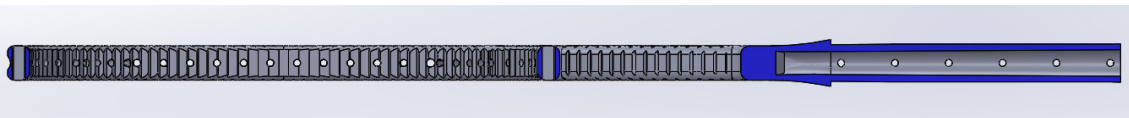
Top View – Cross-section



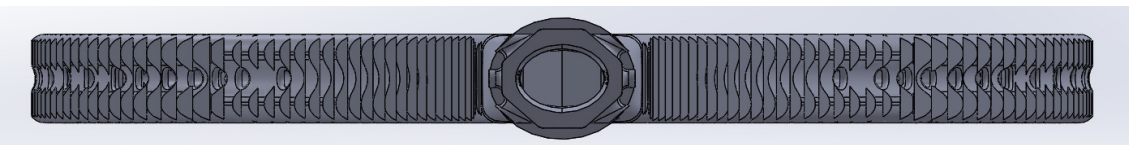
Side view – Overview



Side view – Cross-section



Rear view – Overview



### **3.3 Ordering the printing of the rackets and parts**

1. All relevant files were uploaded to the Shapeways.com website.
2. Quantities were selected.
3. Payment was made to initiate production.
4. A couple weeks later, the parts had been produced and shipped.

### **3.4 Receiving the printing of the rackets and parts**

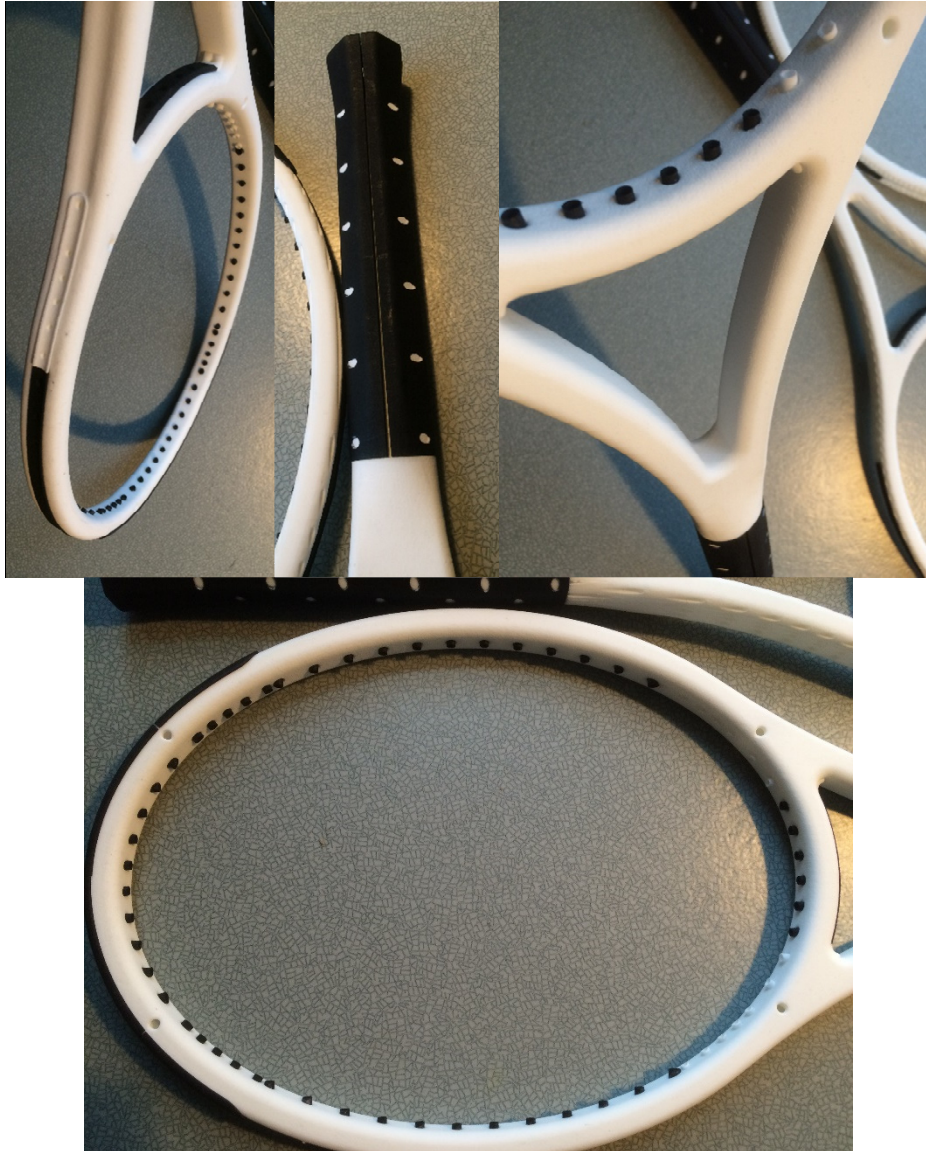
5. The rackets were received.

The next section will focus on the results of the produced parts.



## 4. Results

### 4.1 Basic racket model



*Figure 36: Images of the “Basic” model with grommets, bumpers grip parts, SLS 3D printed models from Shapeways (Photos: Julian Kollataj, 2015)*

### 4.2 Hexa Racket model

Two (2) prints of this model were made, because the first model was of poor quality, while, once this poor quality had been reported to Shapeways with evidence through photos, a re-print was done, and delivered within one week.

#### 4.2.1 Poorly-printed model

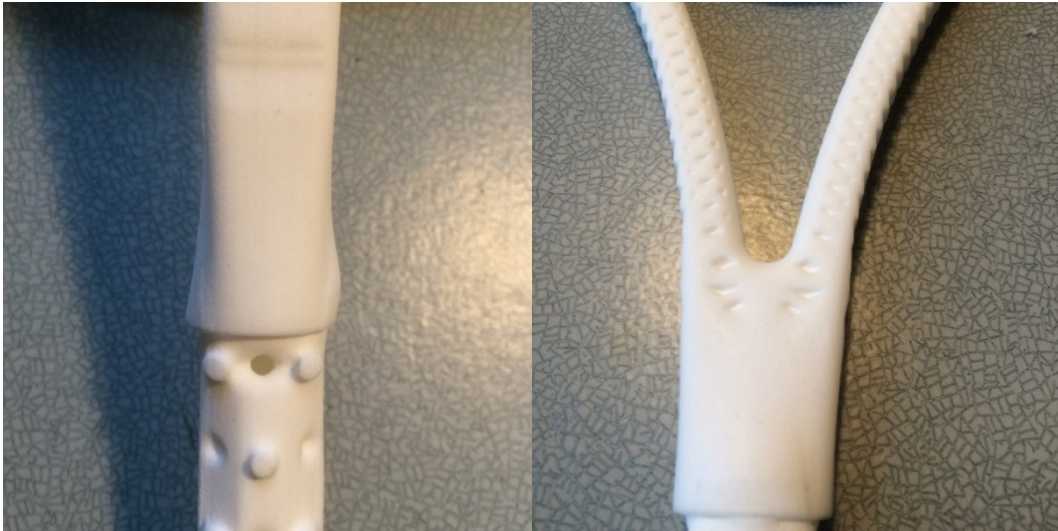


Figure 37: Images of the poorly printed “Hexa” model, SLS 3D printed at Shapeways (Photos: Julian Kollataj, 2016): Left image – non-symmetrical region above handle area; Right image – left over, “stuck” powder

#### 4.2.2 Re-printed, high quality model

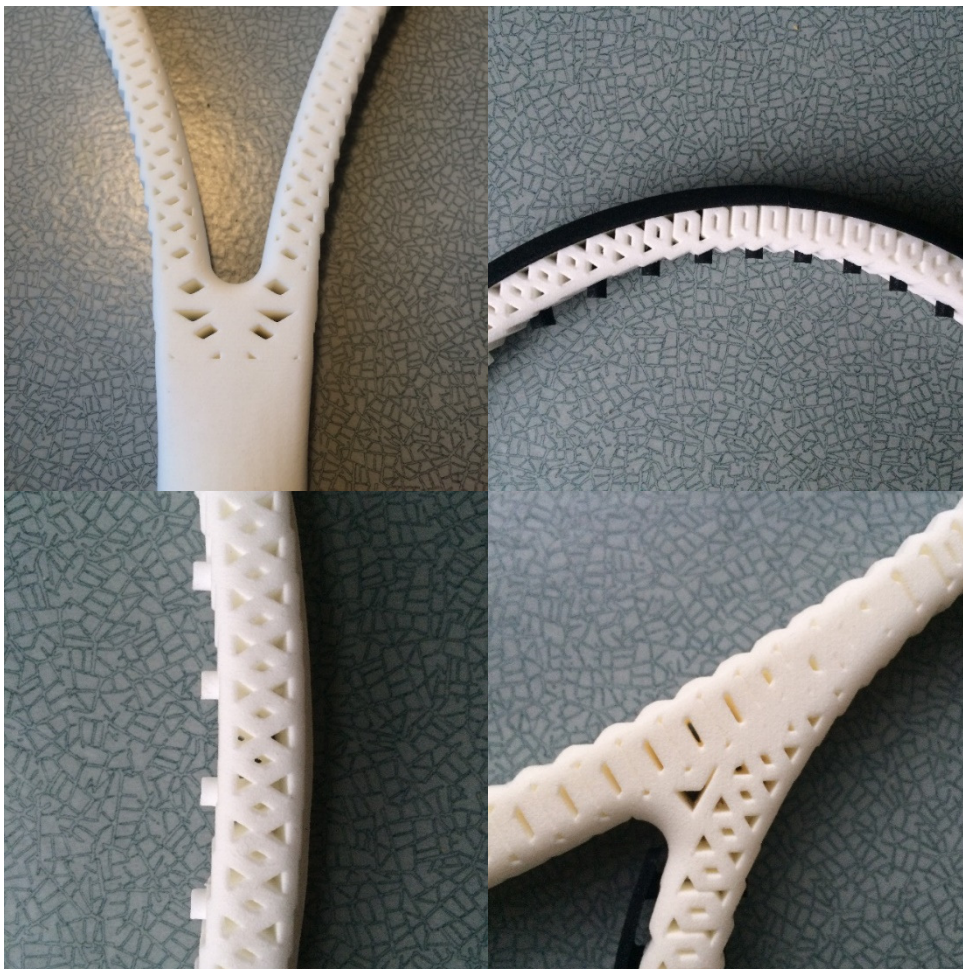


Figure 38: Images of the re-printed, high-quality printed “Hexa” model, SLS 3D printed at Shapeways (Photos: Julian Kollataj, 2016): Photos from top left, clock-wise: Throat-Handle, Racket tip, Head-Throat Intersection (shoulder), 9 o’clock on racket



#### 4.2.3 Comparison



*Figure 39: Images of comparing visible difference of re-printed, high-quality printed “Hexa” model on left, versus initially-received poor-quality “Hexa” model (photos: Julian Kollataj, 2016)*

In general:

The rackets were successfully produced. However, due to the machine’s production, tolerances of holes should be increased by between 0.5 mm and 1 mm larger, on the racket frame, as well as bumper, grommets, and grips.

To make sure the parts fit, Julian Kollataj went to Iso Omena’s Library Paja to use an electric drill set (Dremel), to manually enlarge the grommet holes, with a 4 mm drillbit, and remove extra excess powder.



*Figure 40: Manual adjustments with drill to fit parts (Julian Kollataj, 2016)*

## 5. Discussion

### 5.1 On the racket design and production results, and further investigation considerations

#### From the Basic model (tennis):

With only just picking up the 3D printed racket, feeling its weight and balance, or finding its centre of gravity, swinging with it (as if playing a tennis stroke, such as a forehand or backhand or serve motion):

- a. what would happen to the strength, rigidity/flexibility, torsion;
- b. weight;
- c. force, torque, and moment(s) of inertia,
- d. and feel (not an engineering measurement, but a necessary aspect of playability)

if:

1. the walling thickness were to be increased or decreased?
2. The racket head dimensions grew?

#### For the Hexa model:

What would happen to the strength, rigidity/flexibility, torsion, and weight, and force, torque, and moment(s) of inertia, if:

- a. The wall thickness were to increase/decrease?
- b. The “density”, or closeness, of hexagons, were to increase/decrease?

This would lead to further questions for both models such as:

- “Where are the stronger and weaker points in the racket? How could those weak points be strengthened without sacrificing weight / weight distribution of the racket?”
- “Then, in order to meet or satisfy current market requirements for the production of this Basic model, what
  - a. machinery and quality of 3D printing machinery (3DP) / additive manufacturing (AM),
  - b. and materials,

would be required, to ensure that the rackets are equally just as good as, or better than, current production methods, in order for manufacturers to migrate to and start using 3DP / AM as a mainstream production method?

### 5.2 Potential adoption of 3D Printing as a method of racket manufacturing

The three key variables of production economics are: cost of production activity; time to produce a specific number of units; and materials and equipment to produce the product. These variables need to be optimised to remain sustainable and profitable, while giving the company a competitive edge in the manufacturing industry. What impacts variable costs most is labour.

Up to now, tennis rackets have been produced successfully with lay-up production of composite materials due the strength-to-weight ratio factors, and are mostly made in the Far East (mainly China), due to the labour-intensive method (International Tennis Federation, 2016).

Consider the history of racket production between 1980 and 1990, when Dunlop made the decision to produce the injection-moulded, carbon-reinforced thermoplastic (CFRP) rackets, to remain competitive:

Prior to the 80s, in 1978, the Open Door Policy was setup when Deng Xiaoping let Western companies enter into China, to receive new technology and investments. (BBC, 2009)

In the 80s, composite rackets were made in the USA of carbon fibre, and Japan and Taiwan started producing rackets made of fibre glass and carbon fibre, in addition to wood and metal rackets. (Haines, et al., 1983)

At the same time, Dunlop's thermoplastic production method of CFRP stopped in the UK altogether, because they "could not be adapted to make the larger headed, lighter frames subsequently becoming available using conventional manufacturing techniques" (International Tennis Federation, 2016) – to adapt, Dunlop shifted production to Taiwan to produce carbon composite rackets.

From the 1990s onwards up until today, being able to use carbon composites in rackets meant that the heads could be made larger by 40%, rackets stiffer by 3 fold, and overall lighter by 30 percent, "than the most highly developed wooden version." (International Tennis Federation, 2016)

The current production steps (referring specific steps and images at section 2.3.3 The Current Production Method) involve the following four labour-intensive activities such as preparing the pre-preg lay-ups, setting the moulds, drilling holes in the frames, and setting butts to the rackets.

Currently, designing and producing a tennis racket with the current technologies is not feasible, just from a material performance perspective, as highlighted in Conclusion. However, there are signs that innovators are contributing towards the maturity of 3D Printing / Additive Manufacturing with carbon composites:

- Impossible Objects in the USA is "The first composite-based additive manufacturing method (CBAM) using fabrics of Carbon Fiber, Kevlar, Fiberglass" (Impossible Objects, 2016); while,
- MarkForged in the USA has produced the Mark One: "The Mark One combines the limitless potential of 3D printing with the high strength of carbon fiber. Its patent pending Composite Filament Fabrication™ (CFF™) process is the first ever to enable 3D printing of continuous carbon fiber. CFF parts are up to 20 times stiffer than ABS plastic, five times stronger, and have a higher strength to weight ratio than 6061-T6 aluminum" (Markforged, 2014)
- Continuous Composites uses "co-axial multi material nozzles" to combine "continuous fibers and rapidly cured proprietary formulated thermoset acrylates", "with the capabilities to reach cure speeds of 1200 inch [3048cm]/min including a greater throughput of material for an overall cubic volume output unrivaled by the traditional appliance approach of 3D printing" (Continuous Composites, 2016); and,
- A 3D printed tennis racket in CRP (of Tensile Modulus 8,928 Gpa (WindForm, 2016) ) was produced (WindForm, 2014).

If 3D printing could become an actual production method and become the replacement production method of tennis rackets, then in comparison to current production methods, it would take care of those labour-dependent activities, eliminating the need for labour of those activities, which would:

- free up labour, in a factory setting, to focus on more advanced, mind-stimulating, activities such as design, or overseeing production and being responsible for more technically-involved activities;
- potentially, one person could be responsible for a few machines at a time, affecting scalability;
- lower the barrier of entry for non-mainstream racket manufacturers, leading towards new makers and designers, essentially democratising tennis racket manufacturing;
- real customisation and personalisation of rackets could take place; and,
- locations of production could be more de-centralised, and rather more localised, affecting supply chains, distribution costs, import/export taxes, meaning that money could go into more R & D; and,
- provide for more local employment, by returning production back to Europe / US, depending on the manufacturer's base.

The future could look like this, in Figure 41, where the potential of 3D printing and carbon composites merged:

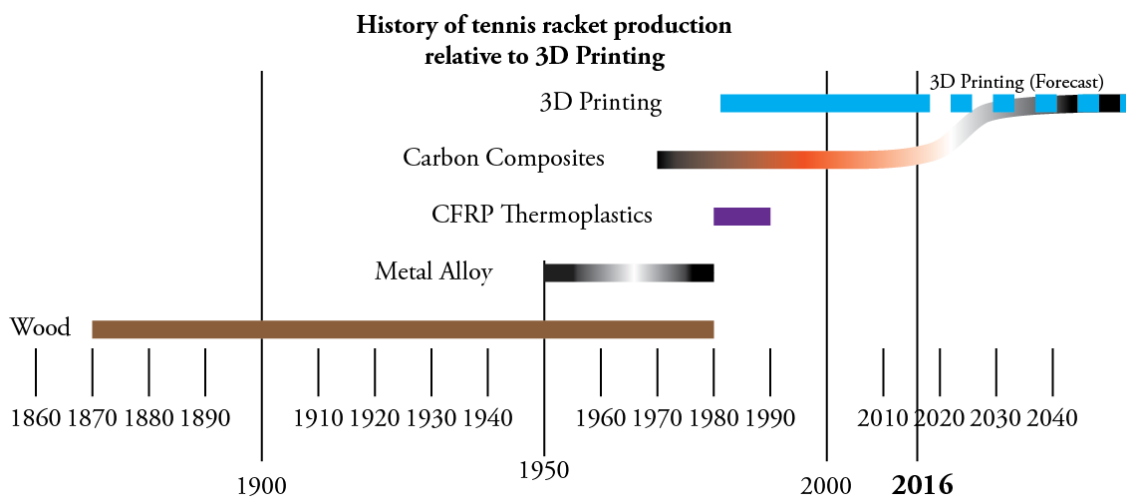


Figure 41: History of tennis racket manufacturing, relative to 3D Printing, forecasted to merge with Carbon composites (Julian Kollataj, 2016)

If 3D printing gets to the point that it can be of equal strength-to-weight ratio and durability of current racket-making methods, and it disrupts the racket manufacturing industry, in terms of lower barriers-to-entry, and new possibilities for extra racket makers, where does this fit into the context of innovation, while not having a negative effect on the nature of the game of tennis? How will the 'new' makers affect the manufacturers, and the game of tennis? How will the standards and regulations of racket production be affected from an International Tennis Federations's perspective?

In the meantime, while 3DP / AM technology is evolving to match the current production method, at least the smaller parts of the racket such as the bumperguards and grommets could be easy parts to reproduce on demand, and only for the parts that are damaged, instead of having to buy a whole new set, as is the current case when buying replacement parts. The grip shape however could become an area for customisation, based on hand-size, so that manufacturers can produce more of the same size gripped rackets, to then be enhanced by its customers.

## 6. Conclusion

The essence of the thesis, is that in 2016, an individual who has not worked for, or with, an established tennis racket manufacturer, is capable of reverse-engineering, designing with CAD software, and 3d printing, a tennis racket, in its most basic of forms, regardless of it being fully-functional and up to standard of an historically-made or present-day, fully-functional, wood, metal, or carbon composite, tennis racket.

It must be said that there has not been a heavy emphasis on the engineering considerations: “A bad idea executed well, is better than not executing a great idea”, comes to mind, because as much as the 3D printed tennis rackets are not anywhere close to performing like the already available commercial ones (CFRP has a Young’s Modulus of 90 GPa (Davis & Swinbank, 2010), while Nylon PA2200 has 1.7 GPa (referenced earlier)), one must start somewhere, and have something real to reflect on, in order to research, develop, and learn, so then 1) adjustments and progress can be made in developing the technology to the needs, or 2) wait and pursue later if the technology is developing too slowly if one is not interested to develop the technology, or 3) not pursue the development at all, regardless of technological and material advancements.

By being able to initiate the process of racket design, by going about doing the research, then have a starting point to produce a physical object / prototype, it becomes easier to establish a more concrete position of where technology is, in the context of history, and present day, with the purpose of identifying how the future could look and feel like – that of giving more effort and time to creativity and innovation, to individuals and businesses, by eliminating creation constraints, and thereby, making life more exciting and interesting.

## **What the author has learned by doing this thesis**

I have found that a thesis can be an emotional rollercoaster. There have been times of total focus, commitment, clarity, and feelings of excitement and contentment, while there has been progress. But then I have experienced resistance, confusion, irritation, frustration, isolation, even despair, considering this a burden and headache, at times of no progress, or no inspiration, affecting other areas of life.

I feel exhausted and relieved as I arrive at the end of this documentation, yet I am proud that I have been patient, determined, and resilient, with my research and design work, and the actions I have taken along this process and journey to want to understand and experience more, to be able to create this thesis, with the purpose of first changing my own beliefs, layer by layer, like a 3d printer, and then potentially allowing others to build on this, to change their own beliefs.

Thank you.

Julian Kollataj

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## 8. Appendices

### 8.1 Literature Review – Research Interview Highlights

As equipment is a key aspect of the tennis game, if it gives too much of an advantage to players, the game becomes less competitive and less interesting. From the interview with James Capel-Davies, the ITF (International Tennis Federation) Technical Manager, he mentioned key aspects (transcribed from video) regarding rackets (equipment) and innovation:

1) “The ITF technical centre was established in 1997 and the mission statement of the technical centre is, well, reasonably long, but essentially, the aim is to protect the nature of tennis and maintain the skills that are required to play the game, and at the same time, encouraging innovation, and making the game exciting to play and watch. So there is sort of, essentially, two elements of preserving that tradition but at the same time encouraging innovation - sometimes those might conflict, and sometimes they go together quite well. Sometimes innovation helps to preserve the tradition. That's our aim and so the purpose of the technical centre itself is to be able to carry out research and development testing programs to meet that goal. The way we do that is we have a process which consists of quantifying, or attempting to quantify, the state of the games in the ways that tennis is being played, and that has three elements - match analysis, player analysis, and equipment analysis.”

2) “There isn't as a program, as such, for racket testing...There's only a few rules for rackets, which are basically dimensions, and stringing patterns, and those are things that are typically regulated by the referee, in terms of if they see a large racket, then they might get a tape measure out, and measure it. Or, if any novel stringing pattern, they would come to us for a decision. It works a bit more like that, in terms of, we report to a technical commission, which is made up of experts, from various parts of the game. So, somebody from officiating, somebody representing The [Grand] Slams, somebody representing from ATP, WTA, and so on. We meet twice a year, and we update them with the work we are doing, and we also take what we call conformity decisions to them - so, if a new racket comes out, and it...not every new racket that comes out, because most new rackets don't sort of push the boundaries in terms of with respect to the rules...They come to us, and we'd either make a decision ourselves using the rule books, or if it's something that hasn't been measured for big use, kind of, very disruptive and not been done before, then it would go to that commission and there would be a discussion and we might do some research to provide the commission with some information about the effects we think this would have on the nature of the game.”

3) “there is like a gradual evolution of the way tennis is being played, so say, wood to metal to composite rackets, but something like this [Spaghetti String pattern (banned)], which is kind of links a step change, in the performance of that equipment, is not typically something we would allow that to happen, because, going back to our mission statement, some sort of consistency...of what tennis is, and in particular, trying to ensure that the player is the primary determinant of the outcome of the game, rather than the equipment they use.”

### 8.2 Excel calculations

1. Racket length and width of accepted international-accepted dimensions:

Racket Length range inches / mm			
min		max	
inch	mm	inch	mm
27.000	685.800	29.000	736.600
Racket Head Length range inches / mm			
min		max	
inch	mm	inch	mm
11.65	296.01	15.51	394
Racket Head Width range inches / mm			
min		max	
inch	mm	inch	mm
8.74	222.01	11.50	292

Figure 42 (Image of table): Min. and Max. dimensions of accepted racket lengths and widths in mm / inches

## 2. Calculating what semi- and full-axis dimensions for varying elliptical areas

	Area		a (semi)	semi-length	Length	b (semi)	semi-width	Length	k
	sq inch	sq mm	inch	mm	mm	inch	mm	mm	
max racket area inches	144.57	90358.49	7.76	197.00	394.00	5.75	146.00	292.00	0.74
min racket area inches	80.00	51612.80	5.83	148.00	296.01	4.37	111.00	222.01	0.75
Yonex VCore 95	93.49	60318.58	6.30	160.00	320.00	4.72	120.00	240.00	0.75
racket 1 k1	92.25	59514.33	6.30	160.00	320.00	4.66	118.40	236.80	0.74
racket 2 k2	91.00	58710.08	6.30	160.00	320.00	4.60	116.80	233.60	0.73
racket 3 k3	89.75	57905.84	6.30	160.00	320.00	4.54	115.20	230.40	0.72
racket 4 k4	88.51	57101.59	6.30	160.00	320.00	4.47	113.60	227.20	0.71
racket 5 k5	87.26	56297.34	6.30	160.00	320.00	4.41	112.00	224.00	0.70
racket 1 A1	95.000	61290.200	6.350	161.284	322.567	4.913	120.963	241.925	0.750
racket 2 A2	96.000	61935.360	6.383	162.130	324.260	4.958	121.598	243.195	0.750
racket 3 A3	97.000	62580.520	6.416	162.972	325.945	4.999	122.229	244.459	0.750
racket 4 A4	98.000	63225.680	6.449	163.810	327.621	5.038	122.858	245.715	0.750
racket 5 A5	99.000	63870.840	6.482	164.644	329.288	5.075	123.483	246.966	0.750
racket 5 A6	100.000	64516.000	6.515	165.473	330.947	5.110	124.105	248.210	0.750

Figure 43 (Image of Table): Yellow highlights the selected iteration used in thesis

## 2. String pattern

String spacing Formula:

- If point C(0,0) is at the centre of the ellipse, then where the Outer tangential Throat Arc and Outer Head ellipse connect is the where a line is drawn to T(x,y). From Solidworks, values are T(85.23951778, -114.5684169).
- Using a 16 x 16 stringing pattern (16 Main, 16 Cross), half of each direction would result in 8x Main(M), and 8x Cross (C)
- Cross positions uses measurement Tx;
  - o Formula for distance from centre S1
  - o  $M1 = \text{Spacing from } C(0,0) = \frac{C_x}{(1+2 \cdot (M_n - 1))}$
  - o  $M2 \rightarrow M6 = M_{n-1} + 2(M_1)$
  - o  $M7 = \text{difference}; M8 = Tx$

Sh (String height)	no. of strings	Spacing	round up		M1	M2	M3	M4	M5	M6	M7	M8
85.23951778	8	5.68	5.70		5.70	17.10	28.50	39.90	51.30	62.70	73.97	85.24
Spacing between strings						11.40	11.40	11.40	11.40	11.40	11.27	11.27

Figure 44 (Image of Table): Space between Mains strings (in mm)

- Mains position along y-axis uses measurement Ty
  - o Formula for distance from centre A1
  - o  $A1 = \text{Spacing from } C(0,0) = \frac{C_y}{(1+2 \cdot (A_n-1))}$
  - o  $A2 \rightarrow A6 = A_{n-1} + 2(M_1)$
  - o A7 = difference (in table)
  - o A8 = Ty

Sh (String height)	no. of strings	Spacing	round up		M1	M2	M3	M4	M5	M6	M7	M8
<b>114.5684169</b>	<b>8</b>	7.64	7.80	109.20	7.80	23.40	39.00	54.60	70.20	85.80	100.18	114.57
<b>Spacing between strings</b>						15.60	15.60	15.60	15.60	15.60	14.38	14.38

Figure 45 (Image of Table): Space between mains strings (in mm)

### 8.3 Parts Feature tree

#### Basic – Face Throat Grip

Process	Feature number	Part section	Folder/Feature/Sketch	Feature/Sketch	Feature/Sketch	Dimensions	comment
1.1	1	Racket Face/Throat	Face-Throat Raw	Boss-Extrude-Racket Shape Unrefined		10	from Top Plane
					Sketch1 (Ellipse/Tangential Arcs)		
1.2	2	Racket Face/Throat		Fillet-Face-Throat		5	mm, Radius
1.3	3	Racket Face/Throat		Chamfer1		4	mm V
						3	mm H
				String pattern			
			Face-Throat Refining				
1.4	4	Racket Face/Throat		Fillet-Face-Inner		5	mm, Radius
1.5	5	Racket Face/Throat		Fillet-Throat-Inner		5	mm, Radius
1.6	6	Racket Face/Throat		Fillet40 (Face-Throat-Outer)		4	mm, Radius
1.7	7	Racket Face/Throat		Mirror20			About Top Plane
			Plane22				at Outer Tangential Arc
1.8	8	Racket Face/Throat	Cut-Extrude26 (Shaft section)			35	mm, from Top of Grip
				Sketch37 (square for cut extrude of shaft)		42.38	mm V
						25.52	mm H



				Sketch71 (Face trace)			
1.9	9	Racket Face/Throat	Fillet48 (Face-Throat Outer wall Fillet)			5	mm, Radius
1.10	10	Racket Face/Throat	Loft6				
				Sketch70			
				Sketch68			
				Edge1			
				Edge2			
			Grommet Holes				
				Plane1			
				Plane2			
				Plane3			
				Plane4			
				Plane5			
				Plane6			
				Plane13			
1.11	11	Racket Face/Throat		Cut-Extrude-M5			
					Sketch4		
1.12	12	Racket Face/Throat		Cut-Extrude-M6			
					Sketch3		
1.13	13	Racket Face/Throat		Cut-Extrude-M7			
					Sketch6		
1.14	14	Racket Face/Throat		Cut-Extrude6-M8			
					Sketch8		
1.15	15	Racket Face/Throat		Cut-ExtrudeC8			
					Sketch5		
1.16	16	Racket Face/Throat		Cut-Extrude5-C7			
					Sketch7		
1.17	17	Racket Face/Throat		Cut-Extrude-C6K			
					Sketch63		
1.18	18	Racket Face/Throat		Cut-Extrude9-C1to5			
					Sketch10		
1.19	19	Racket Face/Throat		Mirror-Cut-Extrude-M78C78			
1.20	20	Racket Face/Throat		Mirror-Cut-Extrude-C12345			
1.21	21	Racket Face/Throat		Cut-Extrude-C6			
					Sketch11		
				Plane12			
1.22	22	Racket Face/Throat		Cut-Extrude-M6K			

					Sketch16		
1.23	23	Racket Face/Throat		Cut-Extrude16			
					Sketch17		
1.24	24	Racket Face/Throat		Cut-Extrude-M123			
					Sketch18		
1.25	25	Racket Face/Throat		Cut-Extrude-M4			
					Sketch18		
1.26	26	Racket Face/Throat		Cut-Sweep1			
					Sketch18		
					Sketch20		
1.27	27	Racket Face/Throat		Shell8		3	mm, Radius
				Fillet-Inner-Grommets-Throat		1	mm, Radius
1.28	28	Racket Face/Throat	Fillet-Grommets-Outer-Lower			1	mm, Radius
1.29	29	Racket Face/Throat	Fillet-Grommets-Outer-Upper			1	mm, Radius
1.30	30	Racket Face/Throat	Mirror35				about Right Plane
			Plane23				
1.31	31	Racket Face/Throat	Loft7 (Shaft)				
				Sketch75			
				Sketch74			
				Sketch77			
				3DSketch7			
				Sketch76			
			Plane24				
			Sketch79				
1.32	32	Racket Face/Throat	Loft9 (Grip Handle - Top)			35	mm, 13.67mm above Top Plane, to, 14mm
				Sketch80			
				Sketch82			
				3DSketch8			
1.33	33	Racket Face/Throat	Boss-Extrude2			134.2	mm, "Up to Vertex"
				Sketch83			
			Plan25				at Total Length of Racket
1.34	34	Racket Face/Throat	Loft10 (Grip - Bottom)			35.8	mm, 14 to max 18mm above Top Plane,

							20mm wide
				Face<1> (Boss-Extrude2)			
				Sketch85			
1.35	35	Racket Face/Throat	Fillet52			100	mm, Radius
1.36	36	Racket Face/Throat	Body-Delete/Keep 1 - Grip				
1.37	37	Racket Face/Throat	Cut-Loft1 (Shaft cutout)			3	mm, Min, Top of Shaft
				Sketch88		7	mm, Max, Bottom of Shaft
				Sketch86			
				Sketch87			
			Powder exit holes				
1.38	38	Racket Face/Throat		Cut-Extrude27		Through All	(11 o'clock position)
					Sketch89		
1.39	39	Racket Face/Throat		Mirror36			About Front Plane
1.40	40	Racket Face/Throat		Mirror39			About Right Plane
1.41	41	Racket Face/Throat		Fillet53		1	mm
1.42	42	Racket Face/Throat		Fillet54		1	mm

### Grip – Outer Right

Process	Feature number	Part section	Folder/Feature/Sketch	Sub-Feature/Sketch	Sub-Feature/Sketch	Dimensions	comment
1.1-34	Face Throat Grip						
1.42	Face Throat Grip						
2.1	1	Outer Grip Right -	Fillet57			3.5	mm, Radius
2.2	2	Outer Grip Right -	Cut-Extrude28			35	mm, "Blind", Selected Contours
				Sketch87		2	mm, Radius
					Spacing	8	mm, V
						15.72	mm, H
2.3	3	Outer Grip Right -	Boss-Extrude3				"Up To Next", "Selected Contours", "Merge Results"
				Sketch91			

2.4	4	Outer Grip Right -	Fillet58 (Rounding Pillars)			2	mm, Radius
2.5	5	Outer Grip Right -	Fillet59 (Rounding Pillars)			3	mm, Radius ("Edge<1>"), "Tangent Propagation"
2.6	6	Outer Grip Right -	Fillet61 (Rounding Pillars)			2	mm, Radius ("Edge<1>"), "Tangent Propagation"
2.7	7	Outer Grip Right -	Fillet62 (Rounding Pillars)			1.5	mm, Radius, Multiple Edges, "Tangent Propagation"
2.8	8	Outer Grip Right -	Fillet63 (Rounding Pillars)			2.5	mm, Radius, Multiple Edges, "Tangent Propagation"
2.9	9	Outer Grip Right -	Boss-Extrude4				"Up To Next", "Merge Results"
				Sketch92		10	mm, 10mm spacing
2.10	10	Outer Grip Right -	Cut-Extrude29				"Through All"
				Sketch95			
2.11	11	Outer Grip Right -	Fillet64 (Rounding Boss-Extrude4, Cut-Extrude29)			3	mm, Radius, Multiple Edges, "Tangent Propagation"
2.12	12	Outer Grip Right -	Fillet65 (Rounding Boss-Extrude4, Cut-Extrude29)			2	mm, Radius, Multiple Edges, "Tangent Propagation"

### Grip – Inner – Right

Process	Feature number	Part section	Folder/Feature/Sketch	Sub-Feature/Sketch	Sub-Feature/Sketch	Dimensions	Comment
1.1-34	Face Throat Grip						
1.42	Face Throat Grip						
2.1	Grip outer - Right						
3.1	1	Grip Outer - Right (Import)					
3.2	2	Grip Inner - Right	Combine				"Subtract", "Fillet57" (Process 2.1) with 3.1
3.3	3	Grip Inner - Right	Cut-Extrude30 (Remove End)				
				Sketch93			"Up To Vertex", "Point352@Sketch1" (650mm mark)

							construction line)
3.4	4	Grip Inner - Right	Cut-Extrude32 (Hollow Out Handle)				"Through All"
				Sketch93		3	mm, Off-set from Outer Grip

### Bumperguard – Top

Process	Feature number	Part section	Folder/Feature/Sketch	Sub-Feature/Sketch	Sub-Feature/Sketch	Dimensions	Comment
4.1	1	Face Throat and Grip (Part Import)					
4.2	2	Bumper - Top	Sweep				"Closed Loop <1>", "Sketch378"
				Sketch377			"Right Plane", "Offset 1mm"
				Sketch378			
4.3	3	Bumper - Top	Combine				"Subtract", "Sweep 1", "Face Throat and Grip"
4.4	4	Bumper - Top	Boss-Extrude1				"Up To Body", Selected Contours", "Combine3", "Merge Results"
				Sketch376			
4.5	5	Bumper - Top	Cut-Extrude1				"Through All", "Selected Contours", "Boss-Extrude1"
				Sketch376			
4.6	6	Bumper - Top	Boss-Extrude3				"Up To Body": "Cut-Extrude1", Selected Contours", "Cut-Extrude1", "Merge Results"
				Sketch380			
4.7	7	Bumper - Top	Cut-Extrude2				"Through All", "Selected Contours", "Boss-Extrude3"
				Sketch380			
4.8	8	Bumper - Top	Boss-Extrude4				"Up To Surface": "Face<1>", Selected Contours", "Cut-Extrude2", "Merge Results"
				Sketch381			
4.9	9	Bumper - Top	Cut-Extrude3				"Through All", "Selected Contours", "Boss-Extrude4"
				Sketch381			
4.10	10	Bumper - Top	Boss-Extrude5				"Up To Surface": "Face<1>", Selected Contours", "Cut-Extrude3", "Merge Results"
				Sketch382			

4.11	11	Bumper - Top	Cut-Extrude4				"Through All", "Selected Contours", "Boss-Extrude5"
				Sketch382			
4.12	12	Bumper - Top	Boss-Extrude10				"Up To Surface": "Face<1>", Selected Contours", "Cut-Extrude4", "Merge Results"
				Sketch383			
4.13	13	Bumper - Top	Cut-Extrude5				"Through All", "Selected Contours", "Boss-Extrude10"
				Sketch383			
4.14	14	Bumper - Top	Boss-Extrude14				"Up To Next", "Selected Contours", "Cut- Extrude5", "Merge Results"
				Sketch383			
4.15	15	Bumper - Top	Cut-Extrude6				"Up To Surface": "Face<1>", "Selected Contours", "Boss-Extrude14"
				Sketch383			
4.16	16	Bumper - Top	Boss-Extrude15				"Up To Body": "Cut- Extrude6", "Selected Contours", "Cut- Extrude6", "Merge Results"
				Sketch386			
4.17	17	Bumper - Top	Cut-Extrude7				"Up To Surface": "Face<1>", "Selected Contours", "Boss-Extrude15"
				Sketch386			
4.18	18	Bumper - Top	Boss-Extrude16				"Up To Body": "Cut- Extrude7", "Selected Contours", "Cut- Extrude7", "Merge Results"
				Sketch387			
4.19	19	Bumper - Top	Cut-Extrude8				"Up To Surface": "Face<1>", "Selected Contours", "Boss-Extrude16"
				Sketch387			
4.20	20	Bumper - Top	Boss-Extrude17				"Up To Body": "Cut- Extrude8", "Selected Contours", "Cut- Extrude8", "Merge Results"
				Sketch388			
4.21	21	Bumper - Top	Cut-Extrude9				"Up To Surface": "Face<1>", "Selected Contours", "Boss-Extrude17"
				Sketch388			
4.22	22	Bumper - Top	Boss-Extrude18				"Up To Body": "Cut- Extrude9", "Selected Contours", "Cut- Extrude9", "Merge Results"



				Sketch389			
4.23	23	Bumper - Top	Cut-Extrude10				"Up To Surface": "Face<1>", "Selected Contours", "Boss-Extrude18"
				Sketch389			
4.24	24	Bumper - Top	Fillet 5 (Round Inner grommets)			1	mm, Radius, 10 Edges, "Tangent Propogation"
4.25	25	Bumper - Top	Fillet 6 (Round Inner grommets)			2	mm, Radius, 10 Edges, "Tangent Propogation"
4.26	26	Bumper - Top	Chamfer3			4	mm, "Edge<1>", "Distance Distance", "Select Through Faces", "Tangent Propogation"
4.27	27	Bumper - Top	Fillet13			20	mm, Radius, "Edge <1>", "Tangent Propogation"
4.28	28	Bumper - Top	Mirror				"Top Plane", "Features to Mirror: "Fillet13", "Chamfer13""
4.29	29	Bumper - Top	Body-Delete/Keep1 - Face Throat Grip (part import)				"Top Plane", "Features to Mirror: "Fillet13", "Chamfer13""
4.30	30	Bumper - Top	Cut-Extrude11				"Through All"
				Sketch395			
4.31	31	Bumper - Top	Fillet14			0.5	mm, Radius, "Items To Fillet: "Edge<1>", "Edge<2>""

### Bumper – Bottom

Process	Feature number	Part section	Folder/Feature/Sketch	Sub-Feature/Sketch	Sub-Feature/Sketch	Dimensions	Comment
5.1	1	Face Throat and Grip (Part Import)					
5.2	2	Bumper - Bottom	Sweep				"Closed Loop <1>", "Sketch378"
				Sketch377			"Right Plane", "Offset 1mm"
				Sketch378			
5.3	3	Bumper - Bottom	Combine				"Subtract", "Sweep 1", "Face Throat and Grip"
5.4	4	Bumper - Bottom	Boss-Extrude1				"Up To Body", Selected Contours", "Combine3", "Merge Results"
				Sketch376			
5.5	5	Bumper - Bottom	Cut-Extrude1				"Through All", "Selected Contours", "Boss-Extrude1"
				Sketch376			
5.6	6	Bumper - Bottom	Boss-Extrude3				"Up To Body": "Cut-Extrude1", Selected Contours", "Cut-Extrude1", "Merge Results"
				Sketch380			

5.7	7	Bumper - Bottom	Cut-Extrude2				"Through All", "Selected Contours", "Boss-Extrude3"
				Sketch380			
5.8	8	Bumper - Bottom	Boss-Extrude4				"Up To Surface": "Face<1>", Selected Contours", "Cut-Extrude2", "Merge Results"
				Sketch381			
5.9	9	Bumper - Bottom	Cut-Extrude3				"Through All", "Selected Contours", "Boss-Extrude4"
				Sketch381			
5.10	10	Bumper - Bottom	Boss-Extrude5				"Up To Surface": "Face<1>", Selected Contours", "Cut-Extrude3", "Merge Results"
				Sketch382			
5.11	11	Bumper - Bottom	Cut-Extrude4				"Through All", "Selected Contours", "Boss-Extrude5"
				Sketch382			
5.12	12	Bumper - Bottom	Boss-Extrude10				"Up To Surface": "Face<1>", Selected Contours", "Cut-Extrude4", "Merge Results"
				Sketch383			
5.13	13	Bumper - Bottom	Cut-Extrude5				"Through All", "Selected Contours", "Boss-Extrude10"
				Sketch383			
5.14	14	Bumper - Bottom	Boss-Extrude14				"Up To Next", "Selected Contours", "Cut- Extrude5", "Merge Results"
				Sketch383			
5.15	15	Bumper - Bottom	Cut-Extrude6				"Up To Surface": "Face<1>", "Selected Contours", "Boss-Extrude14"
				Sketch383			
5.16	16	Bumper - Bottom	Boss-Extrude15				"Up To Body": "Cut- Extrude6", "Selected Contours", "Cut- Extrude6", "Merge Results"
				Sketch386			
5.17	17	Bumper - Bottom	Cut-Extrude7				"Up To Surface": "Face<1>", "Selected Contours", "Boss-Extrude15"
				Sketch386			
5.18	18	Bumper - Bottom	Boss-Extrude16				"Up To Body": "Cut- Extrude7", "Selected Contours", "Cut- Extrude7", "Merge Results"
				Sketch387			

5.19	19	Bumper - Bottom	Cut-Extrude8				"Up To Surface": "Face<1>", "Selected Contours", "Boss-Extrude16"
				Sketch387			
5.20	20	Bumper - Bottom	Boss-Extrude17				"Up To Body": "Cut-Extrude8", "Selected Contours", "Cut-Extrude8", "Merge Results"
				Sketch388			
5.21	21	Bumper - Bottom	Cut-Extrude9				"Up To Surface": "Face<1>", "Selected Contours", "Boss-Extrude17"
				Sketch388			
5.22	22	Bumper - Bottom	Boss-Extrude18				"Up To Body": "Cut-Extrude9", "Selected Contours", "Cut-Extrude9", "Merge Results"
				Sketch389			
5.23	23	Bumper - Bottom	Cut-Extrude10				"Up To Surface": "Face<1>", "Selected Contours", "Boss-Extrude18"
				Sketch389			
5.24	24	Bumper - Bottom	Fillet 5 (Round Inner grommets)			1	mm, Radius, 10 Edges, "Tangent Propagation"
5.25	25	Bumper - Bottom	Fillet 6 (Round Inner grommets)			2	mm, Radius, 10 Edges, "Tangent Propagation"
5.26	26	Bumper - Bottom	Chamfer3			4	mm, "Edge<1>", "Distance Distance", "Select Through Faces", "Tangent Propagation"
5.27	27	Bumper - Bottom	Fillet13			20	mm, Radius, "Edge <1>", "Tangent Propagation"
5.28	28	Bumper - Bottom	Mirror				"Top Plane", "Features to Mirror: "Fillet13", "Chamfer13"
5.29	29	Bumper - Bottom	Body-Delete/Keep1 - Face Throat Grip (part import)				"Face Throat Grip" part import
5.30	30	Bumper - Bottom	Cut-Extrude11				"Through All", "Reverse Direction"
				Sketch395			
5.31	31	Bumper - Bottom	Fillet14			0.5	mm, Radius, "Items To Fillet: "Edge<1>", "Edge<2>"

### Side Grommet – Upper

Process	Feature number	Part section	Folder/Feature/Sketch	Sub-Feature/Sketch	Sub-Feature/Sketch	Dimensions	Comment
6.1	1	Face Throat and Grip (Part Import)					

6.2	2	Bumper (Part Import)				
6.3	3	Side Grommet - Upper	Sweep2			"Closed Loop <1>", "Sketch378"
				Sketch284		"Right Plane", "Offset" 1mm
				Sketch285		
6.4	4	Side Grommet - Upper	Combine8			"Subtract", "Sweep2", Bodies To Combine: "Face Throat and Grip"
6.5	5	Side Grommet - Upper	Body-Delete/Keep1 - Bumper (part import)			"Face Throat Grip" part import
6.6	6	Side Grommet - Upper	Body-Delete/Keep2 - Face Throat Grip (part import)			"Face Throat Grip" part import
6.7	7	Side Grommet - Upper	Boss-Extrude2			"Up To Body": "Combine8", "Selected Contours", "Merge Results"
				Sketch287	2	mm, Radius
6.8	8	Side Grommet - Upper	Cut-Extrude1			"Up To Surface": "Face<1>", "Selected Contours"
				Sketch287	1	mm, Radius
6.9	9	Side Grommet - Upper	Boss-Extrude6			"Up To Surface": "Face<1>", "Selected Contours", "Merge Results"
				Sketch288	2	mm, Radius
6.10	10	Side Grommet - Upper	Cut-Extrude2			"Up To Surface": "Face<1>", "Selected Contours"
				Sketch288	1	mm, Radius
6.11	11	Side Grommet - Upper	Boss-Extrude7			"Up To Surface": "Face<1>", "Selected Contours", "Merge Results"
				Sketch289	2	mm, Radius
6.12	12	Side Grommet - Upper	Cut-Extrude3			"Up To Surface": "Face<1>", "Selected Contours"
				Sketch289	1	mm, Radius
6.13	13	Side Grommet - Upper	Boss-Extrude8			"Up To Surface": "Face<1>", "Selected Contours", "Merge Results"
				Sketch290	2	mm, Radius
6.14	14	Side Grommet - Upper	Cut-Extrude4			"Up To Surface": "Face<1>", "Selected Contours"
				Sketch290	1	mm, Radius
6.15	15	Side Grommet - Upper	Boss-Extrude9			"Up To Surface": "Face<1>", "Selected Contours", "Merge Results"
				Sketch291	2	mm, Radius

6.16	16	Side Grommet - Upper	Cut-Extrude5				"Up To Surface": "Face<1>", "Selected Contours"
				Sketch291		1	mm, Radius
6.17	17	Side Grommet - Upper	Boss-Extrude10				"Up To Surface": "Face<1>", "Selected Contours", "Merge Results"
				Sketch292		2	mm, Radius
6.18	18	Side Grommet - Upper	Cut-Extrude6				"Up To Surface": "Face<1>", "Selected Contours"
				Sketch292		1	mm, Radius
6.19	19	Side Grommet - Upper	Boss-Extrude11				"Up To Surface": "Face<1>", "Selected Contours", "Merge Results"
				Sketch293		2	mm, Radius
6.20	20	Side Grommet - Upper	Cut-Extrude7				"Up To Surface": "Face<1>", "Selected Contours"
				Sketch293		1	mm, Radius
6.21	21	Side Grommet - Upper	Boss-Extrude12				"Up To Surface": "Face<1>", "Selected Contours", "Merge Results"
				Sketch294		2	mm, Radius
6.22	22	Side Grommet - Upper	Cut-Extrude8				"Up To Surface": "Face<1>", "Selected Contours"
				Sketch294		1	mm, Radius
6.23	23	Side Grommet - Upper	Boss-Extrude13				"Up To Surface": "Face<1>", "Selected Contours", "Merge Results"
				Sketch295		2	mm, Radius
6.24	24	Side Grommet - Upper	Cut-Extrude9				"Up To Surface": "Face<1>", "Selected Contours"
				Sketch295		1	mm, Radius
6.25	25	Side Grommet - Upper	Boss-Extrude14				"Up To Surface": "Face<1>", "Selected Contours", "Merge Results"
				Sketch296		2	mm, Radius
6.26	26	Side Grommet - Upper	Cut-Extrude10				"Up To Surface": "Face<1>", "Selected Contours"
				Sketch296		1	mm, Radius
6.27	27	Side Grommet - Upper	Boss-Extrude15				"Up To Surface": "Face<1>", "Selected Contours", "Merge Results"
				Sketch297		2	mm, Radius
6.28	28	Side Grommet - Upper	Cut-Extrude11				"Up To Surface": "Face<1>", "Selected Contours"
				Sketch297		1	mm, Radius
6.29	29	Side Grommet - Upper	Boss-Extrude16				"Up To Surface": "Face<1>",

							"Selected Contours", "Merge Results"
				Sketch298		2	mm, Radius
6.30	30	Side Grommet - Upper	Cut-Extrude12				"Up To Surface": "Face<1>", "Selected Contours"
				Sketch298		1	mm, Radius
6.31	31	Side Grommet - Upper	Fillet3			1.25	mm, Radius, 12 Edges, "Tangent Propogation"
6.32	32	Side Grommet - Upper	Fillet5			0.75	mm, Radius, 12 Edges, "Tangent Propogation"

### Side Grommet – Lower

Process	Feature number	Part section	Folder/Feature/ Sketch	Sub- Feature/Sketch	Sub-Feature/Sketch	Dimensions	Comment
7.1	1	Face Throat and Grip (Part Import)					
7.2	2	Bumper (Part Import)					
7.3	3	Side Grommet (Part Import)					
7.4	4	Side Grommet- Lower	Body- Delete/Keep1 - Bumper (part import)				"Face Throat Grip" (Cut Loft) part import; "Bumper" part import
7.5	5	Side Grommet- Lower	Sweep1				"Closed Loop <1>", "Sketch724"
				Sketch723			on "Plane 2"
				Sketch724			
7.6	6	Side Grommet- Lower	Combine1				"Subtract", "Sweep1", Bodies To Combine: "Face Throat and Grip"
7.7	7	Side Grommet- Lower	Body- Delete/Keep4 - Side Grommet (part import)				"Side Grommet" part import
7.8	8	Side Grommet- Lower	Boss-Extrude1				"Up To Surface": "Face<1>", "Selected Contours", "Merge Results"
				Sketch726		2	mm, Radius
7.9	9	Side Grommet- Lower	Cut-Extrude1				"Up To Surface": "Face<1>", "Selected Contours"
				Sketch726		1	mm, Radius
7.10	10	Side Grommet- Lower	Boss-Extrude2				"Up To Surface": "Face<1>", "Selected Contours", "Merge Results"
				Sketch727		2	mm, Radius
7.11	11	Side Grommet- Lower	Cut-Extrude2				"Up To Surface": "Face<1>", "Selected Contours"
				Sketch727		1	mm, Radius

7.12	12	Side Grommet-Lower	Boss-Extrude3				"Up To Surface": "Face<1>", "Selected Contours", "Merge Results"
				Sketch728		2	mm, Radius
7.13	13	Side Grommet-Lower	Cut-Extrude3				"Up To Surface": "Face<1>", "Selected Contours"
				Sketch728		1	mm, Radius
7.14	14	Side Grommet-Lower	Boss-Extrude4				"Up To Surface": "Face<1>", "Selected Contours", "Merge Results"
				Sketch729		2	mm, Radius
7.15	15	Side Grommet-Lower	Cut-Extrude4				"Up To Surface": "Face<1>", "Selected Contours"
				Sketch729		1	mm, Radius
7.16	16	Side Grommet-Lower	Boss-Extrude5				"Up To Surface": "Face<1>", "Selected Contours", "Merge Results"
				Sketch730		2	mm, Radius
7.17	17	Side Grommet-Lower	Cut-Extrude5				"Up To Surface": "Face<1>", "Selected Contours"
				Sketch730		1	mm, Radius
7.18	18	Side Grommet-Lower	Boss-Extrude6				"Up To Surface": "Face<1>", "Selected Contours", "Merge Results"
				Sketch731		2	mm, Radius
7.19	19	Side Grommet-Lower	Cut-Extrude6				"Up To Surface": "Face<1>", "Selected Contours"
				Sketch731		1	mm, Radius
7.31	31	Side Grommet-Lower	Fillet4			1	mm, Radius, 6 Edges, "Tangent Propagation"
7.32	32	Side Grommet-Lower	Fillet5			1	mm, Radius, 6 Edges, "Tangent Propagation"
7.33	33	Side Grommet-Lower	Cut-Extrude6				"Up To Surface": "Face<1>", "Selected Contours"
				Sketch733		1	mm, Radius
7.34	34	Side Grommet-Lower	Fillet6			0.5	mm, Radius, "Edge<1>", "Tangent Propagation"

### Throat Grommet – Left

Process	Feature number	Part section	Folder/Feature/Sketch	Sub-Feature/Sketch	Sub-Feature/Sketch	Dimensions	Comment
8.1	1	Face Throat and Grip (Part Import)					



8.2	2	Grommet Throat - Left	Sweep1				"Closed Loop <1>", "Sketch724"
				Sketch104			on "Plane 2"
				Sketch105			
8.3	3	Grommet Throat - Left	Fillet1			2	mm, Radius
8.4	4	Grommet Throat - Left	Combine1				"Subtract", "Fillet1", Bodies To Combine: "Face Throat and Grip"
8.5	5	Grommet Throat - Left	Body-Delete/Keep1 - Bumper (part import)				"Face Throat Grip" (Cut Loft) part import
8.6	6	Grommet Throat - Left	Sweep2				"3DSketch1", "3D Sketch2"
				3DSketch2			on "Plane 5"
				3DSketch1			"Top Plane"
8.7	7	Grommet Throat - Left	Cut-Sweep2				"Sketc114", "3DSketch3"
				Sketch114			on "Plane 5"
				3DSketch3			"Top Plane"
8.8	8	Grommet Throat - Left	Fillet2			2	mm, Radius
8.9	9	Grommet Throat - Left	Boss-Extrude1				"Up To Surface": "Face<1>", "Selected Contours", "Merge Results"
				Sketch107		2	mm, Radius
8.10	10	Grommet Throat - Left	Cut-Extrude1				"Up To Surface": "Face<1>", "Selected Contours"
				Sketch107		1	mm, Radius
8.11	11	Grommet Throat - Left	Boss-Extrude2				"Up To Surface": "Face<1>", "Selected Contours", "Merge Results"
				Sketch108		2	mm, Radius
8.12	12	Grommet Throat - Left	Cut-Extrude2				"Up To Surface": "Face<1>", "Selected Contours"
				Sketch108		1	mm, Radius
8.13	13	Grommet Throat - Left	Boss-Extrude3				"Up To Surface": "Face<1>", "Selected Contours", "Merge Results"
				Sketch109		2	mm, Radius
8.14	14	Grommet Throat - Left	Cut-Extrude3				"Up To Surface": "Face<1>", "Selected Contours"
				Sketch109		1	mm, Radius

8.15	15	Grommet Throat - Left	Fillet3			2	mm, Radius, 3 Edges, "Tangent Propogation"
8.16	16	Grommet Throat - Left	Fillet4			1	mm, Radius, Edge<1>, "Tangent Propogation"
8.17	17	Grommet Throat - Left	Fillet5			1	mm, Radius, 4 Edges, "Tangent Propogation"
8.18	18	Grommet Throat - Left	Cut-Extrude4				"Through All"
				Sketch116		1	mm, Radius

### Throat Grommet – Right

Process	Feature number	Part section	Folder/Feature/Sketch	Sub-Feature/Sketch	Sub-Feature/Sketch	Dimensions	Comment
9.1	1	Face Throat and Grip (Part Import)					
9.2	2	Grommet Throat - Right	Sweep1				"Closed Loop <1>", "Sketch724"
				Sketch104			on "Plane 2"
				Sketch105			
9.3	3	Grommet Throat - Right	Fillet1			2	mm, Radius
9.4	4	Grommet Throat - Right	Combine1				"Subtract", "Fillet1", Bodies To Combine: "Face Throat and Grip"
9.5	5	Grommet Throat - Right	Body-Delete/Keep1 - Bumper (part import)				"Face Throat Grip" (Cut Loft) part import
9.6	6	Grommet Throat - Right	Sweep2				"3DSketch1", "3D Sketch2"
				3DSketch2			on "Plane 5"
				3DSketch1			"Top Plane"
9.7	7	Grommet Throat - Right	Cut-Sweep2				"Sketc114", "3DSketch3"
				Sketch114			on "Plane 5"
				3DSketch3			"Top Plane"
9.8	8	Grommet Throat - Right	Fillet2			2	mm, Radius
9.9	9	Grommet Throat - Right	Boss-Extrude1				"Up To Surface": "Face<1>", "Selected Contours", "Merge Results"
				Sketch107		2	mm, Radius
9.10	10	Grommet Throat - Right	Cut-Extrude1				"Up To Surface": "Face<1>", "Selected Contours"
				Sketch107		1	mm, Radius

9.11	11	Grommet Throat - Right	Boss-Extrude2				"Up To Surface": "Face<1>", "Selected Contours", "Merge Results"
				Sketch108		2	mm, Radius
9.12	12	Grommet Throat - Right	Cut-Extrude2				"Up To Surface": "Face<1>", "Selected Contours"
				Sketch108		1	mm, Radius
9.13	13	Grommet Throat - Right	Boss-Extrude3				"Up To Surface": "Face<1>", "Selected Contours", "Merge Results"
				Sketch109		2	mm, Radius
9.14	14	Grommet Throat - Right	Cut-Extrude3				"Up To Surface": "Face<1>", "Selected Contours"
				Sketch109		1	mm, Radius
9.15	15	Grommet Throat - Right	Fillet3			2	mm, Radius, 3 Edges, "Tangent Propogation"
9.16	16	Grommet Throat - Right	Fillet4			1	mm, Radius, Edge<1>, "Tangent Propogation"
9.17	17	Grommet Throat - Right	Fillet5			1	mm, Radius, 4 Edges, "Tangent Propogation"
9.18	18	Grommet Throat - Right	Cut-Extrude4				"Through All", "Reverse Direction"
				Sketch116		1	mm, Radius

### Hexa – Face Throat Grip

Process	Feature number	Part section	Folder/Feature/Sketch	Feature/Sketch	Feature/Sketch	Dimensions	comment
10.1	1.1 to 1.26	Racket Face/Throat	Racket Face/Throat				
10.2	1.27			Shell8 (Suppressed)		3	mm, Radius
				Fillet-Inner-Grommets-Throat		1	mm, Radius
10.3	1.28-36	Racket Face/Throat	Racket Face/Throat				
10.4	1.37		Cut-Loft1 (Shaft cutout) - SUPPRESSED			3	mm, Min, Top of Shaft
				Sketch88		7	mm, Max, Bottom of Shaft
				Sketch86			

				Sketch87			
10.5	1.38-42	Racket Face/Throat	Racket Face/Throat				
10.6	6	Grip Inner - Right - for negative plate					
10.7	7	Hexa - FTIH	Mirror40				About "Right Plane"
10.8	8	Hexa - FTIH	Boss-Extrude3				"Through All" (Both Directions)
				Sketch93		678.81	mm, Length
						322.57	mm, Wide
10.9	9	Hexa - FTIH	Combine1				"Subtract" Operation Type
							Bodies to Combine: "Mirror35", "Loft7", Grip inner - right - for negative plate"
10.10	10	Hexa - FTIH	Split1				2 Bodies
				Sketch94			Trim Tool
10.11	11	Hexa - FTIH	Import: Template				
10.12	12	Hexa - FTIH	Split2				2 Bodies
				Sketch94			Trim Tool

### Grip Inner – Right – Negative

Process	Feature number	Part section	Folder/Feature/Sketch	Sub-Feature/Sketch	Sub-Feature/Sketch	Dimensions	Comment
1.1-34	Face Throat Grip						
1.42	Face Throat Grip						
2.1	Grip outer - Right						
11.1	1	Grip Outer - Right (Import)					
11.2	2	Grip Inner - Right	Combine				"Subtract", "Fillet57" (Process 2.1) with 3.1
11.3	3	Grip Inner - Right	Cut-Extrude30 (Remove End)				
				Sketch93			"Up To Vertex", "Point352@Sketch1" (650mm mark construction line)
11.4	4	Grip Inner - Right	Cut-Loft1 (Hollow Out Handle) - SUPPRESSED				
				Sketch95			
				Sketch96			

Hexa (Up) – Head Throat Grip

Process	Feature number	Part section	Folder/Feature/Sketch	Feature/Sketch	Feature/Sketch	Dimensions	comment
12.1	1	FTIH	FTIH (Part import)				
12.2	2	Hexa (up)		Surface-Offset1		0	mm, Off-set; multiple objects
12.3	3		Boss-Extrude1				
				Sketch92		10	mm, Both directions, "Blind"
12.4	4		CrvPattern1				36 Instances, "Align to seed", "Offset Curve", Along "Sketch91", "Bodies"
				Boss-Extrude1			
12.5	5		CrvPattern2				28 Instances, "Align to seed", "Offset Curve", Along "Sketch94", "Bodies"
				CrvPattern1[15] (Boss-Extrude1)			
12.6	6		Combine1				"Add", "Bodies To Combine": Multiple (along Ellipse curve section, from tangential arc until 3 o'clock)
12.7	7		Combine2				"Add", "Bodies To Combine": Multiple (along Ellipse curve section, from tangential arc until 6 o'clock)
12.8	8		Scale2				Scale Parameters: Multiple bodies of CrvPattern2 (along Tangential arc, section from tangential arc until top of Grip section); X:"1.2", Y:"1"; Z:"1.2"; Scale about: "Centroid"
12.9	9		Scale3				Scale Parameters: Scale2[23]; X:"1.1", Y:"1"; Z:"1.1"; Scale about: "Centroid"
12.10	10		Scale4				Scale Parameters: Scale2[24]; X:

							"1.2", Y:"1"; Z:"1.2"; Scale about: "Centroid"
12.11	11		Body- Move/Copy1				Bodies to Move/Copy: Scale2[25]; X: "-1.25mm", Y:"0"; Z:"- 5.00mm";
12.12	12		Scale5				Scale Parameters: Body- Move/Copy1; X: "1.4", Y:"1"; Z:"1.4"; Scale about: "Centroid"
12.13	13		Scale6				Scale Parameters: Scale2[26]; X: "1.4", Y:"1"; Z:"1.4"; Scale about: "Centroid"
12.14	14		Body- Move/Copy2				Bodies to Move/Copy: Scale6; X: "- 1.00mm", Y:"0"; Z:"- 3.00mm";
12.15	15		Body- Move/Copy3				Bodies to Move/Copy: Scale5; X: "0.00mm", Y:"0"; Z:"4.00mm";
12.16	16		Scale7				Scale Parameters: Body- Move/Copy3; X: "0.9", Y:"1"; Z:"0.9"; Scale about: "Centroid"
12.17	17		Combine3				"Add", "Bodies To Combine": Multiple (along Throat curve section, from tangential arc top of Grip)
12.18	18		Mirror3				Mirror Face/Plane: "Front Plane", Bodies to Mirror: Multiple Selected
12.19	19		Combine5				"Add", "Bodies To Combine": Multiple (along Throat curve section, and Ellipse section)
12.20	20		Cut-Extrude4				Direction: "Up to Next",

							Selected Bodies: "Combine5"	
				Sketch98				
12.21	21		Loft2				Face<1>, Face<2>	
12.22	22		Loft3				Face<1>, Face<2>	
12.23	23		Loft4				Face<1>, Face<2>	
12.24	24		Loft5				Face<1>, Face<2>	
12.25	25		Loft6				Face<1>, Face<2>	
12.26	26		Loft7				Face<1>, Face<2>	
12.27	27		Loft8				Face<1>, Face<2>	
12.28	28		Mirror4				Mirror Face/Plane: "Right Plane", Bodies to Mirror: "Loft 8", "Merge Solids"	
12.29	29		Face Throat and Grip - Negative Plate (part import)					
12.30	30		Combine9				"Subtract", Main Body:"Mirror4", Bodies To Combine: "Face Throat and Grip - Negative Split [1] and [2]"	
12.31	31		Combine10				"Subtract", Main Body:"Mirror4", Bodies To Combine: "Face Throat and Grip - Negative Split [1] and [2]"	
12.32	32		Body- Delete/Keep1				Bodies to Delete: "Face Throat and Grip" part import (Throat and Grip)	

### Hexa (up) – Face Throat Grip (2)

Process	Feature number	Part section	Folder/Feature/ Sketch	Feature/Sketch	Feature/Sketch	Dimensions	comment
13.1	1	FTIH	Hexagon - up (Part import)				
13.2	2	Grip Inner - Right	Grip Inner - Right - solid 1(Part import)				
13.3	3	Grip Inner - Right	Grip Inner - Right - solid 2(Part import)				
13.4	4		Combine				"Add", Feature No.1-3

8.4 Records of Sketches on Paper

08/01/2015

$95 \text{ mm}$   
 $322.57 \text{ mm}$   
 $205 \text{ mm}$   
 $658.8 - 205 - 322.57 = 158.23 \text{ mm}$   
 $a = 2.5, b = 1.0$

Focus: - focus curve of equal line length of tangent and (offset) Neck line parallel with y-axis  
 $L_N = L_P$

$y = mx + c$   
 eg. for  $N_x = 0$   
 $m = \text{Slope} = \frac{0x}{b \cdot (b^2 - x^2)}$   
 $= \frac{2.5 \cdot (0.7)}{-(10)^2 - (0.7)^2}$   
 $= \frac{-1.775}{-(10704)}$   
 $= 2.52$

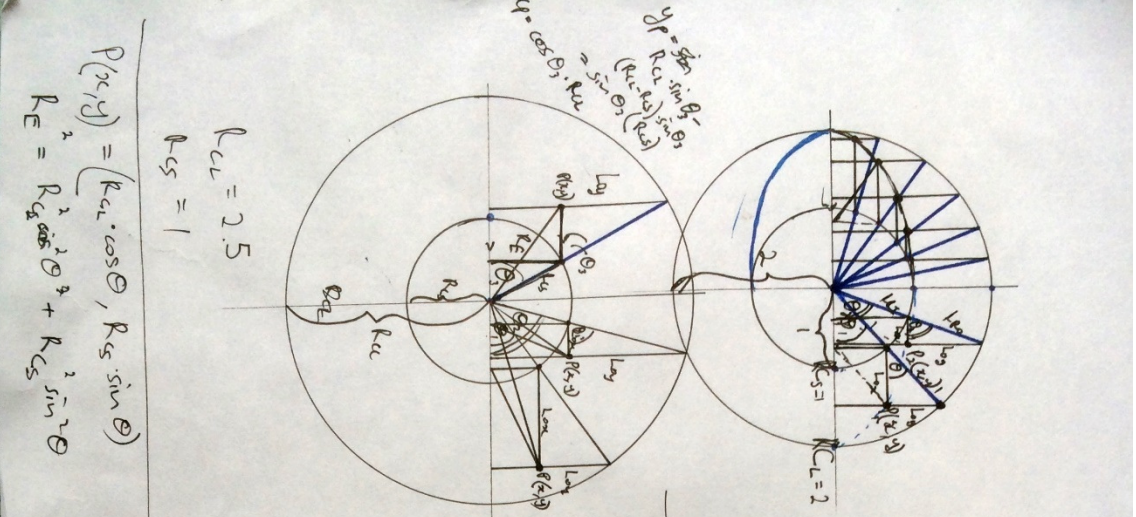
Question: If offset of  $N_x = 10 \text{ mm}$ ,  $572$  of  $L_N, L_P, \theta, \rho(x, y), \beta, B(x, y)$

11/01/2015  
 Where will length of tangent & equal length of line along y-axis from top of as in, but angle will  $\beta$  be  
 have an length of line along y-axis from top of

if  $N_x = 0 \text{ mm}$ , where does the slope touch y-axis, such that  $L_P = L_N$ ?  
 or where is  $\beta < 90^\circ$  such that  $L_P = L_N$ ?

$(1) (2) (1) (2) (1) (2)$   
 $(2) (1) (2) (1) (2) (1) (2)$





$$P(x,y) = (R_{CL} \cdot \cos \theta, R_{CS} \cdot \sin \theta)$$

$$R_{CL}^2 = R_{CS}^2 \cos^2 \theta + R_{CS}^2 \sin^2 \theta$$

$$R_{CL} = 2.5$$

$$R_{CS} = 1$$

$$R_{CL} = 2$$

$$R_{CS} = 1$$

at  $\theta_1 = 40^\circ$

$$L_{R_{CS}} = R_{CS} = 1$$

$$L_{R_{CL}} = R_{CL} = 2$$

$$L_{R_{CS}} = R_{CL} - R_{CS} = 2 - 1 = 1$$

at  $\theta_2 = 70^\circ$

$$R_{CS} = 1$$

$$R_{CL} = 2$$

$\theta_1 = 40^\circ$	$\theta_2 = 70^\circ$
$L_{\theta_1} = (R_{CL} - R_{CS}) \sin \theta_1$ $= (2.5 - 1) \cdot \sin 40^\circ$ $= 0.964$	$L_{\theta_2} = (R_{CL} - R_{CS}) \sin \theta_2$ $= (2.5 - 1) \cdot \sin 70^\circ$ $= 1.41$
$L_{\theta_1} = (R_{CL} - R_{CS}) \cos \theta_1$ $= (2.5 - 1) \cdot \cos 40^\circ$ $= 1.145$	$L_{\theta_2} = (R_{CL} - R_{CS}) \cos \theta_2$ $= (2.5 - 1) \cdot \cos 70^\circ$ $= 0.513$

$$L_{\theta_1} = \frac{1}{\sin 40^\circ} = 1.556$$

$$L_{\theta_2} = \frac{1}{\sin 70^\circ} = 1.064$$

$$L_{\theta_1} = L_{R_{CS}} \cdot \sin \theta_1$$

$$= 1 \cdot \sin 40^\circ = 0.643$$

$$L_{\theta_2} = L_{R_{CS}} \cdot \sin \theta_2$$

$$= 1 \cdot \sin 70^\circ = 0.94$$

$$L_{\theta_1} = L_{R_{CL}} \cdot \cos \theta_1$$

$$= 2 \cdot \cos 40^\circ = 1.556$$

$$L_{\theta_2} = L_{R_{CL}} \cdot \cos \theta_2$$

$$= 2 \cdot \cos 70^\circ = 0.742$$

$$P(x,y) = f(L_{\theta_1}, L_{\theta_2})$$

$$= P\left(\frac{L_{\theta_1}}{R_{CS}}, L_{\theta_1}, L_{\theta_2}\right)$$



$y = mx + c$   
 $h \frac{dy}{dx} = \frac{1}{2}$   
 $\frac{6c}{99} = \frac{2c}{33} = \frac{2}{3} \pm \frac{1}{3}$   
 $0 \leq t \leq 4$

$0 : 100$   
 $(0 : 2, 6)$

$15 = 1 + 2 + 3 + 4 + 5$   
 $3 \quad 6 \quad 10 \quad 15$

Cartesian  
 Polar

$P(x, y)$   
 $r = \sqrt{x^2 + y^2}$   
 $\theta = \tan^{-1} \frac{y}{x}$

$\frac{1}{5} = \frac{1}{5} \cdot \frac{1}{5}$   
 $\frac{1}{5} = \frac{1}{5} \cdot \frac{1}{5}$

$0.000000$   
 $0.000000$   
 $1 \rightarrow 1.0000$   
 $0 \leftarrow 0$

$h \frac{dy}{dx} = \frac{1}{2}$   
 $y = mx + c$

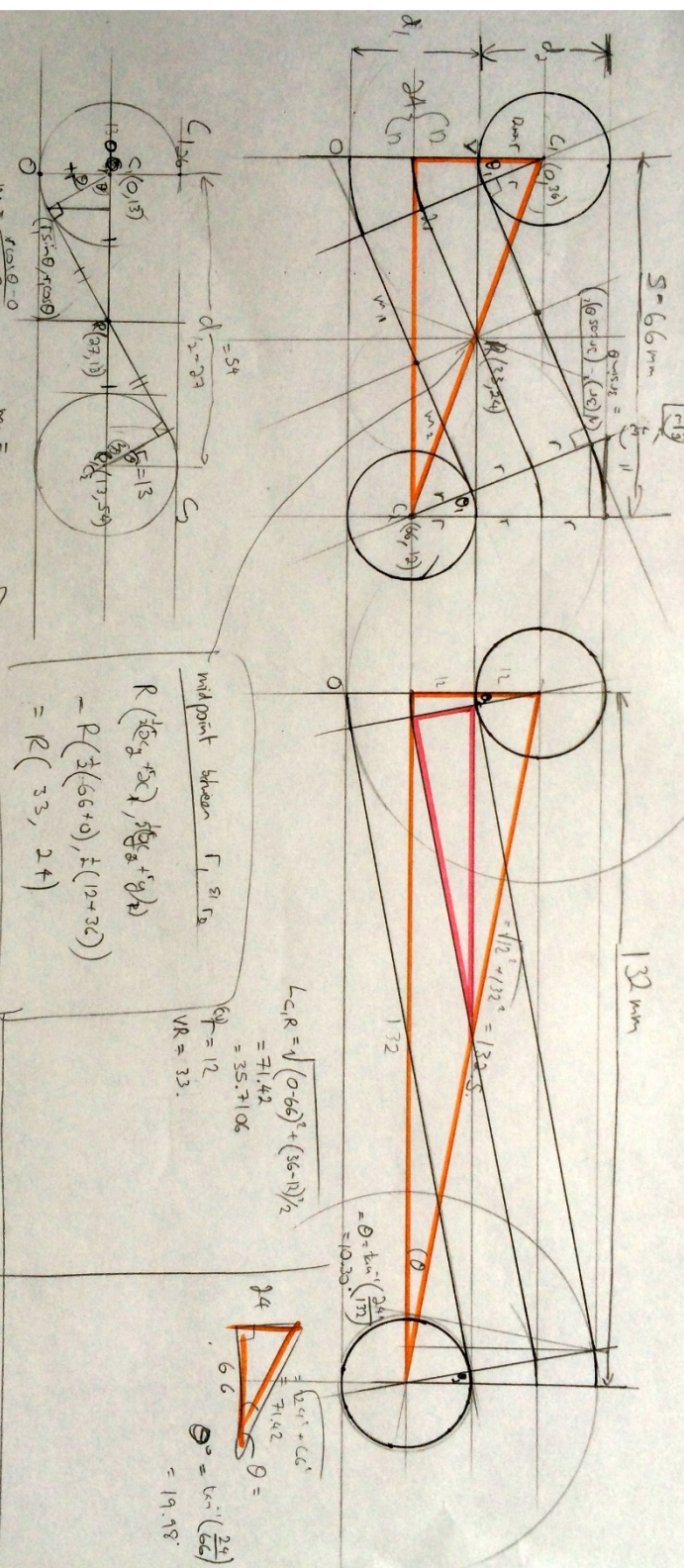
$0.5x$   
 $12.5$   
 $62.5$   
 $100$   
 $x=1$   
 $y=1$

Various geometric diagrams including circles, triangles, rectangles, and coordinate systems.



14.01.015 ①

String w/ same radius  
 Q: What is ① length various string?  
 ② angles above tangent starts?



$$r = 12$$

$$s = 66 \text{ mm}$$

$$\theta = \cos^{-1} \left( \frac{r}{s} \right) = \cos^{-1} \left( \frac{12}{33} \right)$$

$$w_1 = \frac{r \sin \theta}{\cos \theta} = \frac{12 \sin \theta}{\cos \theta}$$

$$w_2 = \frac{r \sin \theta}{\cos \theta} = \frac{12 \sin \theta}{\cos \theta}$$

$$\text{looking for such that } w_1 = w_2$$

$$\frac{r \sin \theta}{\cos \theta} = \frac{r \sin \theta}{\cos \theta}$$

$$\frac{1}{\cos \theta} = \frac{1}{\cos \theta}$$

midpoint between  $r_1$  &  $r_2$

$$R \left( \frac{1}{2}(c_1 + c_2), \frac{1}{2}(y_1 + y_2) \right)$$

$$= R \left( \frac{1}{2}(0+0), \frac{1}{2}(12+12) \right)$$

$$= R(0, 12)$$

$$L_{C_1 R} = \sqrt{(0-6)^2 + (12-12)^2}$$

$$= \sqrt{36} = 6$$

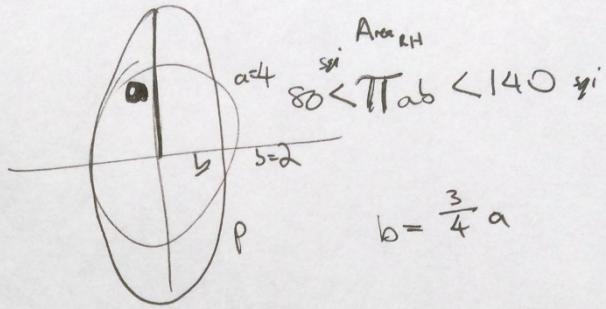
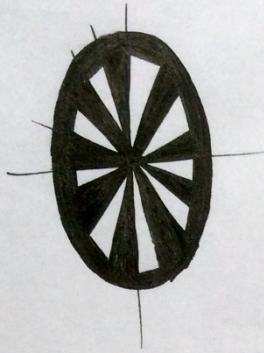
$$VR = 33$$

right triangle with sides 6, 6, and hypotenuse 7.142

$$\theta = \cos^{-1} \left( \frac{6}{7.142} \right)$$

$$= 19.48^\circ$$





$$\text{Area} = \pi ab$$

$$\text{Perimeter} = h = \frac{(a-b)^2}{(a+b)^2} = \frac{(4-2)^2}{(4+2)^2} = \frac{4}{36}$$

$$p = \pi(a+b) \left( 1 + \frac{3h}{10 + \sqrt{4-3h}} \right)$$

$$= \pi(4+2) \left( 1 + \frac{3\left(\frac{4}{36}\right)}{10 + \sqrt{4-3\left(\frac{4}{36}\right)}} \right)$$

$$=$$

$$80 \rightarrow 137 \frac{1}{2} \text{ inches}$$

$$b = k \cdot \frac{A}{\pi} \quad (0.5 \leq k \leq 1)$$

$$a = \sqrt{\frac{1}{k} \cdot \frac{A_{RH}}{\pi}}$$

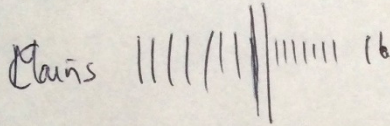
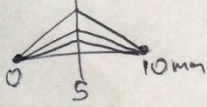
$$A_{RH} = \pi ab \quad \text{with } b = \frac{3}{4}a$$

$$= \pi a \left(\frac{3}{4}a\right)$$

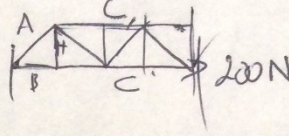
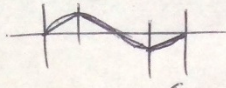
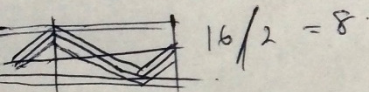
$$= \pi \frac{3}{4}a^2$$

$$\therefore \sqrt{\frac{4}{3} \cdot \frac{A_{RH}}{\pi}} = a$$

Tennis strings

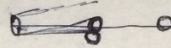
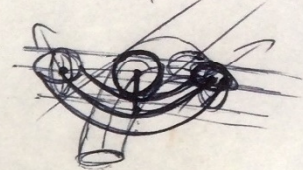
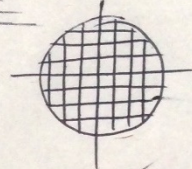
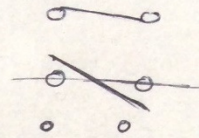


Mains

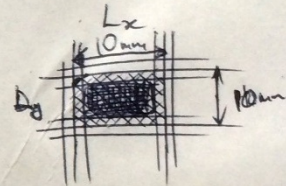


$L_i = 200 \text{ mm}$

$L_f$



String  $w = 1.2 \text{ mm}$



$$A = 10 \text{ mm} \times 10 \text{ mm} = 100 \text{ mm}^2$$

radius is 0.6 mm.

hole area

$$= (10 \text{ mm} - 0.6 \times 2)(10 - 2 \times 0.6 \text{ mm})$$

$$= (8.8 \text{ mm})(8.8 \text{ mm})$$

$$= 77.44 \text{ mm}^2$$

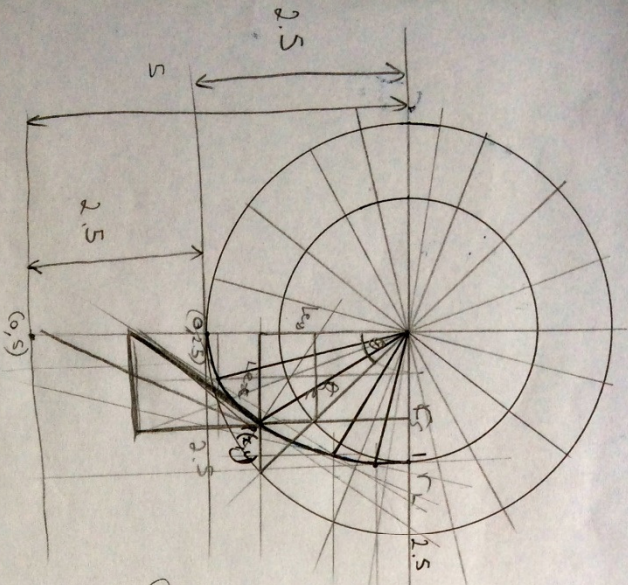
∴ Hole area

$$= (L_x L_y - 2 \times 2r)(L_y - L_y - 2r)$$

$$= L_x L_y - 2 \times 2r(L_y - 2r)$$

$$= L_x L_y - L_x 2r - L_y 2r + \frac{4r^2}{2}$$





$$r_2 = 2.5$$

$$r_1 = 1$$

$$P(x, y) = x : L_{ex} = r_s \cdot \sin \theta = P(r_s \cdot \sin \theta, r_L \cdot \cos \theta)$$

$$y \neq L_{ey} = -r_L \cos \theta$$

$$\therefore r_e = \sqrt{(r_s \cdot \sin \theta)^2 + (r_L \cdot \cos \theta)^2}$$

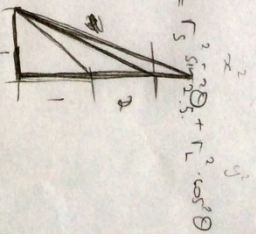
$$\text{at } 45^\circ = \sqrt{1^2 \sin^2(45^\circ) + 2.5^2 \cos^2(45^\circ)}$$

$$= \sqrt{0.5 + 6.25(0.5)}$$

$$= 1.9$$

$$P(x, y) = (1 \cdot \sin 45^\circ, 2.5 \cos 45^\circ)$$

$$= P(0.71, 1.77)$$



$$r_e^2 = r_s^2 \sin^2 \theta + r_L^2 \cos^2 \theta$$

$$\frac{r_e}{r_s} = \text{ratio}$$

$$a = 1$$

$$b = 2.5$$

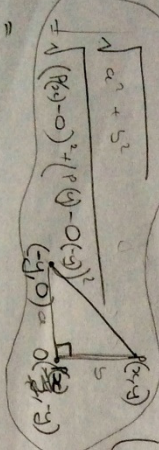
tangent will between  $(0, 2.5 \leq y \leq 5)$  and  $(1 \leq x \leq 2.5, 0)$

$$y = mx + c$$

$$y = \frac{1.5x \leq 2.5}{2.5y \leq 5} \cdot x + (2.5y \leq 5 \cdot 0)$$

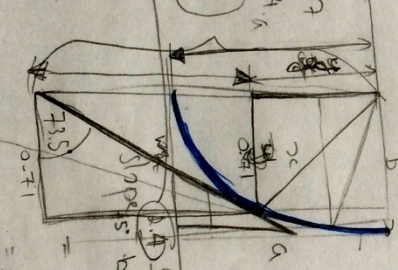
$$y = mx + c$$

$$y = 2.5x + c$$



$$y\text{-intercept} = \sqrt{1-x^2} + y$$

$$\cos^{-1}\left(\frac{0.71}{1.5}\right) =$$



$$\text{slope} = \frac{-5x}{0.71x - 2} = \frac{-5(\sqrt{1-x^2})}{0.71x - 2}$$

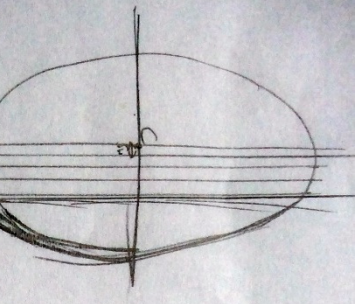
$$= \frac{-0.7104}{2.5 \cdot 0.71}$$

$$= -0.7104$$

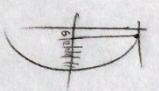
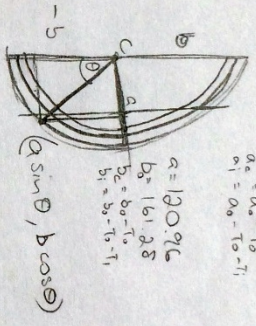
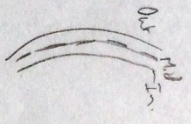
$$= 0.4$$

$$= \frac{1.775}{0.7104} = 2.52$$





- Inner Thickness
- Ellipse Midline
- Outer Thickness (Max of Force/Ellipse Area)



Main  
 $S_{m1}$  when  $x = b$   $y = ?$

$a \sin \theta = b$   
 $\therefore \sin \theta = \frac{b}{a}$   
 $\theta = 2.84321$

~~MAINS~~  
 $C_y + \frac{1}{2}(S_w)$

$S_{m1} + \frac{1}{2}(S_w) = \text{desired width of}$

$S_w = \frac{100.96}{1+2(\sin \theta)} = 5.864 \text{ mm}$

$S_{m1}$  at  $\sin^{-1} \theta = \frac{6+12}{120.96} = 8.55794$

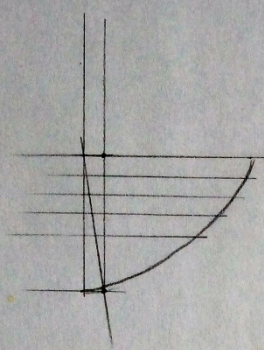
$y = b \cos \left( \sin^{-1} \left( \frac{S_w}{a} \right) \right)$   
 $= 161.28 \cos \left( \sin^{-1} \left( \frac{18}{120.96} \right) \right)$   
 $= 159.484$

$S_{m2} (S_w + \frac{1}{2}(S_w)) b \cos \left( \sin^{-1} \left( \frac{(S_w/2) + (S_w)}{a} \right) \right)$

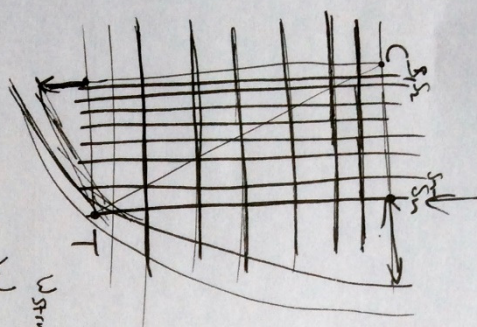
$S_{m5} (7 + (5-1)2(4)) 161.28 \cos \left( \sin^{-1} \left( \frac{7 + (5-1)2(4)}{120.96} \right) \right)$   
 $S_{m5} = (63, 161.28 \cos \left( \sin^{-1} \left( \frac{63}{120.96} \right) \right))$   
 $= S_{m5} (63, 137.678)$

Check at last stage:

$S_{m1}$	(100.96, 161.28)
$S_{m2}$	(100.96, 88.828)
$S_{m5}$	(87.96, 161.28)
	(87.96, 110.7044)







$$\frac{\text{Main } ||||}{\text{no. of strings}} \quad \frac{V}{\text{width of strings}} \quad \text{eg } \frac{8}{8}$$

target from C (L):

- width  $(F_w \sin \theta)$

- length  $(F_l \cos \theta)$

$V$  String width

$v$  String length

$$W_{S_{n-1}} = \frac{P_{S_{n-2}} \cdot v_{\text{string width}} - P_{S_{n-2}}}{2} + P_{S_{n-2}}$$

$$W_{S_n} = v_{\text{string width}} \quad (0.1 \text{ mm})$$

$$W_{S_{n-1}} = \text{roundup}(v_{\text{string width}} \cdot S_{n-1})$$

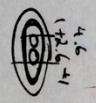
$$W_{S_{n-2}} = S_{n-2} + 2 \cdot (v_{S_{n-1}} \cdot S_{n-1})$$

$$W_{S_2} = S_{n-1} + 2 \cdot (W_{S_{n-1}}) \cdot S_{n-1}$$

$$S_6: S_6 = S_6 = S_{n-1} + 2 \cdot (3) \cdot S_{n-1}$$

$$= 5.7 + 2 \cdot (5.7) \cdot (5)$$

$$= 61.4$$



Calc

$$① v_{\text{string width}} = C \times (0)$$

$$+ \text{Space } C_{S_1} + 2 \cdot (S_{n-1})$$

$$S_{n-1} \cdot (S_{n-1})$$

$$n=5$$

$$v_{\text{string width}} = \frac{85.2395}{85.2395}$$

$$(0 + w_{\text{string}} + 2 \cdot (n-1) \cdot v_{\text{string}})$$

$$= 85.2395 = w_{\text{string}}$$

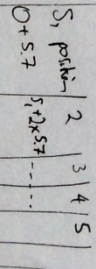
$$+ 2 \cdot (8-1) \cdot w_{\text{string}}$$

$$w_{\text{string}} = \frac{85.2395}{15}$$

$$= 5.68$$

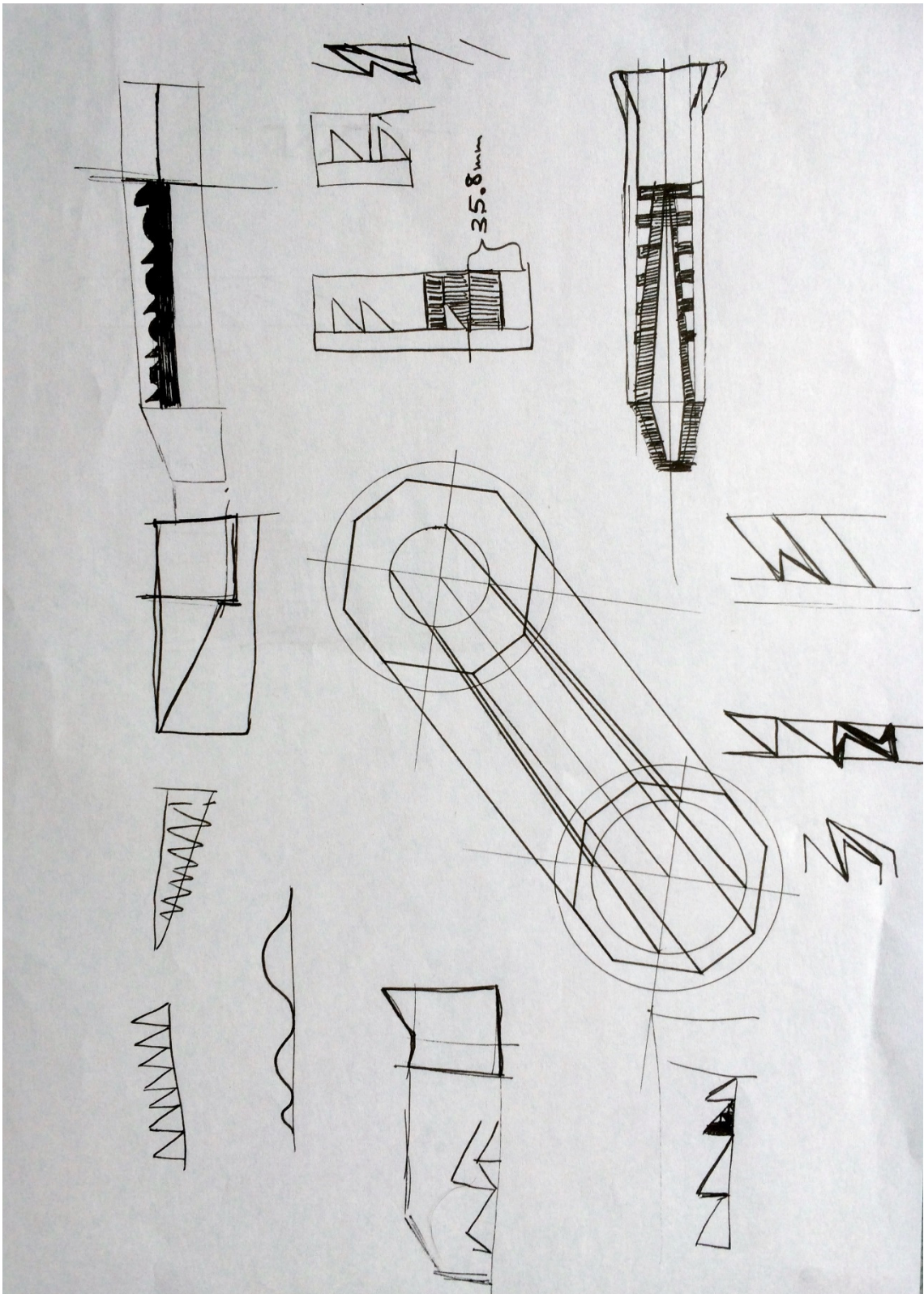
∴ round to nearest atom

$$= 5.7 \times$$



∴ round to nearest atom







NSP @ x-point of  $T_1 (F_w \cdot \sin \theta, F_H \cdot \cos \theta)$

$$= T_1 (120.96 \sin 39^\circ, 161.28 \cos 39^\circ)$$

$$= T_1 (76.1225, 125.338)$$

if  $T (85.24, 114.568)$

Means:  $S_0 + 2(n-1)S_w = S_{total}$

$$S_w = \frac{S_{total} - S_0}{2(n-1)}$$

$$= \frac{85.24 - 15}{2(8-1)}$$

$$= 5.6826$$

Working out giving distance

CROSS

$$S_w = \frac{S_{total}}{2(n-1)}$$

$$= \frac{114.568}{1+2(8-1)}$$

$$= 7.63786$$

$$7.5 \times 15 = 112.5 \text{ mm}$$

added to left width.

$$\frac{114.56837 \text{ mm} / 15}{7.637}$$

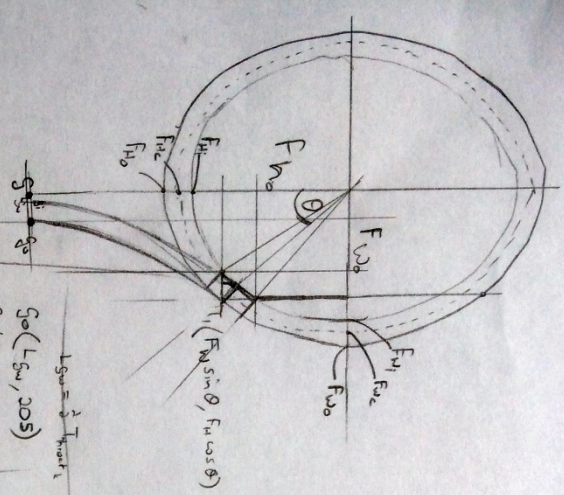
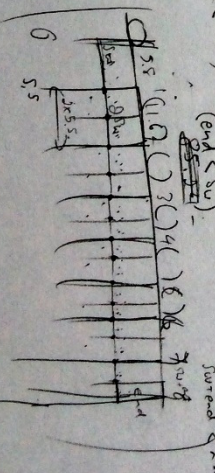
$$7.3 \times 14 = 102.8$$

$$6.76835$$

Solidworks

$$\frac{85.24}{15} \Rightarrow \frac{85}{15} = 5.67 \approx 55$$

$$55 \times 24 = 1320$$



Thickness wall = 13mm  
(F<sub>w</sub> wall)

Means:  $E_I (E_{I_x}, E_{I_y}) = (F_w \sin \theta, F_H \cos \theta)$

Inner meeting of T

$$120.96 \cdot \sin 39^\circ = 75.24$$

$$E_I: 120.96 - 13 \text{ mm } (F_w E_z)$$

$$= 107.96 \text{ mm}$$

$$F_H: 161.28 - 13 \text{ mm}$$

$$= 148.28 \text{ mm}$$