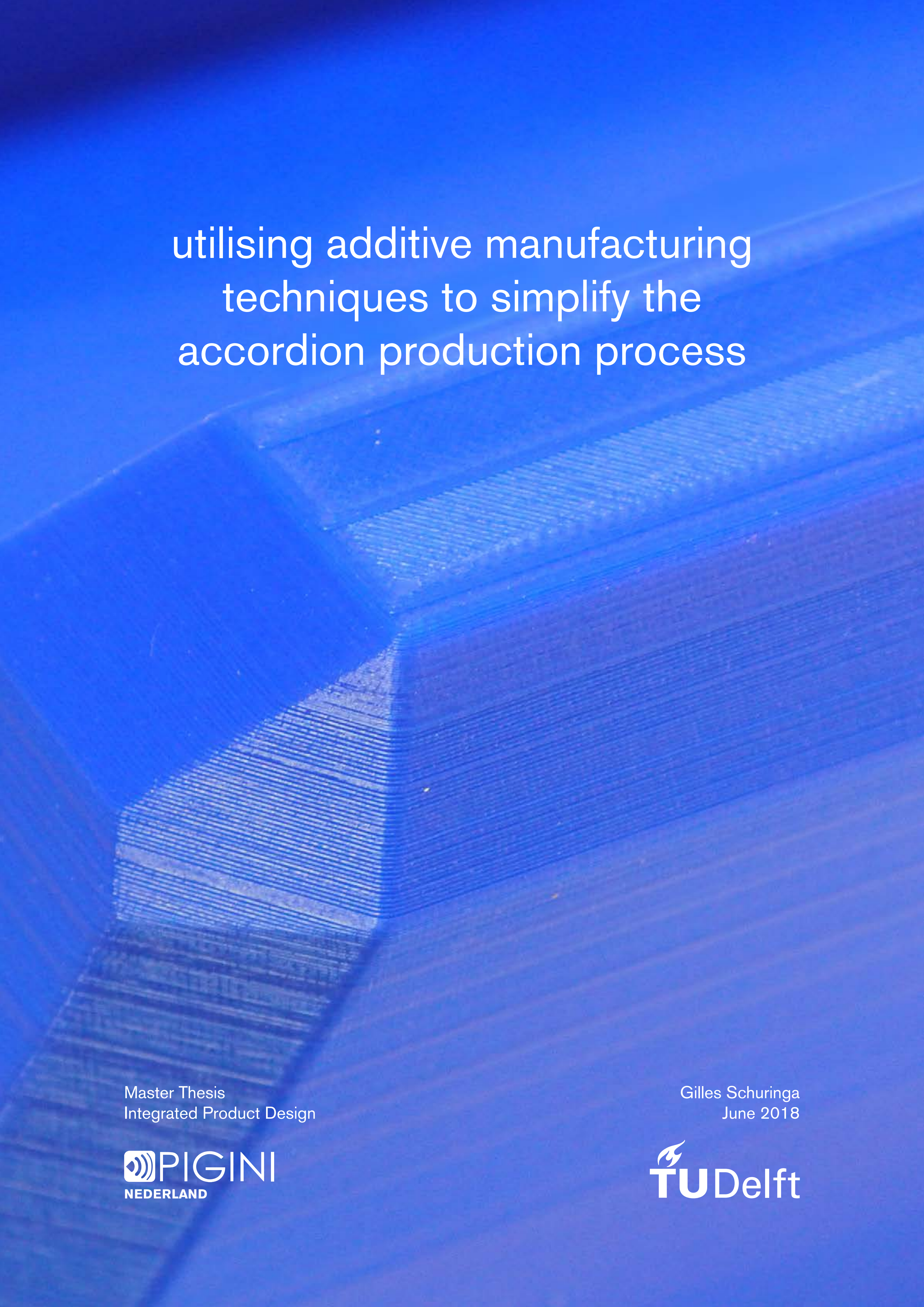

utilising additive manufacturing techniques to simplify the accordion production process

Master Thesis
Integrated Product Design

Gilles Schuringa
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PIGINI
NEDERLAND

TU Delft

Utilising additive manufacturing techniques to simplify the accordion production process

This master thesis is part of the Integrated Product Design master programme at the Industrial Design Engineering faculty of Delft University of Technology.

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EXECUTIVE SUMMARY

GOAL

This thesis focuses on the utilisation of additive manufacturing (AM) technologies for the production of accordions. The goal is to reduce the man hours required in the production and repair of the instrument. The client, Pigini Nederland, currently produces a small accordion for children and adults: the MiniMouse. This instrument is sold for 999 euros, which is a relatively low price for the amount of man hours invested. Pigini Nederland wants to lower the threshold of becoming familiar with the accordion by reducing the price of an entry-level instrument, similar to the MiniMouse in terms of functionality.

ACCORDION CONSTRUCTION

The sound of an accordion is produced by a reed: a piece of spring steel that vibrates when air flows past. To create a tone, the reed's valve needs to be opened and an airflow needs to be created using the bellow. A mechanical structure of aluminium bars forms the connection between reed valve and button. A torsion spring keeps the valve in a closed position and creates resilience for the button.
The production of an accordion is a complex process consisting of mostly manual operations. Some of these operations are rather time and labour intensive, such as shaping the body and inner mechanics, and creating the bellow. The repair of an instrument can be an inefficient process: the complete disassembly of certain components is sometimes necessary to replace a single component.

ADDITIVE MANUFACTURING

Producing parts with complex geometry is one of the strengths of AM. This can lead to a reduction in tooling and inventory and part consolidation. This is an important driver for choosing AM as a means of production.
Fused Deposition Modeling (FDM) is chosen as the production technique for this project. FDM prints have good mechanical properties and require little post-processing. There is a wide range of materials available and the process and printer are relatively cheap. Pigini Nederland is interested in in-house production, which is realisable using an FDM printer.

DESIGN

The assignment focuses on the right hand side of an accordion, which has been fully designed and 3D printed. The fundament of the design is the **instrument body.** Multiple components are attached to it, resulting in a full-fledged instrument. For these attachments, non-printed connectors have been used as little as possible so that assembling the instrument is easy.

The **mechanical structure** consists of separate arms that are placed in the body using snap fits. A printed spring-like element is incorporated so that the arms of the structure bend when a button is pressed to open the reed valve. As the material loses its natural resilience during the expected 10 year product lifetime, a steel compression spring is added to regulate the button pushing force.

The **buttons** are attached to the mechanical structure using a snap fit. This makes it possible to quickly detach all buttons when repairing the instrument. In a conventional instrument, buttons are attached using glue and need to be broken off in such a scenario.

The **reeds** of a conventional accordion are attached using molten wax. Since this is labour-intensive during production and repair, the reeds in the printed instrument are clamped onto the body using a rubber gasket, nuts and bolts. The size of the reed sound chambers is determined by analysing sound samples and comparing them pairwise in a user test.

RESULTS

The project outcome provides an indication on how to use AM for accordion production. A printed proof of concept showcases that the instrument is fully functional, while minor design recommendations need to be addressed. An estimation of the material cost and labour during production is made, and a cost reduction of roughly 15% of the full instrument is established. This is a large step forward, as only the right hand side of the product has been redesigned. It is a clear indication that additive manufacturing can be a valuable tool in lowering the engagement threshold for future accordionists.

TABLE OF CONTENTS

1. PROJECT SETUP

This project covers the development of a small accordion design. The goal is to indicate where and how the use of additive manufacturing techniques as a means of production can increase the cost-effectiveness of accordion production. The project is assigned by Pigini Nederland, which is run by Casper Burkhardt.

COMPANY

Pigini Nederland is the Dutch importer of Pigini accordions. Pigini is a family business established in 1946, producing high-grade accordions. All their instruments are handmade in Italy and often last for decades. Their portfolio ranges from small beginner accordions, starting at 1600 euros, to large concert instruments up to 32.000 euros. The larger instruments are usually custom builds. This concerns not only the visual components, but also the functioning of the instrument. For instance, an accordion has preset registers, and a customer can ask to replace certain registers with others that he prefers.

Currently, Pigini produces around 1500 accordions a year. These are all hand-built in Castelfidardo, Pigini's headquarters in Italy. Most materials used for production are self-made or procured in the area, where many part suppliers are located.

Pigini is one of the leading players on the international accordion market. In the past years, it has incorporated Excelsior, a large accordion brand that produces several thousands of instruments each year. Quite a few of Pigini's main competitors are also based in Castelfidardo. They are high-end accordion manufacturers and create instruments of superb quality. Their instruments sound good, are technically advanced , incorporating many functions while trying to keep the weight low. What differentiates Pigini from competitors is the good in balance of the left and right side of the instrument in terms of volume and timbre. Some parts of Pigini's instruments are similar in layout to that of competitors' accordions. Other part layouts, such as the bass system, are specifically designed by Pigini.

The instrument in this project is relatively small and simple for a Pigini instrument. Even so, Pigini's quality and their instruments' high-end reputation are determinant for the desired project outcome.

PIGINI

Printed accordion body prototype by Pigini Nederland

DESIGN BRIEF

The design of the accordion can be considered as traditional, as it has not been changed a lot over the past decades. Accordions are made out of a wooden basis, on which a mechanical system is attached. A result of this is that it takes a lot of man hours to assembly a single instrument, even with cellular manufacturing techniques. This makes an accordion a high investment for potential accordionists. It creates a threshold not only for them, but also for others, such as music teachers who want to offer children the possibility to try out different instruments.

Pigini Nederland currently sells a self-produced small accordion meant for children, the MiniMouse. This instrument can be used in for instance musical classes. The consumer price for this relatively simple instrument is currently 999 euros. Market-wise, this is considered as an acceptable price for such an instrument. However, considering the labour required to make these instruments, the price should be higher. Pigini Nederland is currently looking into new design approaches. They want to analyse where the traditional concept of the accordion can be adapted in order to improve its efficiency, operation and sound. Pigini Nederland has already created a 3D-printed prototype of a small accordion body, similar in size to the small Pigini model. Va this project, they hope to take their innovation process a step further. The goal is to create a final design that can eventually be implemented on larger instruments as well.

Pigini Nederland's MiniMouse (left) forms the inspiration for this project. The Pigini Simba (right) is Pigini Italy's smallest accordion.

INTERPRETATION

In short, the problem provided by Pigini Nederland can be defined as follows: *There is no affordable yet full-fledged alternative to traditional starter accordions on the market.*

Full-fledged here means being comparable to the traditional accordion in terms of playing interaction and sound quality. The playing interaction is defined by multiple aspects. The most important ones are the feeling and sensitivity of pressing a key, the pressure on the bellow to create a certain volume and the presence of background noises while playing. The sound quality is defined by sound accuracy (pitch), but also by sound enjoyability as perceived by the user.

The assignment is to find out how additive manufacturing technologies can be used to simplify the production of a small accordion, focusing on a small batch of instruments. This does not mean a whole new accordion needs to be designed. Rather, it focuses on finding new solutions for parts of the existing instrument.

How can additive manufacturing technologies be used to simplify the production of a small accordion, for a small batch of instruments?

Although the starting point is Pigini Nederland's current small accordion, possibilities to scale to larger instruments should be kept in mind. The aim of the assignment is a design that is suitable for small-scale production in the Netherlands. The result should not per definition be an accordion as we know it in terms of physical appearance. It should, however, have a comparable sound perception and playing interaction.

PROJECT STRUCTURE

In order to redesign the accordion, it is necessary to research the accordion itself and the way it produces sound. This knowledge needs to be combined with insights in additive manufacturing processes.

With all necessary information at hand, it is possible to choose a certain scope and define the different design challenges. The different components of the instrument need to be translated into a design that can be produced by means of additive manufacturing.

Since the instrument has many components and they all have an influence on each other, the design process will be far from linear. Test results of one component might influence the design of others. This means multiple components can be worked on during the same phase of the process, although their level of detailing might differ from each other. For instance, the body of the instrument needs to hold all components together and is to be detailed at the end of the process, when all other components are finished.

Designing a component will be done according to the relevant requirements, while keeping the production parameters in mind. Ideas for a certain part are worked out to concept level. One of the concepts is then worked out into a final design. If necessary, decisions can be made using known techniques such as a Harris profile (Van Boeijen, Daalhuizen, Zijlstra, & Van der Schoor, 2014).

Once the design of all components is finished, the functionality and sound of the instrument has to be evaluated.

PROJECT SCOPE

The project will focus on the production of an accordion with 19 buttons on the right hand side. While conventional reeds will be used, any other part of the instrument can be altered as long as it meets the requirements. The main requirements for the project are:

- The material, component, machine and assembly/ labour cost combined do not exceed the cost of the current MiniMouse (999 euros). The focus here is on man hours.
- Additive manufacturing techniques are used to create the core parts of the instrument. This can eventually be combined with other parts.
- The product dimensions are comparable to that of the current MiniMouse.
- The product lifetime is expected to be at least 10 years considering a use scenario of 30 minutes a day.
- The product playing interaction is comparable to the current MiniMouse. This means that instrument configuration and tone production for the user will be similar.
- Although the sound of the instrument does not have to be exactly similar to that of a conventional instrument, it is important that users perceive the sound as a pleasant and full-fledged accordion sound.
- The (future) facilities of Pigini Nederland are suitable to produce and assemble the instruments in the Netherlands.
- The production time of an instrument after an order is placed is under two weeks.

Because of the size of the project, it is chosen to focus on the right hand side and bellow of the instrument only. The left hand side is more complex, as one button on the left can produce multiple tones. Starting with the right hand side is therefore a logical choice.

During this project, the focus is on functionality. Some requirements, however important, are considered outside the scope of this project:

- *Weight of the instrument*
  During this project's design stage, the precise weight of the product is subordinate to its functionality. Weight adjustment is possible during next steps.
- *Aesthetics*
  The aesthetics of the design as a whole are important to make the product a success. However, aesthetic detailing is not considered to be part of this project. For instance, in conventional instruments, mother-of-pearl can be used for button aesthetics. During this project, the button aesthetics will probably be defined by the material that is used for functional reasons. Such specific aesthetic elements are of low importance during this project.
- *Sustainability*
  This element is considered important by all stakeholders. While clearly unsustainable design choices should be avoided, the precise environmental impact of the design needs be considered in a later phase.
- *Precise timbre influence of certain components*
  For instance the influence of the material of the body and gasket on tone production will not be researched thoroughly.
- *Production error reduction*
  Some elements may have dimensions that are suboptimal for the additive manufacturing process, resulting in longer production times. Creating a functional prototype is currently more important than reducing errors in the long run.

2. ACCORDION ANALYSIS

After interpreting the assignment, it is important to know what an accordion is and how its functional components are positioned.

2.1. accordion - the basics

The accordion is a relatively young instrument, although its basic principle is very old. Its basic functions are simple, but there many parts are required to make everything work.

HISTORY OF THE ACCORDION

The accordion is a descendant of the sheng. This is a Chinese mouth organ consisting of pipes mounted on a base. It was invented around 1100 BCE.

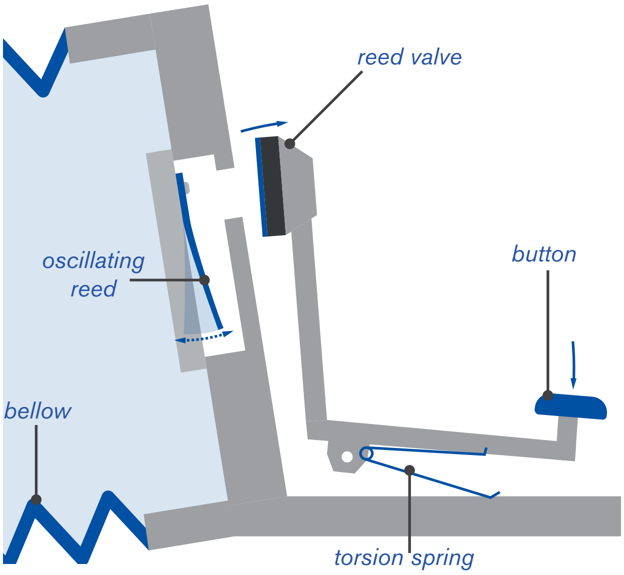
Each pipe has a free reed that produces a sound when air flows past. The accordion uses the same principle as the sheng, although its reeds are heteroglottal. This means that the reed is made separately from the reed holder. The reeds are made out of spring steel. Furthermore, the accordion does not have a coupled pipe resonator (Ricot, 2005).

The accordion in its current shape dates from 1829, when a small four-octave instrument was patented. Later, the accordion industry was born in Italy. In the middle of the 19th century, a pilgrim stopped by chance at Antonio Soprani's house, carrying an accordion. It got the attention of Antonio's eldest son, who disassembled it overnight and later opened his own accordion workshop in Castelfidardo. Nowadays, this is still the world's accordion capital, housing dozens of accordion manufacturers, including Pigini.

One of the world's first accordions, built in 1829 by Cyrill Demian

WORKING PRINCIPLE

The accordion is a free reed wind instrument. This means it produces sound by making air flow past a vibrating reed in a frame. The self-excited oscillations of the reed occur without acoustic coupling (Ricot, Caussé, & Misdariis, 2005; Tonon, 2009). The air flow is produced by a bellow, made of cardboard. When you press a key, a cover is lifted from the reed opening and air is able to flow through. The key is brought back in place via a torsion spring.



The term free reed indicates that the reed can move without obstruction. Unlike a saxophone reed, which is a beating reed, the metal accordion reed does not beat against a mouth piece. The accordion reed is a dominant reed that operates operating without resonators. This means that the oscillation and the sound the reed produces do not depend on the acoustic influence of the up- and downstream volumes (Ricot, Caussé, & Misdariis, 2005; Cottingham, 2011).

The vibration of the reed influences the airflow through the reed opening. This results in sound waves: a longitudinal wave of air pressure. The reed creates a vortex as it is continuously opening and closing the airhole (Tarnopolsky, Lai, & Fletcher, 2001). Each reed produces a different tone, and since the air can move in two directions, every tone requires two reeds. These two similar reeds are mounted onto an aluminium block with two reed-shaped holes. A leather valve on the back of each reed hole prevents the air from flowing in the wrong direction.

The reeds are mounted on a wooden block that is placed inside an accordion. The body of the accordion undergoes forced vibration because the reeds are connected to it. The instrument will vibrate in its natural frequency, influencing the sound. Furthermore, the aerodynamics of the sound chambers can have a large influence on the timbre. Wood is an orthotropic material, which also influences the path of the vibrations. Additive manufacturing material is to some extent anisotropic.

The reeds used for the instrument in this project will be the same as for a conventional instrument. This provides a similar starting point for the sound of the conventional design and the redesigned instrument. When designing this instrument, there is a lot to learn from the components in conventional instruments and their working principles.

Sound chambers in a conventional instrument

A finished conventional instrument, using wax to attach the reeds

2.2. accordion production

Every Pigini accordion is handmade in their factory in Castelfidardo, Italy. Via cellular production, all employees focuse on their own speciality within the production process.

Accordion bodies in the Pigini factory, awaiting further treatment

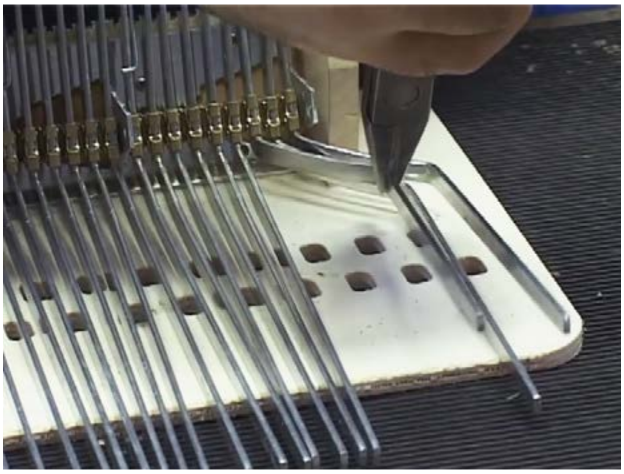
PRODUCTION FACILITIES

A visit to the Pigini factory in Castelfidardo provides insight on the production process of Pigini. Their factory layout is fit for sequential production, where every employee has its own specialized task. When necessary, some people can switch to another task in order to optimize the process flow: these are cellular elements within the sequential process.

It is remarkable that many process steps have grown over the years, while there is not always a scientific ratification for the design of certain components. For instance, there are no clear guidelines for the design of the button spring system. Many things are executed based on trial and error and intuition.

The production begins in the wood workshop, where the rough shape of the body is put together. It is then sanded to create the right shape, for instance rounded corners are created. A separate part to hold the mechanics is prepared, consisting of a wooden frame and a wooden or aluminium plate with holes for the airflow. Up to seven types of wood are used for the largest instruments in order to create the desired sound.

The next step is to build in the mechanics. Once the aluminium bars of the right hand side mechanics are all in place an axis, they are bent into the right position above the air holes and cut off manually. The springs have to be placed inside the instrument by placing the ends into tiny holes. This creates a tension onto the aluminium bars. When the basic mechanics have been placed inside the instrument, the body parts can be put together into one piece and covered in celluloid.



Manual bending of right hand side mechanics

Fixation of arms on the left hand side

Placing the torsion springs in the arms

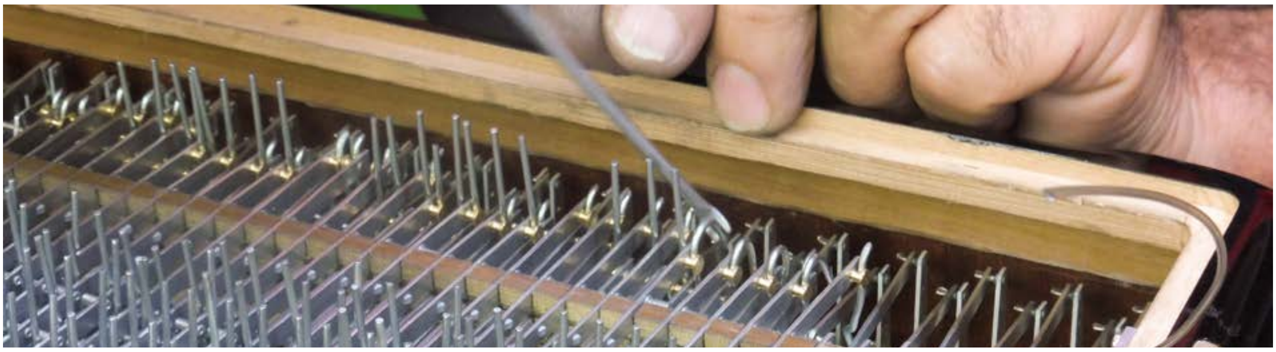
Finishing hooked branches

The left hand side works via a similar production process. However, because of the complexity of the mechanics here, there are a few extra steps. When a button is pressed, one bar actuates the next in order to open multiple valves.

The assembly of the mechanics is started from the valves, and all bars are mounted on a metal rod. The valves themselves are fixed on the bars by manually casting them in hot wax. A hooked branch that can be triggered by a rod with multiple branches is connected to the arm. This way, the rod can trigger multiple valves when set in rotary motion.

The hooked branches can be welded using a robot nowadays, as well as the pins on the bars that connect with the branches. Still, they need to be post-processed by manual sanding in order to make the detailed mechanics function properly. Furthermore, every bar is unique in its shape, and has to be bent accordingly.

To finish the mechanics, all parts are placed inside the instrument and the last metal parts are bent into shape. A plastic base for each button is put on the end of each bar and glued to it with great care for its position. After this, a cover is put over the mechanics, and the buttons are glued onto the bases, once more with great care for their position.



Many components are manually bent into place, such as these rods on the left hand side of the instrument

The reeds, mounted on blocks, are placed inside the instrument and fixated using a form closure. Now, the body parts can be polished in order to make them look as good as possible. Furthermore, some visual components like the grille and logo are attached. A bellow is added next. A final quality check is done both visually by inspecting the instrument and functionally by tuning and playing the instrument.

Custom orders are normal business for Pigini. Custom adjustments are indicated by writing them on a layer of tape that's on the instrument. This way, no worker will miss a customization that is relevant for his part of the process.

Applying wax on the reeds

Custom components are written out on a layer of tape for the relevant production steps

A bellow during production. The cardboard base has been established, the corners are covered by leather. Applying fabric is the next step.

BELLOWS

Pigini does not produce their own bellows. Instead they acquire most of them via Marconi, another company from Castelfidardo. They produce bellows from folding cardboard that is being cut to any desired size. Four cardboard parts are stapled together, and the corner borders are covered in fabric. Diamond-shaped pieces of leather are placed over the holes in the corners. More fabric is added while the bellow is in a stretched position, creating any desired pattern. On the outer corners, plastic and metal corner strips are placed to prevent the bellow from being damaged. The bellow is then heavily pressurized in a mechanical press, in order to keep it in a closed shape.

Five empoloyees of Marconi produce 20 to 30 bellows a day. They are sold to multiple accordion manufacturers.

Bellows are pressurised to keep them in a closed position

Aluminium reed housings are produced using a punch. Here, they await assembly of the reed.

REEDS

The reeds in a Pigini accordion can come from multiple sources. For this project, we will incorporate industrially produced reeds. They are less expensive than hand-made reeds, which solely used in the most high-end accordion models.

In the reed factory, the reed holder is produced by punching four holes out of an aluminium block: two rectangular, and two small circular holes. The reeds themselves are punched from a spring steel sheet. The reed is then mounted on the aluminium block by hand, using a metal rivet. Subsequently, the reeds movement is tested on obstructions or air leaks. Eventually, the reeds are pre-tuned into the right tone using a very fine band grinder.

A reed is pretuned after assembly. After accordion construction, all reeds are tuned once more, this time more precise.

PRODUCTION TIME

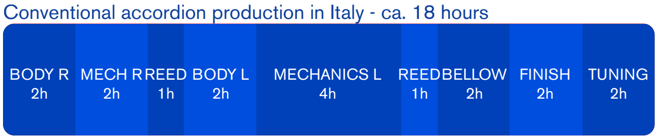
The assignment focuses on the construction of an accordion that is to be produced by Pigini Nederland. This means that the production is likely to be done by a single person. Therefore, the production time for Pigini Nederland's small accordion is given as a baseline for the design.

The production of a conventional instrument this size takes about 31 man hours (see figure). The focus of the assignment will be on 18 man hours of production, since the left hand side is out of its scope, while finishing and tuning the instruments are parts that remain necessary in order to deliver a similar quality.

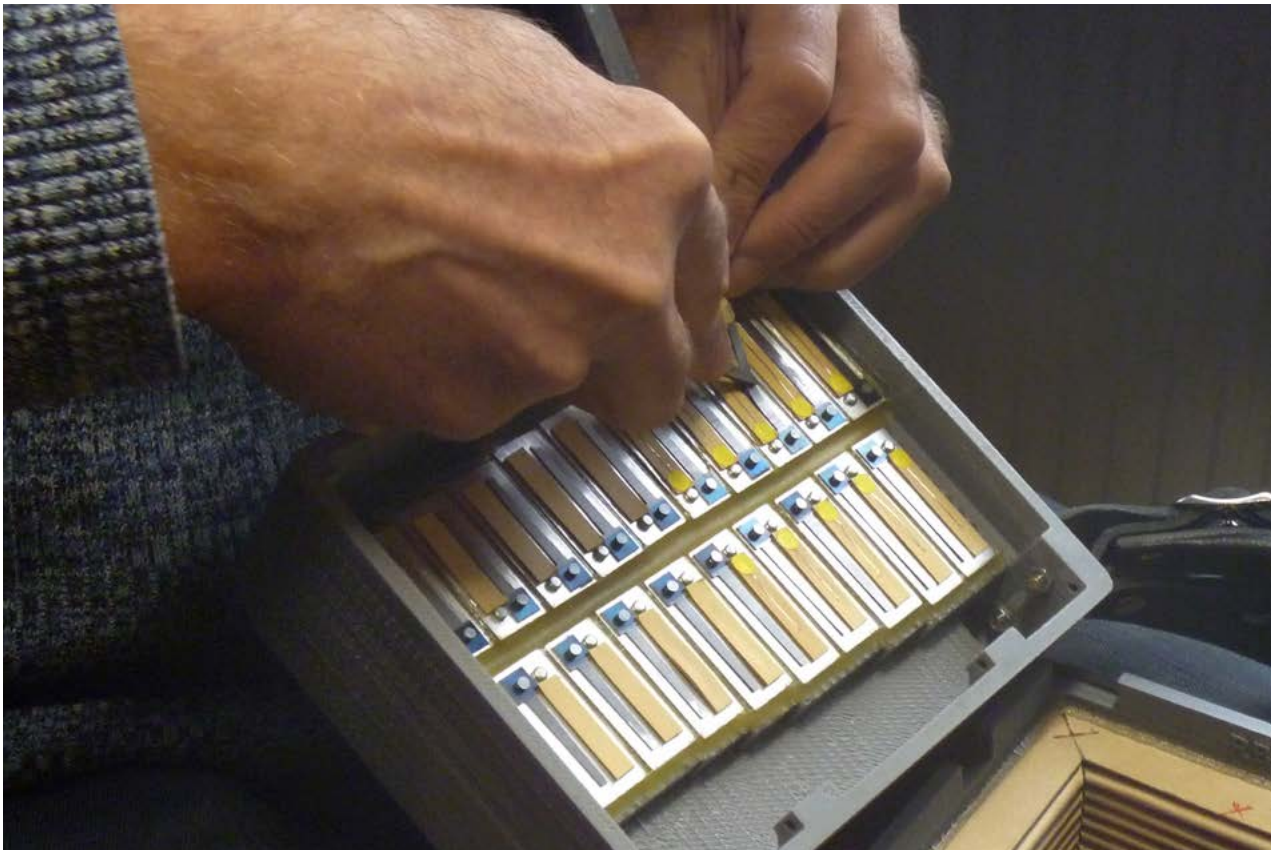
Glued components in the wooden body take approximately 24 hours to dry. The reed wax hardens out rather quick. During bellow production, overnight drying is also required. Furthermore, the bellow needs to be placed under pressure during production, which easily takes 48 hours. This makes the bellow the bottleneck in the production. If the work on the bellows starts at the beginning of production, the instrument can be produced in 8 (assembling bellow) + 12 (drying bellow) + 48 (pressurising bellow) + 2 (tuning) = 70 production hours.

Conventional accordion production in the Netherlands - ca. 35 hours

Conventional accordion production in Italy - ca. 18 hours



An overview of the man hours required for accordion production in Italy and the Netherlands, considering a batch of ~10 instruments.



Reeds are tuned by scraping material off its base or bottom. The reeds of this instrument are attached directly onto the body. The reeds that lie upside down (behind the leather ventiles) can be reached using special tools.

MAINTENANCE

It is important to take maintenance into account when designing an accordion. Every year or so, the instrument will have to be tuned, and sometimes components need to be replaced.

Tuning is the most common type of maintenance. It is done by scraping material off the base (to lower the pitch) or end (to raise the pitch) of the reed. To do so, the reeds should be easily accessible. For tuning, the bellow needs to be disconnected from the body, and the reed blocks are taken out.

It is an option to attach the reeds directly onto the body of the instrument instead of using separate reed blocks. The orientation of the reeds should provide the possibility to reach both reeds without too much obstruction. The lower reed can be accessed by pulling it up with special tools.

When the bellow is put back after scratching the reed, the sound is most true to the original sound of the instrument. This is an action that will have to be performed quite a lot while tuning the instrument.

Another type of maintenance is that of replacing a reed in case it is broken, or replacing the wax when it has become too old. This means all wax should be heated up and removed, which is a labour intensive process.

A more rare type of maintenance is the replacement of parts of the mechanics. Still, such replacements should be possible. Currently, all buttons need to be broken off in order to reach the right hand side mechanics. Furthermore, in order to replace one metal arm, all of them have to be removed. For the left hand side, this is less of a problem.

Other types of maintenance include visual revision of the instrument, or the revision of other parts, such as a bracket or bearing foot.

In order to take the button cover off for repairs, all buttons need to be removed from their cylindrical base, since they form an obstruction.

Conclusion

The bottom line is that the production of an accordion is a complex process consisting of mostly manual operations. Some of these operations are rather time- and labour extensive, such as shaping the body and inner mechanics, and creating the bellow.
Repairing and revising an instrument can be labour intensive as well: the complete disassembly of certain components is sometimes necessary to replace a single part. Opportunities for improvement lie in both of these fields.

3. ANALYSIS - ADDITIVE MANUFACTURING

What is additive manufacturing (AM), and how can it be useful in building an instrument such as the accordion? There are many different AM processes that all have their advantages and drawbacks. Analysing them gives an indication of the relevance and limitations of additive manufacturing for this project.

3.1. the AM principle

The term additive manufacturing covers multiple processes that build up objects out of individual layers. The geometric input comes from a digital file: a computer-aided design (CAD) file is converted to a stereolitography (STL) file, which represents the model in triangles. This is subsequently sliced into layers in order to print the model.

ADVANTAGES OF AM

AM can have several advantages over traditional production processes (Wohlers Associates, 2015:186):

- *Reduction of tooling*
  The possibility of direct part production leads to a reduction of tooling, which influences not only cost, but also lead time, time to market and tool maintenance.

- *Agile manufacturing operations and decentralisation*
  AM processes provide more control and flexibility in the production process. Decentralised manufacturing makes it possible to produce for instance standard parts centrally, and local variations on location using AM.

- *Reduction in inventory and part consolidation*
  AM can lead to a reduction in inventory and part consolidation. This means a product consists of fewer, more complex parts. It cuts the labour cost for assembling the product, as well as the overhead for documentation and production planning and control.

- *Lightweighting*
  The weight of some parts can be lowered using material reductions in regions with low stress (topology optimization). For instance, a (regional) lattice structure can significantly reduce part weight.

- *Less waste*
  Building not by means of cutting away material, but by putting layers on top of each other, material waste can be prevented. The cradle-to-gate footprint of components can be reduced further because there is less need for tools and dies. Furthermore, human error in production can be reduced. However, many current AM processes are time and energy intensive.

DRAWBACKS OF AM

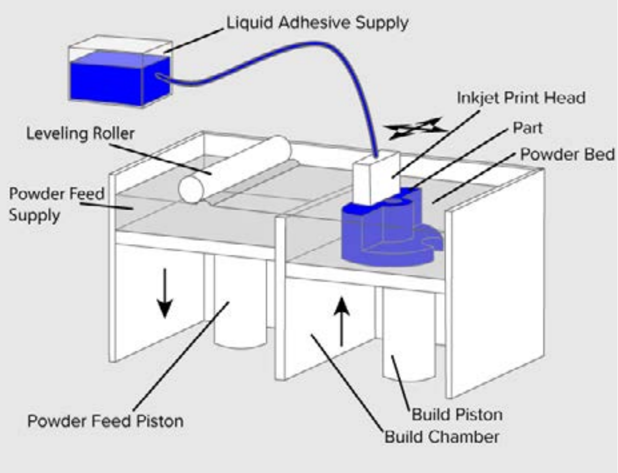
There are also some challenges and potential drawbacks to AM. First of all, it should be noted that the need for intensive post-processing can make the advantages of AM be (partially) lost. When designing a part and selecting a process, this should be taken into consideration.

Currently, AM machines and materials do not come cheap. Machines are still produced in relatively small numbers, and the price for polymer filament can be 58 to 125 times higher than injection moulding pellets of the same polymer material. This is because the market for conventional pellets is about 100.000 times larger than the AM filament market (Wohlers Associates, 2015:54). Furthermore, the speed of AM processes is very low when compared to for instance injection moulding. Also, the machines do not yet have a continuous throughput, requiring workers to remove the finished parts. There are also requirements like production standards and quality control that simply take time to move along.

The cost of AM parts cannot be justified for all products. For some parts, AM can save money in the long run, for example when reducing the weight of an airplane part. Other production parts, like hearing aids, have advantages because they can be customised to the user needs. However, AM is currently far from replacing conventional processes for most products.

For this project, the reduction in tooling and inventory and part consolidation are important drivers for choosing AM. This can reduce the labour required to assemble the product. Local and agile manufacturing operations can further reduce the lead time for the customer. Other aspects such as reducing weights and option for customization are not the drivers for this project, but they certainly are interesting to research.

The printing processes differ in the way the layers are laid out. The ISO/ASTM standard currently distinguishes seven different AM process categories (ISO/ASTM, 2016). We take a closer look at these processes in the next pages.



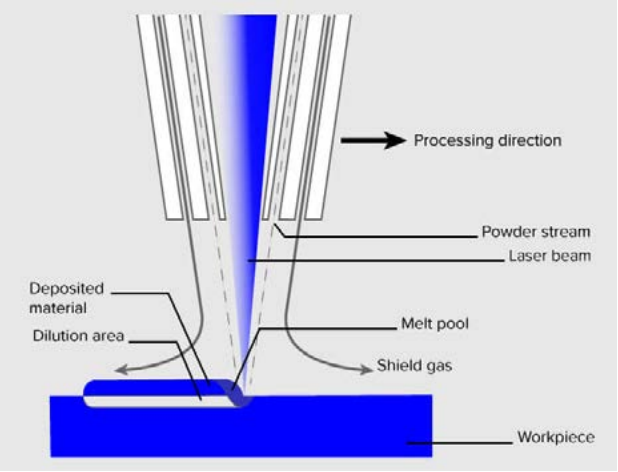
1 - BINDER JETTING

The binder jetting process was developed in the early 1990s at MIT. It is based on reactive curing: a roller spreads a layer of powder material on a printing bed, which is then cured selectively using a binder material. After each layer, the print platform is lowered in order to create another layer on top. Binder jetting can be done using a wide range of materials: different types of plastics, but also ceramics, metal (for example stainless steel), or sand. A typical layer is about 0,1mm thick, and the end result has a rough surface finish (Gibson, Rosen & Stucker, 2015).

Because the process is powder-based, the print is self-supportive, so no separate support material is necessary. It is possible to print in full colour: the printhead can load different colours with the binder material. The print process itself is relatively fast and cheap because of its simplicity: it is a process without heat that does not require any protective environment. The greatest disadvantage of binder jetting is the mechanical properties of the end result. Because the final product is nothing more than a lot of particles glued together, the result is quite fragile, and often not suitable for structural parts. Sometimes prints are, depending on the application, sintered in an oven to enhance mechanical properties. Another option to make the print stronger is infusing the print with resin. This also enhances color saturation. However, these kinds of post processing add significant time and cost to the process.

Binder jetting is often used to create visual prototypes in full colour. It is also used for structural parts, mostly made of post-processed metal, or to create casting patterns made of casting sand.

In terms of part cost and design freedom, this process is a good candidate for this project. The mechanical properties of the end result, however, do not make it a likely choice.



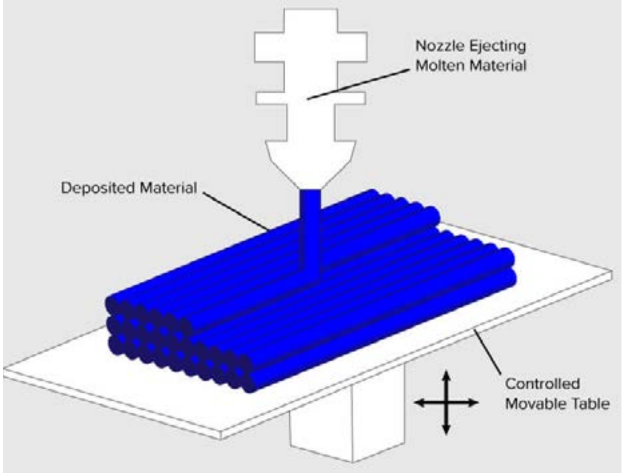
2 - DIRECTED ENERGY DEPOSITION

Directed Energy Deposition (DED) makes use of a focused energy source (a laser, electron beam or plasma arc) to deposit and melt material onto an existing surface of an object. It can use both powder or wire material, the latter of the two being the most material efficient. The process is mostly used for metal powders, with typical layer thicknesses of 0,25-0,5mm.

The nozzle arm can have up to 5 axis, enabling more form freedom in the design of products. This makes DED a good process for repairing broken parts. The fine grain structure of the end result is also a plus. However, the equipment is expensive, and manufacturing complex parts is difficult with DED.

DED is mainly used in the repair and modernisation of metallic structures. It is also used in material research for testing new alloys and their applications. Also, DED can be used to add new features to existing structures in order to improve their performance. For instance, it is used to deposit wear-resistant alloys in the high-wear locations of injection moulding dies (Gibson et al, 2015).

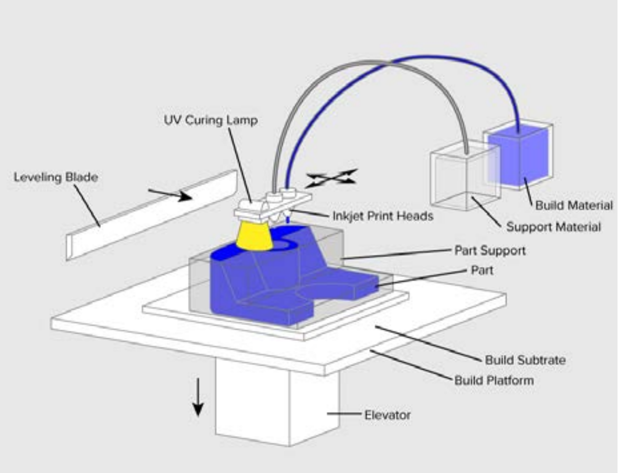
While this process offers a mechanically satisfactory outcome, the limited material possibilities and their cost can be a reason not to select this process for this project.



3 - MATERIAL EXTRUSION

Material extrusion, often referred to as Fused Deposition Modelling (FDM), makes use of plastic filament that is melted and extruded through a nozzle. It was invented in 1980 by Scott Crump and commercialised by his company Stratasys, founded in 1988. By moving the nozzle horizontally, a part is created on the build platform. FDM works mostly with thermoplastics, the most common being PLA, ABS, PC and PA (Loughborough University AMRG Group, n.d.). More experimental materials are also available, combining a thermoplastic binder with a powdered filler material, such as wood or metal. Multi-material extrusion is possible when using multiple nozzles. Typical layer heights range from 0,05 to 0,3mm. Layers are clearly visible on the surface of the prints.
The available materials offer the possibility for good structural properties (Wohlers Associates, 2015), although this depends on many factors (Floor, 2015). Because some of the key patents on the technique have expired in 2009, a lot of development is taking place. This means there is a lot of knowledge, products and materials available. FDM does not have a support material inherent to the technique, so it has to generate its own support. This can be done in the printing material, resulting in a lot of post-processing. It is also possible to use a dual material printer to create dissolvable support. The nozzle radius dictates the final quality, and accuracy and speed are relatively low compared to other processes.
FDM is used most for all kinds of prototypes, as well as small series production parts and replacement parts. Sometimes these are printed by the end user, since the technique has a relatively low entry level and benchtop printers are widely available.

The number of printers and materials available at a relatively low price and the good mechanical properties of the print make FDM a good candidate for this project, although its surface quality and form freedom are not the best available.



4 - MATERIAL JETTING

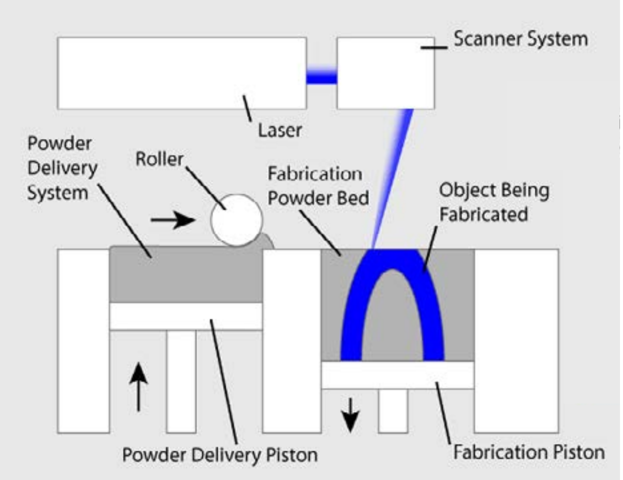
Material jetting makes use of droplets of build material that are selectively deposited using an inkjet printhead. It is like a regular 2D inkjet printer, depositing melted materials in layers via Drop on Demand (DOD) technique. The melted material solidifies, the platform lowers and the next layer is placed on top of it. The materials are cured using ultraviolet light. The amount of materials that can be deposited in drops is limited: photopolymers and waxes are commonly used. Multi-material and - colour parts can easily be created. Layers can be about 0,015-0,06mm thick, and the surface finish is smooth (Wong & Hernandez, 2012).

The DOD technique creates a high accuracy. The possibility to print multi material parts creates potential for products with gradually differing mechanical properties (e.g. flexibility, strength) for different areas. A gel-type polymer can support overhangs. It requires water jetting to remove this.

Due to the available material types, the end result is fragile, making the prints less suitable for functional use.

Common applications of material jetting are visual prototypes and casting patterns. The latter is mostly used in medical appliances in lost wax casting.

It is not likely that material jetting will be used in this project. The fragile end result of this process does not make it suitable for creating a durable accordion.

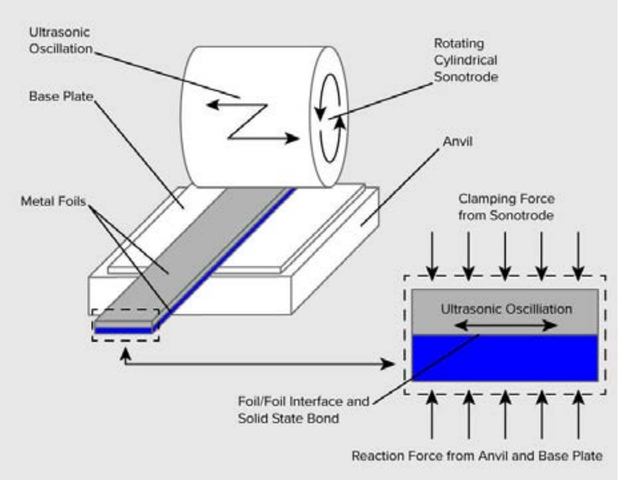


5 - POWDER BED FUSION

There are many different powder bed fusion (PBF) processes, but their basic principles are the same: a layer of powder is spread out over a build platform. Then, a thermal source induces fusion between powder particles at a certain location on that layer. The platform lowers after each layer, spreading out a new layer of powder.
Depending on the exact process, many powder based material can be used: while selective laser sintering (SLS) makes use of polymers, direct metal laser sintering (DMLS) focuses on metals. The most common thermal source is a laser, but other types are also used. Electron beam melting (EBM) uses, as its name implies, an electron beam to melt metal powders, and selective heat sintering (SHS) makes use of a thermal printhead to fuse powder together. Layers are typically between 0,05-0,15mm thick, and the surface is rough (Loughborough University AMRG Group, n.d.).

The patent on the SLS process, which belonged to 3D systems, has expired in june 2014. Since then, there is a lot of development going on for lower cost SLS printers. There is no need for additional support material as the process is powder based, making complex geometry easy to print. Also, prints have good mechanical properties and there are many materials available to print in. For small lot sizes, the process is relatively cheap. The powdery surface finish may need post-processing for some uses. The layers are visible, but not as much as with material extrusion. Tiny details can be a problem, depending on the powder grain size. PBF is often used for functional prototyping purposes, but it can be used to produce small batch end products as well.

With enough materials available and good mechanical properties, this process can be suitable for this project. A drawback is the price of the printer itself.



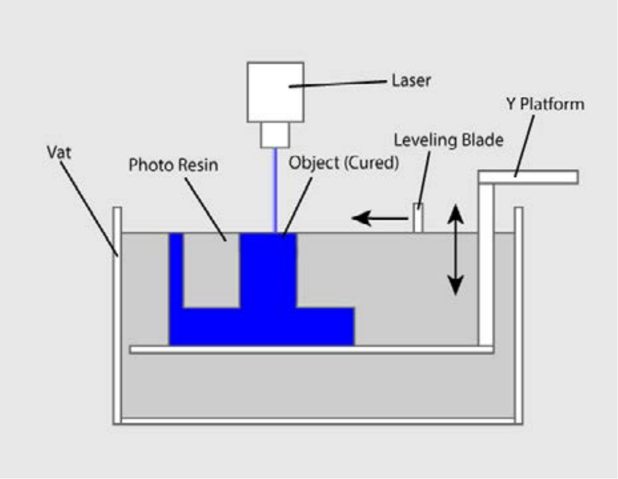
6 - SHEET LAMINATION

Sheet lamination is a process where sheets of material are bound together, forming an object. Layered object manufacturing (LOM) makes use of paper sheet material, A4 sheet paper being the most common. Ultrasonic additive manufacturing (UAM) uses metal sheets that are bound via ultrasonic welding. Different types of paper and metal can be used, and the surface finish is quite rough, with visible layers.

Sheet lamination is a fast and relatively cheap process, especially when using paper. Little energy is required for the process. However, the end result does not have good structural properties, and post processing may be required to improve the surface quality (Gibson et al, 2015).

LOM is mostly used for visual models, while UAM can be used to create multimaterial metal sheets with unique mechanical properties. Because it does not heat the metal, it is also suitable for repair applications of heat treated material.

Sheet lamination is not a logical process to choose in this project. Its end result is usually not suitable for intensive use without post-processing and there are serious limitations to the geometry of the end result.



7 - VAT PHOTOPOLYMERISATION

A liquid photopolymer resin is put in a vat, where layers are constructed via polymerisation, which is activated via an ultraviolet laser. This is done on the surface of the vat. The model is built upon a platform inside the liquid. The best-known vat photopolymerisation process is stereolitography (SL) and is known for its good surface quality and accuracy, with layers starting from 0,025mm thickness.

Continuous liquid interface production (CLIP) is another vat photopolymerisation process, where a projector is placed under the vat. In between is an oxygen permeable window, which is able to change pulses of the ultraviolet radiations and allows for faster continuous building of the model. This makes CLIP up to 100 times faster than SL.

Vat photompolymerisation can print features as small as 0,1mm at a reasonable speed. Because of the liquid base material, the model is not self-supportive, so support structures have to be printed and post-processed. The photopolymer materials are expensive and not durable in a way that their mechanical properties change over time. In order to make them suitable for structural use, lengthy post-processing is required.

Because of the durability of the materials, vat photompolymerisation is mostly used for prototyping purposes. Because of the good surface finish and accuracy, the technique is also used for creating casting patterns (General Electric, n.d.).

The surface quality and accuracy of parts created with vat photopolymerisation make it an attractive process. The mechanical properties and their durability, however, can be a problem. This can eventually be resolved with post-processing if this process is to be used during this project.

AM MARKET

The AM market is rapidly growing and is expected to continue doing so in the upcoming years. In 2014, a total of 640,0 million dollar was spent on AM system materials: a 29,5% increase from the 493,9 million dollar in 2013 (Wohlers Associates, 2015:123). New materials are being developed rapidly, and their cost has decreased considerably over time.
The maturing of the AM market started around 2012 and was caused by the expiration of patents on certain techniques combined with increased media attention. FDM printers started dropping in price, and the home printing market grew rapidly. According to Wohlers Associates, this is just the tip of the iceberg.

Currently, AM is mostly used to produce low volumes of products with complex parts. For production applications, the aerospace and medical/dental industries form a large part of the market. For some AM processes, the machines cost hundreds of thousands of euros, and some of them need facility requirements for inert gas and safety. This is why parties that offer commercial AM services are large players in the AM market. Stratasys and 3D Systems are currently the largest players on the market. They both offer such services, and develop a wide range of machines and materials.

In the future, the AM market is expected to keep growing, with costs of both machines and materials decreasing. Each different AM process has its own advantages and disadvantages, both in cost, possibilities and product quality. There are still some issues to be resolved, such as the recycling of polymer powders, and production flaws can occur in each process. A careful process selection for this specific project is necessary, based on the project-specific requirements and the process information available.

CONCLUSION

While there are serious advantages to additive manufacturing, there are also drawbacks and pitfalls. For instance, tooling can be reduced, but if post-processing is needed, this advantage can easily be lost. ISO/ASTM distinguishes seven different types of additive manufacturing processes, of which FDM, PBF, DED and eventually Vat Photopolymerisation seem suitable for this project in terms of mechanical properties of the end result. The expectation is that print quality will improve over the next years, while the cost of printers and material decreases.

3.2. relevant AM projects

It is important to know what has already been produced with AM techniques in terms of musical instruments and other parts. Inspiration and learnings from these projects can be used during the design of the accordion. This paragraph provides a short overview.

PRINTED INSTRUMENTS

Most of the research on the production of (parts of) musical instruments through additive manufacturing focuses on small instrument, such as certain wind instruments.

One approach in the additive manufacturing of instruments is the customization of their tones. A relatively simple instrument to do this is a flute. Dabin et al. (2016) did so for a microtonal flute via material jetting. This allows customers to customize their own flute in terms of tuning and shape. The result was a playable instrument, although the mouthpiece characterization needs some improvement. Another example of tone customization is the clarinet that Bailey, Cremel and South (2014) printed in multiple parts. This instrument has been modeled in such a way that it can play the microtones of the 19 equal temperament.

Others use AM to showcase the possibilities of the technique and to find out up to which level certain complex instruments can be produced. A concert flute was printed at MIT by Zoran (2011). The first version was fabricated through FDM, with felt on the holes and metal springs to make the pads function properly. The FDM flute was problematic to be played on musically because of a loss of mechanical energy. This was mainly caused by tolerances in the hinges. A second version was created using material jetting, and this one had better acoustic properties. However, the printing material decomposes over time.

The research of Lorenzoni, Doubrovski and Verlinden (2013) focuses on tonal properties. They used different materials and geometries to print saxophone mouthpieces. The aerodynamics of each type of geometry is investigated and the influence of shape and material on the tone characteristics of the instrument is described.

AM can change the way the user interacts with an instrument as well. The reAcoustic eGuitar by Zoran and Maes (2008) is a concept that allows users to create their own acoustic instrument via AM techniques. They can assemble different small sound chambers themselves, influencing the sound.

Other projects include a 3D printed violin, created to promote a new vat photopolymerisation resin. There currently is a 3D printed electrical violin on the market, made using an SLA printer and several post-treatments and adjustments (3D-Varius, 2017).

Furthermore, 3D models for many instruments are available to download via online communities. One example of this is a trombone (Bos, 2016). However, most of these are hobby projects where the end results lacks the quality of a “real” instrument.

3D printed flute by Zoran (2011).

A ball of gears like this could not be produced without additive manufacturing techniques

OTHER PROJECTS

Non-musical AM projects can also teach us a lot about AM, especially for showcasing functionalities and techniques. Noteworthy projects include a laser-sintered gear ball. It consists of a frame with a complex mechanism of interconnected gears. This object can only be produced via AM, because assembling the parts separately would not be possible.
Another project is Theo Jansens “Strandbeest”, originally a large moving structure of PVC pipes. Its components can be printed via SLS without the need for assembly, allowing the full structure to walk.

AM can be used to produce all types of moving parts, such as springs or hinges. This needs to be done with care, selecting the right material and dimensions. TNO Eindhoven showcases a lantern/lampshade that has been laser sintered from nylon (see page 45). It can fold open while being printed from one piece, with only a few layers of powder between the solid parts. Using dissolvable support material, it is even possible to create models like the ball bearing shown below.

Post-processing can not only be done to improve or stabilise mechanical properties or finalise a shape, but also to create a smooth surface finish. This can be done for all types of materials, using different processes. While metal can easily be polished, it is more difficult with polymers. FDM usually gives a rough surface where the separate layers are visible. An acetone vapour post-processing can create a smooth and shiny surface on for instance ABS.

CONCLUSION

Overall, AM provides many opportunities for the design of musical instruments and mechanical systems, while creating a full-fledged instrument is still a challenge. The sound of an instrument will be influenced by its shape and material. While creating moving parts or mechanisms is well possible using AM, mechanical parts like flute valves turn out to be a challenge.

Using dissolvable support material (white), complex geometries can be printed.

The ABS FDM print on the left has been smoothened using acetone vapour.

3.3. process selection

Which of the many AM processes suits this project best? Different qualities of the processes are compared in order to find out.

Pigini Nederland is looking for an AM process that can be used to print the upcoming design of an accordion. The price and mechanical properties of the result are important. Post-processing should be avoided as much as possible, as it requires extra labour. The products may not be produced all at once, so it might not be possible to do post-processing for multiple products at once.

Plastics are a logical material choice for the design of the accordion. They are lightweight and relatively inexpensive, while offering sufficient mechanical properties. Therefore, only the AM processes that can produce plastic parts have been compared.

A chart has been made to compare the different AM techniques. The most important aspect of the design are the mechanical properties, since the result should be a functional product. Some processes require post-processing to achieve these properties, which influences the required labour. Together with the expected cost, these properties are on the top of the comparison. Being able to produce the parts at home would put Pigini Nederland in charge of the whole production process, something they highly desire. Such an approach fits in the operational mode of the company, which has always included in-house production and development of instruments.

Further aspects of importance are form freedom, production speed, build size, accuracy, sustainability and surface quality. Build size is interesting for producing larger instruments in the future. Accuracy is important, but no very dimensionally critical parts are expected to be in the final design.

Surface quality is mostly important for the visual appearance of the end result, but should not be leading in the selection of a process.
Although not within the scope of the project, sustainability is important for Pigini: they are used to making products that last for decades. It added to the matrix to foresee any future sustainability problems.

These properties form the basis for the process selection. Other unique AM properties, such as full-colour printing, are not directly relevant within the scope of this project and are therefore not present in the comparison.

Looking at the process diagram, the choice was made for a benchtop material extrusion printer. This offers good, stable and reliable structural properties, is relatively inexpensive and easy to operate. The start-up costs are low, and no post-processing is required. The form freedom is high when using dissolvable support. Many materials are available, including recycled and recyclable materials. Disadvantages are that accuracy is limited to the material nozzle thickness and heavily dependent on the printing speed.

Another good option is powder bed fusion, namely selective laser sintering of PA polymer. This material is the most common material used for this process.
A switch to SLS can easily be made, but it would mean that Pigini Nederland becomes dependent on a commercial partner to produce the design. As long as this is not necessary, Pigini Nederland's preference is to fully keep production in-house.

	BINDER JETTING	VAT PHOTO-POLYMERISATION	MATERIAL EXTRUSION (INDUSTRIAL)	MATERIAL EXTRUSION (BENCHTOP)	MATERIAL JETTING	POWDER BED FUSION	SHEET LAMINATION
MECHANICAL QUALITY	●●○ if post-processed	●●○ if post-cured	●●●	●●●	●○○ UV-cured wax-like materials	●●●	●○○
NO POST-PROCESSING REQUIRED	●○○ required to create strength	●○○ required to create strength and remove resin	●●●	●●●	●●●	●●●	●●○
LOW COST PER PART	●●○	●●○	●●●	●●●	●●○	●●○	●●●
SURFACE QUALITY	●●●	●●●	●●○	●●○	●●●	●●●	●●○
BENCHTOP PRINTING POSSIBILITIES	●○○	●●●	●○○	●●●	●○○	●○○	●●○
FORM FREEDOM	●●● powder-based	●○○ support required	●●○ dissolvable support available	●●○ dissolvable support available	●●○ support easily removed	●●●	●○○
ACCURACY	●●●	●●●	●●●	●●○ highly depending on speed	●●●	●●●	●●○
SPEED	●●●	●●●	●●○	●●○	●●○	●●○	●●○
BUILD SIZE	●●○	●●●	●●●	●●○	●●○	●●●	●●○
(POSSIBLE) SUSTAINABILITY	●○○	●●○	●●○ depending on material	●●○ depending on material	●●○	●●○ if powder is recycled	●●○

The selection of a process is done using this comparative diagram. A larger version can be found in Appendix A.

PRINTING PARAMETERS

The quality of an FDM print depends on many factors. Floor (2015) found that fill density, print speed, layer height, orientation, and temperature all have an influence on the tensile strength of a print. It is important that the method and parameters of printing are taken into account while designing a part. Stresses should be among the direction of the print fillament as much as possible, while layer heights could for mechanically challenging and neutral parts of the product. Overhangs should be avoided in order to decrease the need for support.

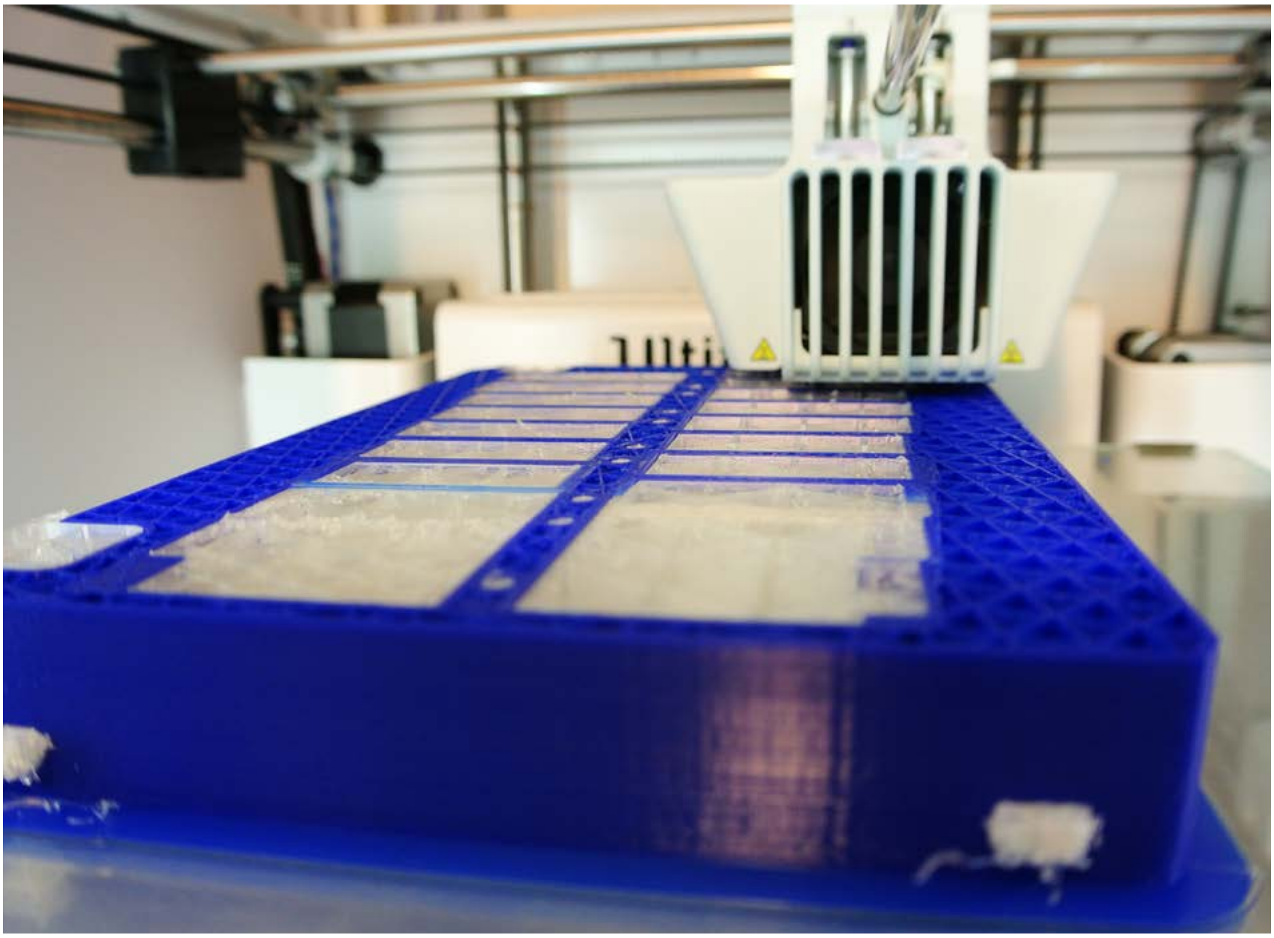
A printer nozzle of 0,4mm is the selected to produce the design. A nozzle this size offers enough detail, while still operating at an acceptable speed. It is a reliable size when compared to the 0,25mm nozzle: because of its small aperture, this one tends to jam more easily, which can disrupt production. The precise material will depend on the availability and the printer that is being used. The material should be strong, durable in the expected use environment. It needs to resist temporary UV-light, possible impacts through falling, temperatures up to 50 degrees Celcius and should work with soluble support material (PVA). Examples of such materials are PC-ABS or Ultimaker CPE (a form of PET-G material).

Please note that some materials are not suitable: ABS is usually not UV-stable, which is a risk for an instrument that might be used outdoor. Some materials, for example most of the PLA and PA filaments, are hygroscopic: they absorb moisture from the air (Simplify3D, 2018). This makes them not durable in the long term.

To reduce support material cost, being more expensive than the build material, only a few layers of PVA can be used between support structures and production parts. The rest of the support can be built up from regular material.

CONCLUSION

While FDM and SLS both have a lot of potential as a means of production in this process, a benchtop FDM printer is selected since it fits Pigini Nederland’s current facilities better. A durable material is required for daily use of the instrument, so that the product will not break easily, or for example melt in heavy sunlight. Examples of durable materials are PC-ABS or Ultimaker CPE. The latter can be used with soluble PVA support.



The instrument body is printed on an Ultimaker 3.

4. DESIGN REQUIREMENTS

In the following pages, a list of design requirements is presented. These requirements are important for both the functioning and the user perception of the final design. They form the bottom line during the design process. Besides integral requirements that concern the complete instrument, there are component-specific requirements that usually describe a single phenomenon.

In later chapters, the relevant requirements for the components discussed are listed in blue text fields. Where necessary, information on the origin of a requirement is listed in its respective chapter.

INTEGRAL REQUIREMENTS

1. Cost

The material, component, machine and labour cost combined do not exceed the cost of the current MiniMouse (999 euros). The focus is on man hours.

2. Means of production

Additive manufacturing techniques are used to create the core parts of the instrument. This can eventually be combined with other parts, such as standard parts or traditional parts.

3. Production logistics

The (future) facilities of Pigini Nederland are suitable to produce and assemble the instruments in the Netherlands.

4. Dimensions

The product dimensions are comparable to that of the current MiniMouse.

5. Tonal range

The right hand side of the accordion for this project incorporates 19 reeds, ranging from A#3 (220 Hz) to E5 (~659 Hz).

6. Product lifetime

The product lifetime is expected to be at least 10 years considering a use scenario of 30 minutes a day.

7. Use environment

The product can be used in both in indoor and outdoor conditions, with temperatures up to 50 degrees Celcius and exposure to normal levels of outdoor UV light for a maximum of 1 hour a day.

8. User interaction

The product playing interaction is comparable to the current MiniMouse. This means that the instrument configuration and tone production for the user are similar to that of the current MiniMouse.

9. Sound perception

Although the sound of the instrument does not have to be exactly similar to that of a conventional instrument, it is important that users perceive the sound as a pleasant and full-fledged accordion sound.

10. Production time

The instrument can be produced within two weeks after an order is placed.

11. Instrument air leakage

The maximum air leakage for the full instrument is 25cm^3/s for each Newton of bellow pulling force (*chapter 6*).

BELLOW REQUIREMENTS

The following requirements correspond to the content of chapter 6. Further explanation can be found here.

12. Man hours bellow production

The man hours required to produce a bellow should not exceed the current value, which lies at 8 hours.

13. Bellow opening force

The force required to open the bellow should be similar to that of an conventional bellow. The max. bellow opening force without attached air column is 15,1N.

14. Air pressure on bellow

When no button is pressed but the bellow is being pushed/pulled at full force in order to produce a loud note, the bellow needs to be able to withstand an air pressure on its walls of 1000N/m^2.

15. Dimensions - bellow

The bellow fits on the instrument bodies without interacting with internal components, such as vibrating reeds.

16. Lifetime - bellow

The bellow material should not fail over time. With 6 open/close cycles per minute on average, the bellow needs to withstand at least 6*30*365*10=657.000 bending cycles during its lifetime.

17. Playing interaction - bellow

The playing interaction of the bellow is similar to that of a conventional bellow. For instance, the bellow should not displace in a direction perpendicular to its axis, or deform in any other way than through folding. This means a rigid bellow framework is required.

INTERNAL MECHANISM

The following requirement corresponds to the content of chapter 7.1.

18. Dimensions - internal mechanism

The mechanical parts are not larger than necessary and fit the buttons and air holes so that they function well. This is necessary in order to keep the instrument compact and functional.

The following reqiurements correspond to the content of chapter 7.2. Further explanation can be found here.

19. (Dis)Assembly - internal mechanism

Mechanics can be disassembled when a certain part requires repair. The time to remove a single beam should be under 1 minute. With 19 arms on the right hand side, this enables repair on the right hand side mechanic within 40 minutes (excluding repair operations), the time it would also cost with the current MiniMouse.

20. Snap fit force - internal mechanism

The snap fit can be placed and replaced by a human, eventually with a tool. The snap fit should not open during use. When placing the snap fit, user feedback should indicate that the snap fit is well connected. The maximum snap fit push and pull force is 50N.

21. Snap fit clearance - internal mechanism

Any clearance would make it easier for the snap fit to loosen. It is not desirable for the user either. The snap fit should not have a noticeable clearance. This can be verified by moving the snap fit mount by hand.

22. Spring-button force

The current MiniMouse has button forces ranging from 0,8N (first row) to 1,7N (third row). Values for the redesign need to be in between these values.

23. Spring Lifetime - internal mechanism

The springs in the instrument can endure 10 years of playing. Pigini users are used to such a quality for their instruments. For the spring, this is around 1.500.000 pressing cycles.

The following reqiurements correspond to the content of chapter 7.3.

24. Beam Torsion - internal mechanism

Torque in the mechanics should not obstruct playing of the instrument, and the user should not notice any influences created by the torque (e.g. no skewing buttons).

25. Beam Deflection - internal mechanism

The deflection of parts in the mechanical system does not result in plastic deformation of the material. It is not larger than 1,1mm at the button (20% of button pressing), and neither does it obstruct the playing of the instrument in any other way.

BUTTONS

The following requirements correspond to the content of chapter 7.4. Further explanation can be found here.

26. Button fixation

Buttons can be detached from their base and put back on. Detachment is not required very often. A lifetime of 10 button detachments is sufficient.

27. Max. button attachment force

No extra tools should be required for attaching a button. This means the snap fit can be attached by hand by at least 95% of all users. Therefore, the maximum button push force is 50N (Department of Trade and Industry, 2002).

28. Max. button detachment force

No extra tools should be required for detaching a button. This means the snap fit can be detached by hand by at least 95% of all users. Therefore, the maximum button pull force is 40N (Department of Trade and Industry, 2002).

29. Clearance in button attachment

Button snap fits have no noticeable clearance: they should feel stuck to the rest of the mechanic, like in a conventional accordion.

30. Clearance in button system

A max. clearance of 1mm, both left and right, is acceptable for the system (the complete button on its mechanical system). This is similar to that of conventional instruments. Within this range, any type of movement is acceptable for the scope of this project, including partly rotational movements.

31. Smooth button movement

The buttons move smooth when pressed down, without a noticeable rough interference between parts.

32. Dimensions - buttons

The button dimensions are similar to those of the current instrument: a diameter of 14mm, with the buttons placed 18mm apart from each other. They have rounded corners and can be pressed down 5 to 6mm.

33. Landing properties - buttons

When pressed down fully, the buttons land softly. The landing of the buttons should not make a noticeable sound for the user, and feels like it does on the current instrument.

VALVES

The following requirements correspond to the content of chapter 7.5.

34. False air - valves

Besides the air leakage of the full instrument, eventual false air flowing around the valves should not cause any reed to play unwantedly.

35. Soft closure - valves

The closing of a valve should not produce a loud noise when a button is released rapidly. Furthermore, it should not feel harsh for the user. Both the feel and sound of the valve closure need to be similar that in a conventional instrument.

REED BLOCKS

The following requirements correspond to the content of chapter 8.1. Further explanation can be found here.

36. Easy reed (un)mount

The reed mount time of a redesign needs to be under 30 minutes for mounting or remounting right hand side in order to make it more convenient than the traditional waxing process.

37. Reed reachability

No direct obstructions perpendicular to the reed surface are allowed. This makes the reeds reachable for tuning. If necessary, reed blocks can be taken out of the instrument before tuning.

38. Dimensions - reed blocks

The width of the reeds influences the size of the instrument as a whole. In order to keep the instrument compact, there should not be more space between the reeds than necessary. The reed block length and width should remain under 110% of the total reed length and width. This is extra important for the length, since this is most critical for printer dimensions.

BODY

The following requirements correspond to the content of chapter 8.3. Further explanation can be found here.

39. Archetypical shape

The user needs to easily recognise the instrument as an accordion. This can be accomplished by the archetypical shape of an accordion, that is defined by the components housed inside.

40. Modest appearance

As the instrument combines modern production techniques in a tradional instrument, it is desirable to have both progressive and conservative elements in the design of the body.

41. Rigid body

The user should not feel any movement between parts of the body structure when handling the instrument. This ensures product stability to the user and is beneficial to the sound of the instrument.

5. FINAL DESIGN OVERVIEW

The following pages present the final design of the 3D printed accordion body. This concerns the right hand side body and its components, as indicated in the impression below.

Impression of the final design in a complete instrument. As the design focuses on the user's right hand side of the instrument (displayed here on the left), a conventional bellow and left hand instrument side have been used to create this impression.

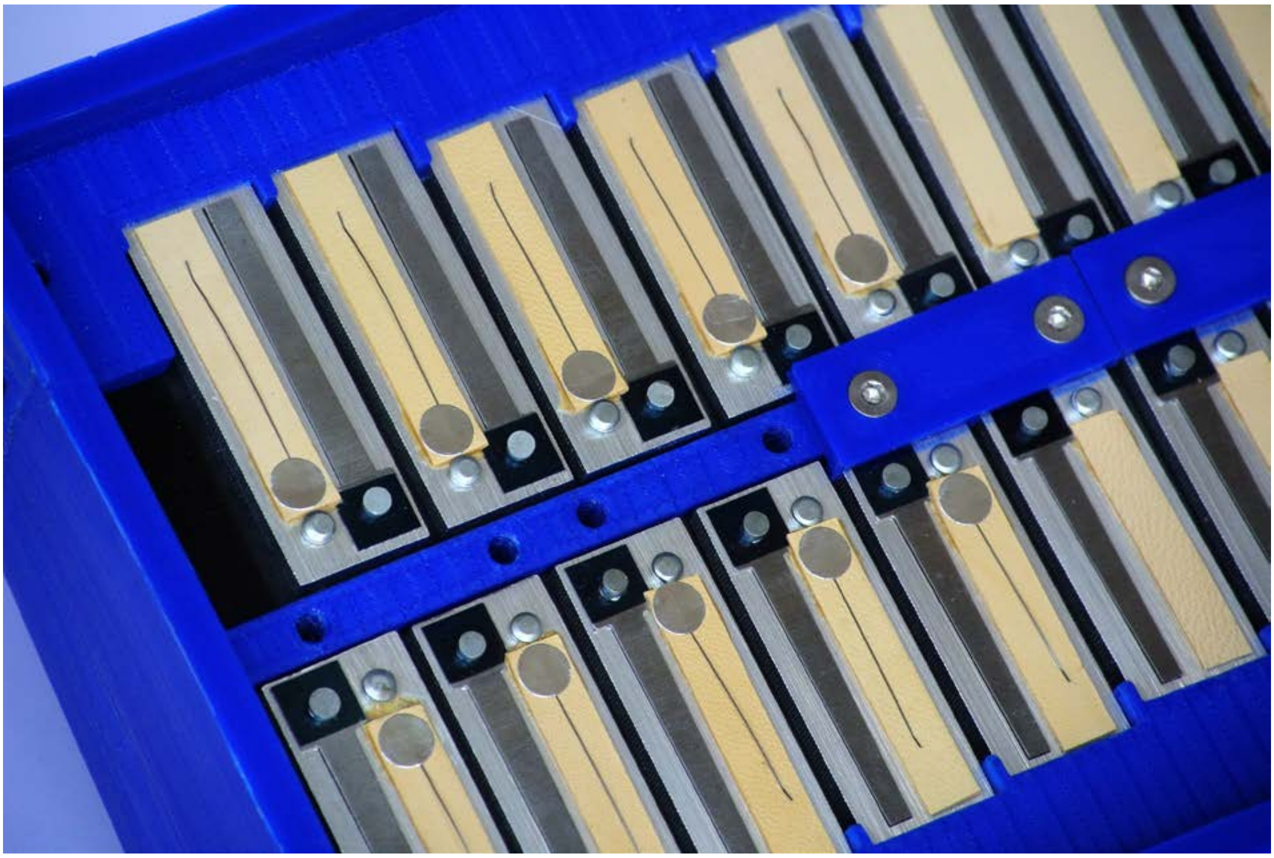
The instrument consists of a body that functions as a basis to attach other components to. The arms of the mechanical system can be attached to the body separately using a snap fit connection. This makes eventual repair easier. Buttons are placed onto the arms using another kind of snap fit. This means they do not have to be broken off in case of repair. Felt is used for damping and leather valves make the instrument airtight.

The reeds are not attached using wax, but clamped onto a gasket. Bolts and insert nuts are used to create the necessary clamping force. Several other connections use bolts and inserts as well.

The result is an instrument that is easy to produce and repair. If one part would break down, a new one can be printed and placed accordingly.

The fully assembled proof of concept

Section view of the final design, which is explained further in the following pages.



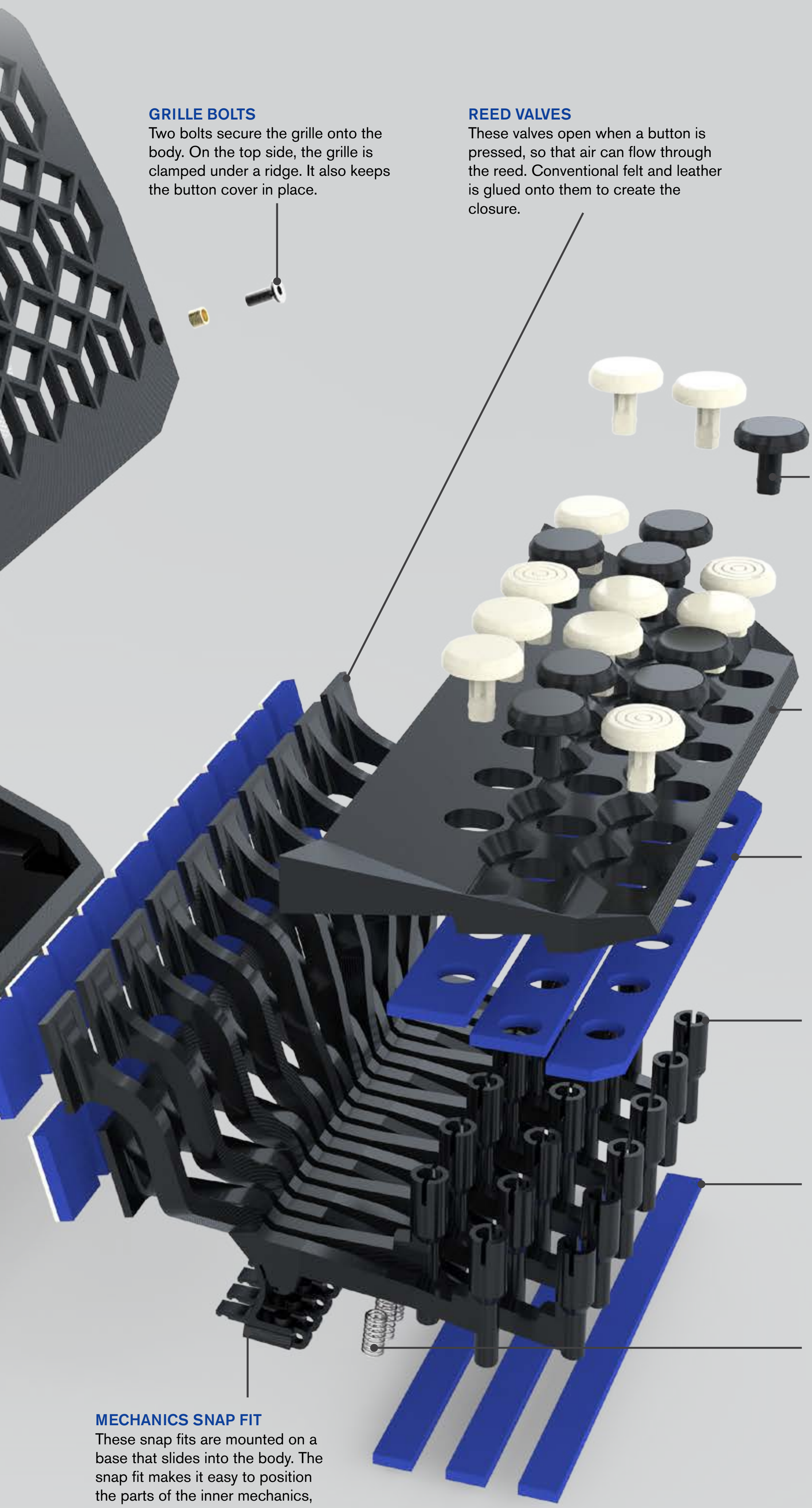
The reeds during the process of clamping them onto the gasket

The arms that connect the valves and buttons are separate parts that can easily be replaced

BODY
This is the right hand side body of the instrument. It is a printed part that serves as the basis for all the other parts. Different systems for connecting these parts have been incorporated into the design of the body.

GRILLE
The sound of the instrument reaches the user via the holes in the grille. A gauze is glued onto its back.

STRAP MOUNT
This steel rod is used to attach the straps of the instrument. There is another one at the bottom of the body.



GRILLE BOLTS
Two bolts secure the grille onto the body. On the top side, the grille is clamped under a ridge. It also keeps the button cover in place.

REED VALVES
These valves open when a button is pressed, so that air can flow through the reed. Conventional felt and leather is glued onto them to create the closure.

BUTTONS
The buttons come in two colours. The snap fit system that connects them to the inner mechanics makes the buttons easy to attach and detach.

BUTTON COVER
Under the buttons, there is a cover that ensures the mechanical parts are closed off. Furthermore, it creates a mount for the button felt.

BUTTON FELT
This felt keeps the buttons in place and makes sure that no interference between parts takes place when pressing a button.

FEMALE SNAP FIT
The button connects to the female part of the snap fit, that is attached to the inner mechanics. This part is guided by the button felt.

LANDING FELT
These strokes of felt accomodate a smooth button landing. The inner mechanics are outfitted with landing cylinders that ensure the correct travel distance.

SPRINGS
The springs are mounted onto the inner mechanics. They press the button valves onto the body. This pretension is necessary to form an airtight connection. Furthermore, the springs create resilience for the buttons.

MECHANICS SNAP FIT
These snap fits are mounted on a base that slides into the body. The snap fit makes it easy to position the parts of the inner mechanics, and create an easy but durable attachment.

BELLOW FLANGE

The bellow flange forms the connection between the body and the bellow. Its back is glued onto the bellow. On the other side, it is secured airtight onto the body using a gasket.

REEDS

These 19 reeds is the same as in a conventional instrument and range from A#3 to E5. They define the typical accordion sound.

GASKET

Rather than mounting the reeds using conventional waxing techniques, they are clamped onto the body. The gasket ensures an airtight connection.

REED CLAMPS

Five clamps are used to secure all the reeds onto the gasket. They are attached using M3 bolts that go through the body.

BELLOW GASKET

This gasket secures the bellow flange airtight to the instrument.

BELLOW FLANGE CONNECTOR
Two bolts are used to secure this side of the bellow flange. An insert nut is put into the bellow flange so that the bolt is fastened.

INSERT NUTS
These nuts are inserted into the front of the body. They secure the reed clamp bolts, so that the reeds are firmly pressed onto the instrument. As different lengths of bolts are used, each insert nut has its own position.

STRAP MOUNT
Conventionally, an external attachment point is added for the straps. Here, this is incorporated into the body by sliding a steel rod into a hole. The straps can be attached from the outside of the instrument.

6. BELLOW

The bellow pumps the air through the reeds. It is mostly made out of folding cardboard. It is supposed to open and close many times during its lifetime, and should do so with little force. The size of the bellow depends on the dimensions of the body, which itself is dependent on the size of the reed blocks.

BELLOW DESIGN OPTIONS

The folding cardboard that is used for the straight bellow parts is a cost- and function-efficient material. Because of its fibre structure, it can bend millions of times without breaking with very little bending resistance. Still, it forms a rigid structure in other directions, so that the bellow is easy to keep under control. Printing a rigid structure is not difficult, but printing an airtight structure that can bend endlessly with little resistance is.

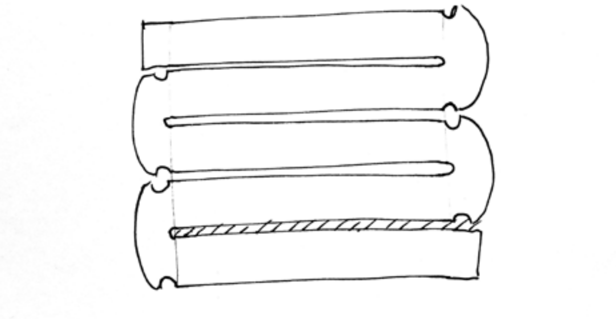
If the bellow corners would consist of a rigid material, a stress concentration will form in the corners when opening it. In traditional bellows, this is prevented by using a flexible material (leather) for the corners. The leather can (un)fold along with the opening and closing of the bellow, something a rigid material cannot do.

A conventional bellow consists of five different basic components. A bellow design that consists out of multiple printed/non-printed parts that need to be assembled is not a serious option for the design, as cardboard is more cost-effective than a printed part.

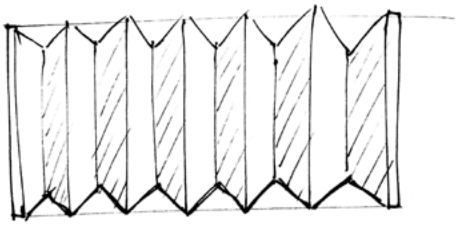
The first concept for the bellow is printing it in one piece in closed position. This would be very convenient for this project, as there is no more need for assemblying separate bellow parts.

Another option is buying a different (less expensive) type of bellow to reduce cost. This can be an industrial bellow that is moulded in one piece.

The third option is using a conventional bellow. This is acceptable if the quality and feel of a conventional bellow cannot be reproduced otherwise.



A bellow can be printed in closed position using support material between the different horizontal parts.



A conventional bellow can be used in the design if necessary.

AIR LEAKAGE

Only a small amount of air leakage is allowed for the full instrument. Usually, most of this leakage comes from the bellow and the reed valves. Any significant air leakage will cause serious troubles for the playing of the instrument, because this means less air is available for the reeds to sound and the user will have to work harder to play the same note.

The maximum air leakage for the full instrument is 25cm^3/s for each Newton of bellow pulling force. This is twice the measured air leakage of the conventional MiniMouse. As this instrument has little air leakage, its value is doubled as a maximum.

requirement #11

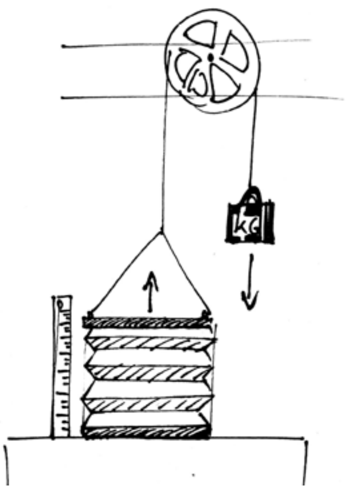
BELLOW PRODUCTION TIME

If a regular bellow is faster (and thus less expensive) to produce in terms of man hours, a redesign is not benificial. Therefore, the man hours required to produce a bellow in the Netherlands should not exceed 8 hours.

requirement #12

BELLOW MEASUREMENT

The force required to open a traditional bellow is measured using a counterweight system. The bellow is separated from the instrument bodies and placed upon a table. A rope connects the the top of the bellow to a counterweight, via a pulley. The force required to open the bellow increases with the opening distance. The bellow is opened 50, 100 and 150mm. This takes respectively 3,7N, 8,0N and 9,9N. This means an average person uses 13% of his/her force to open the bellow 150mm. This distance is sufficient for playing a small accordion conveniently. For the redesign, the maximum bellow force is set at 20% of the user's arm force, a value of 15,1N.



Bellow opening force measurement setup

BELLOW OPENING FORCE

The user should not spend too much force on opening the bellow, because this reduces the potential power of the instrument. Thus, the force required to open the bellow should be similar to that of a conventionalbellow.

The max. bellow opening force (without attached air column) is 15,1N, or 20% of the user's available arm force.

requirement #13

BELLOW PRESSURE

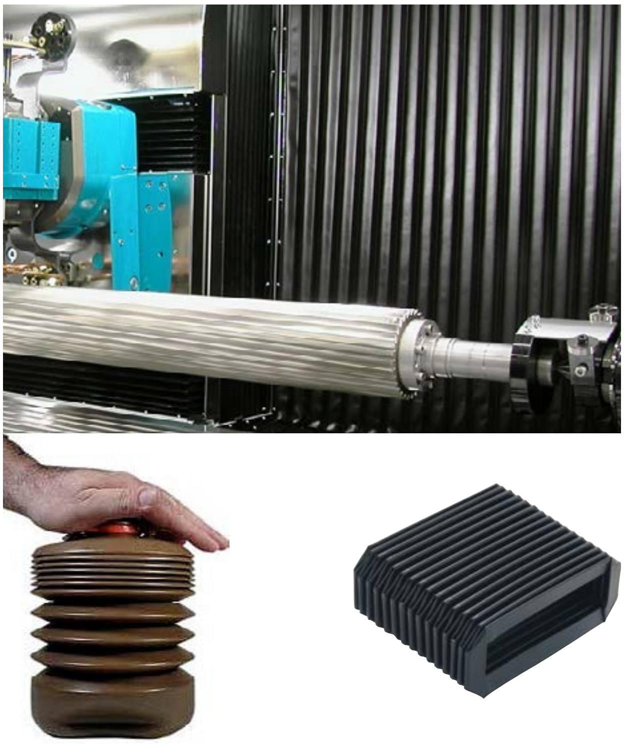
When no button is pressed but the bellow is being pushed/pulled at full force in order to produce a loud note, the bellow needs to be able to withstand an air pressure on its walls of 1000N/m^2.

*The mean strength when pulling a straight arm to the right lies at 17 pounds = 75,6N (Rochester Institute of Technology, 2006). This is doubled in order to find the P95 value. The bellow inner area is 0,15*0,1=0,015m^2. When simplified as an air cylinder, this results in a max. air pressure of 150/0,015=1000N/m^2.*

requirement #14

INDUSTRIAL BELLOW

From bottles that can fold like a bellow, and companies that specialise in producing rubber bellows out of one piece. Still, the requirements do not easily match the bellows available. An ideal accordion bellow is made out of stiff material so that it does not move easily in a wrong direction. It also needs to function as a pump, which means that air pressure will build up inside. A stiff and strong industrial bellow is hard to find, which means this concept has little viability.



Examples of industrial bellows

BELLOW DIMENSIONS

The bellow should fit on the instrument bodies without interacting with internal components, such as (vibrating) reeds. The dimensions of the bellow itself and the width of its folding structure define the space that is available for these components.

requirement #15

BELLOW LIFETIME

Because the bellow is a moving part, its material properties are important. Moving parts can fail because of internal stresses and/or fatigue. The bellow material should not fail over time. With 6 open/close cycles per minute on average, the bellow should withstand at least 6*30*365*10=657.000 bending cycles.

requirement #16

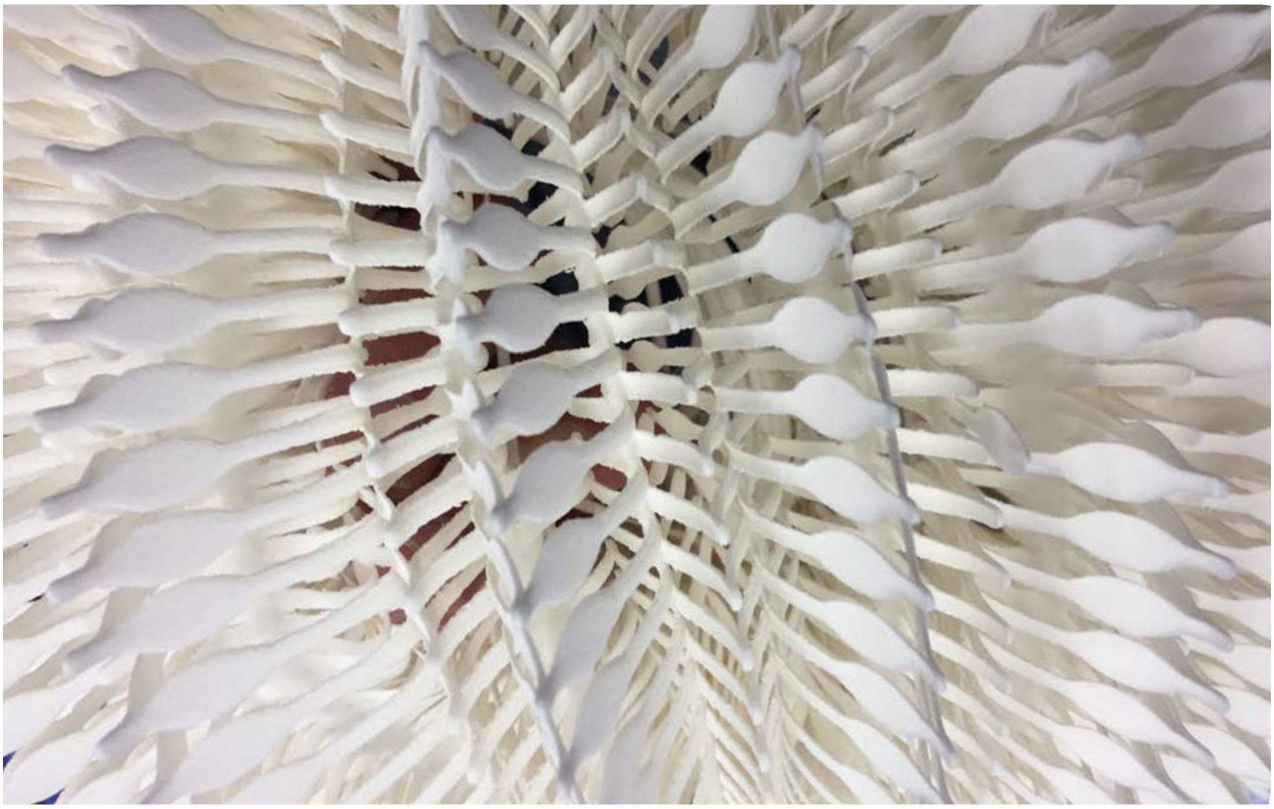
PRINTED BELLOW

The concept of a printed bellow poses serious problems, namely the bending mechanism and stress concentrations. The bellow needs to be able to open and close smoothly, which requires the material to bend. In order to do this easily with a non-fibrous material, reducing the thickness would be a logical choice. This can only be done up to a certain extent, because the bellow is expected to last for years and a too thin layer of material could easily lead to air leakages.

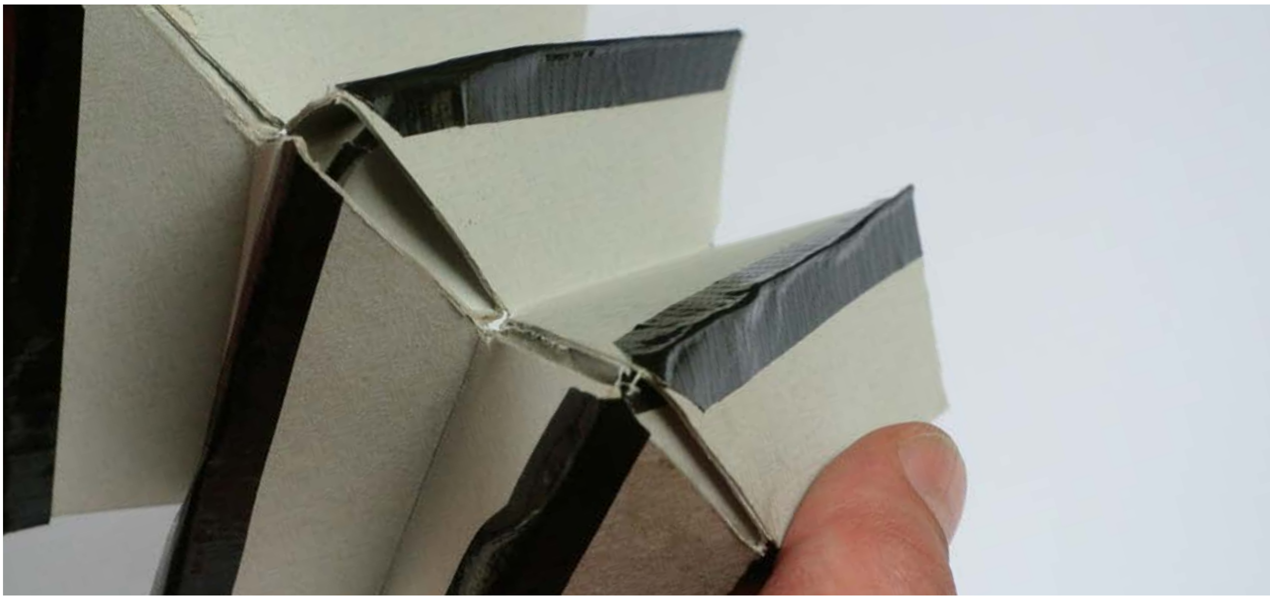
When the bellow opens, a stress concentration in the corners is hard to avoid with a non-flexible material. It happens because the inner ribs will move outward when the angle between the ribs is increased, and vice versa.

As mentioned earlier, the relatively low force required to open a conventional bellow is caused by the material (fiber) properties of the cardboard. Printing a comparable bellow is a real challenge, since printing materials are not fiber-based. The flexible printing materials that are currently on the market are not durable enough to make a moving component airtight for a long time. This leaves more standard polymer materials to print with. Test prints were made to find out if a printed bellow is a serious option.

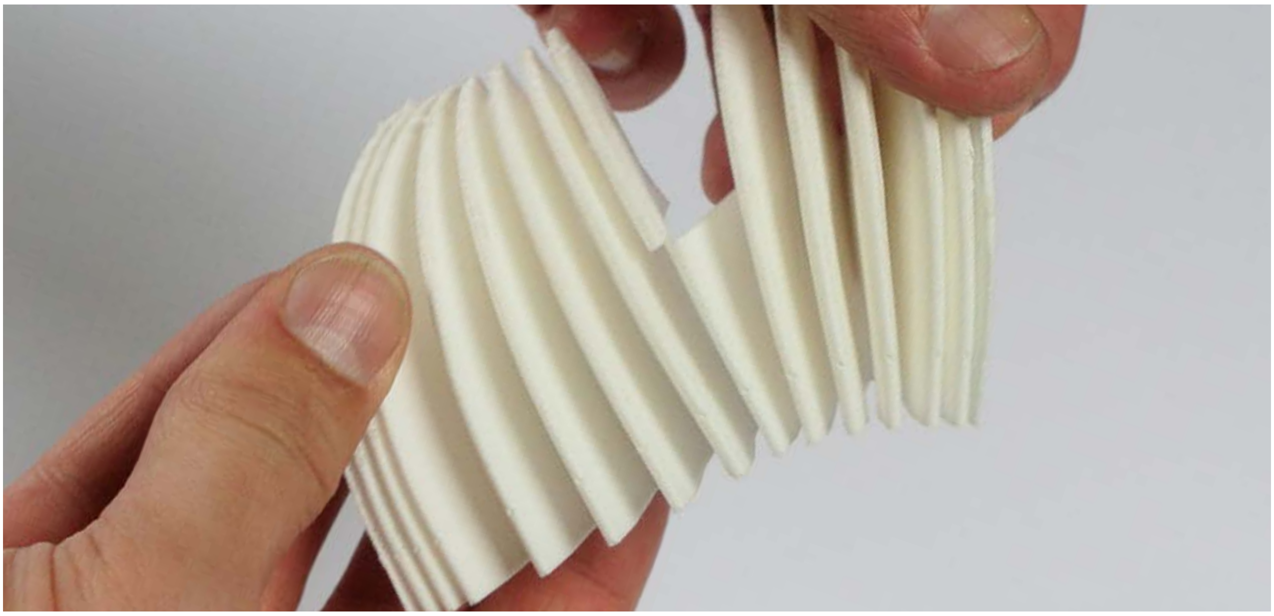
TNO's PA lantern produced using SLS techniques gave inspiration for a printed bellow. However, this design mainly works because the hinge points are small. The open space between them allows the material to deform smoothly in all directions.



The lantern that is printed using SLS techniques, shown at TNO Eindhoven.



A model of a double-walled cardboard bellow for principle testing



Prints tend to break along the material layers. The bellow planes are oriented in two different directions, and the third direction is used for bellow movement. This makes print layer orientation a problem.

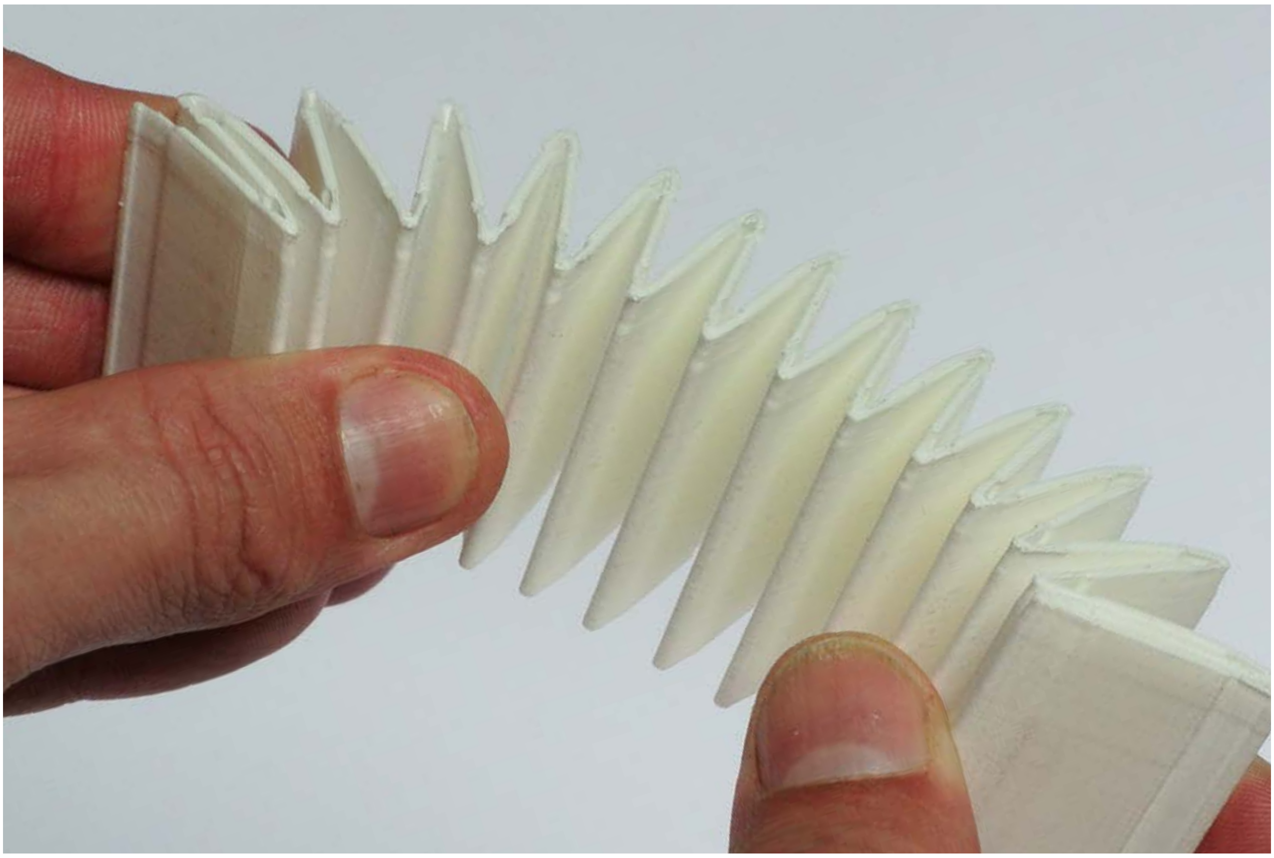
BELLOW INTERACTION

The playing interaction of the bellow should be similar to that of a conventional bellow. For instance, the bellow should not displace in a direction perpendicular to its axis, or deform in any other way than through folding. This means a rigid bellow framework is required.

requirement #17

Several different design for the printed bellow are worked out, and multiple models for the bellow are printed to test their extension. Some working principles are worked out in other materials, most importantly to test systems for the corners.

Finding a system that handle the material displacement in the corners turns out to be a real struggle. Either the material is too thick for bending, or it tears too easily due to the material and production process properties. There is no ideal printing orientation for the bellow, because it has folds in two directions, as well as corners. This means that some folds will be folding along with the printing layers. The material is likely to tear along the layer where it does so. Test prints confirm this.

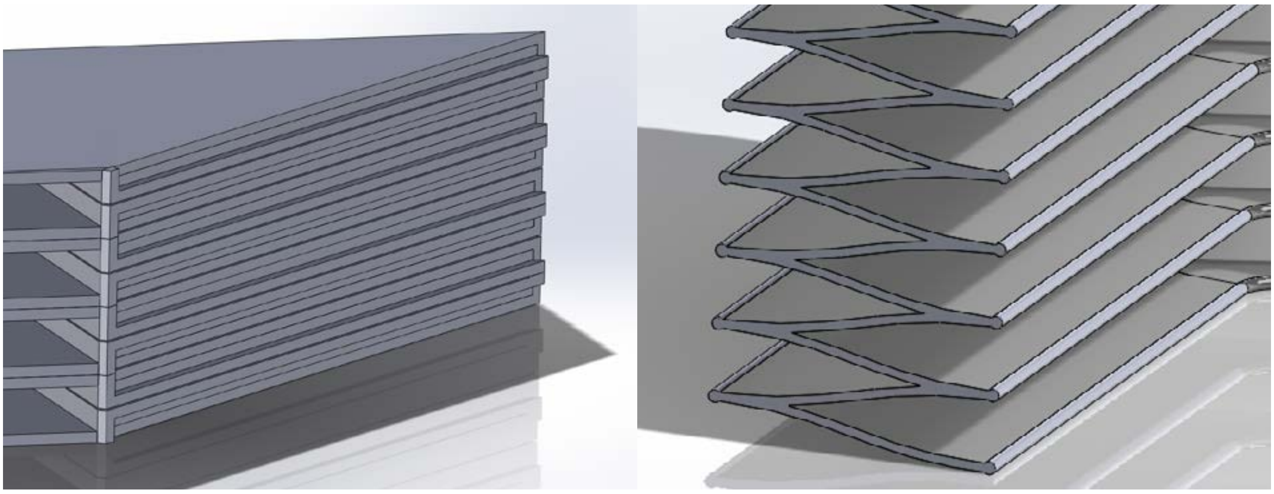


This print does not break when stretched, but it requires a lot of force to do so.

A relatively promising design provided a starting point for a finite element analysis. This design consists of a thick bellow plane, with thinner corners, making them foldable. Extra material on the outside of the corner protects it from leakage caused by normal use. The bellow pressure was simulated, resulting in an acceptable pressure of 2,1MPa. This can be seen on the next page.

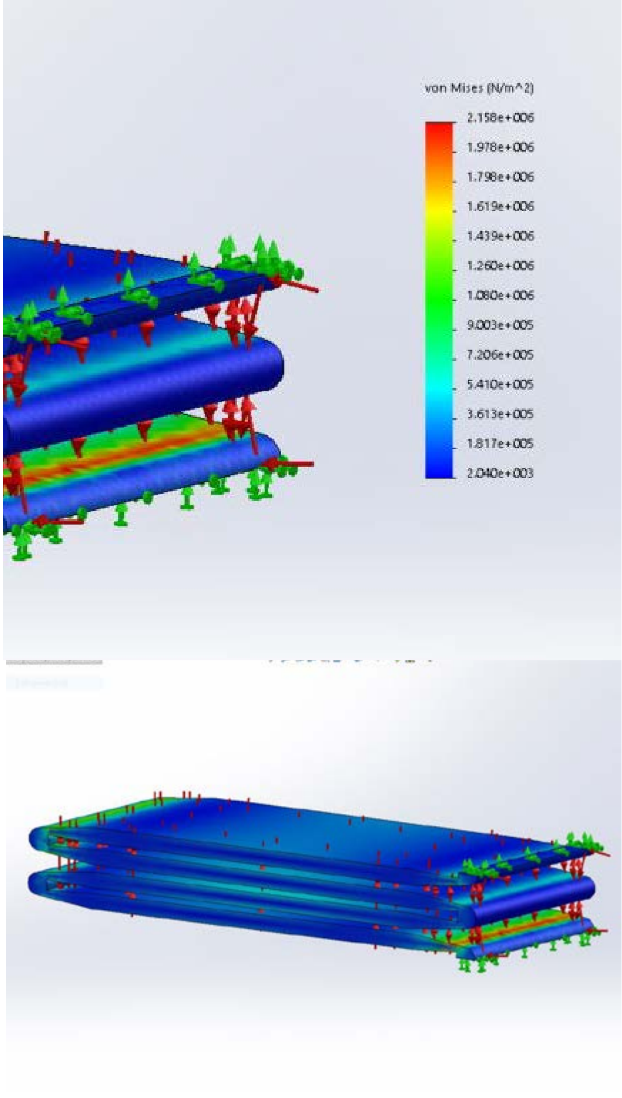
A model of a complete bellow with the same profile as the print was opened 150mm. This requires 230N of pulling force, and results in stresses of up to 103MPa, which is far above the tensile strength of most FDM polylmers.

It is possible to reduce the required force and the internal stress by optimising the design further. However, it is not possible to print a bellow in one material with similar properties to the standard bellow. Some ideas, such as radically increasing the corner radius to lower stresses there, conflict other parts of the instrument: the reeds need space inside the bellow. Other ideas, such as making the material very thin, conflict with the lifetime requirement. Even when neglecting the bellow corners, it seems impossible to produce a single material long-lasting bellow with the right properties through AM processes.

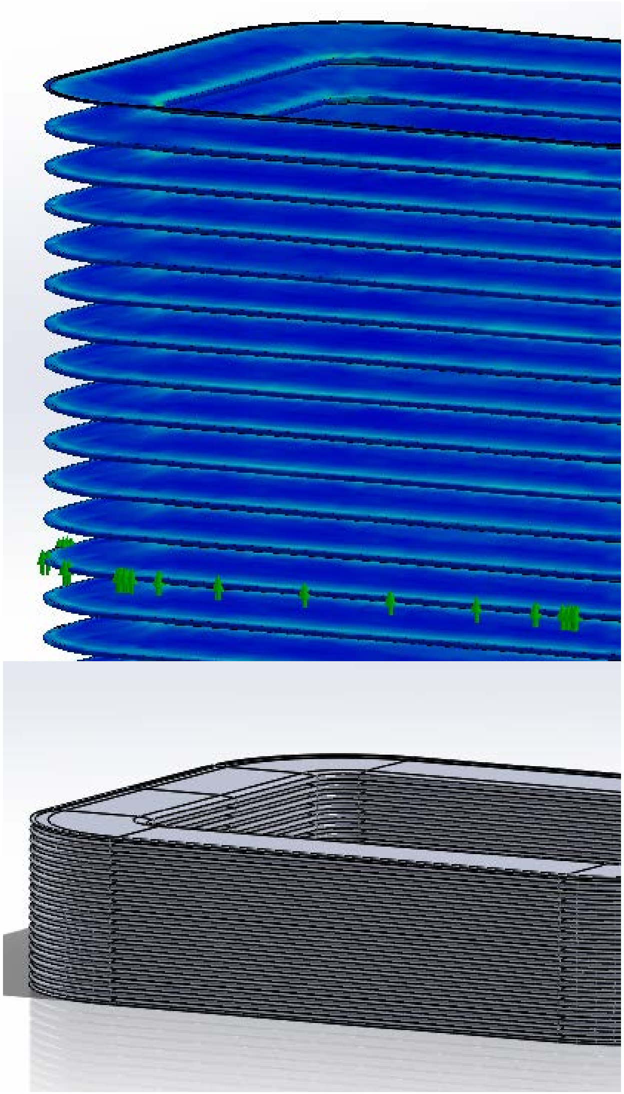


Different 3D models for bellow designs all proved problematic in terms of opening force and strength.

Flexible FDM-material could be used for the hinging parts of the bellow. However, a non-flexible material is required for the non-hinging parts, since the bellow needs to be rigid here. If this is not the case, the bellow will become one completely flexible balloon-like structure, making it unuseful for accordion purposes. Printing in flexible material would therefore require a printer with three nozzles (rigid material, support material and flexible material), increasing the printer cost and, more importantly, the chance of print defects. Furthermore, it is not clear how the bond between flexible and rigid material will hold over time. This material transition would be a likely candidate for air leakage, as the high bellow pressure might cause the materials to part. This is problematic, as the bellow needs to be airtight.



A bellow pressure of 1000N/m² results in a material stress of up to 2MPa. This is not a problematic value.



Simulating a stretch of 150mm here results in stresses up to 102MPa, which is unacceptably high for FDM materials.

Conclusion

Printing a functional accordion bellow that can compete with a conventional bellow is not possible using current additive manufacturing techniques and materials. Finding a suitable material is difficult, as the bellow needs to be airtight, light in handling and flexible but rigid at the same time. A mix of materials solves this last problem, but creates new ones instead. Because of this, the bellow is left out of the assignment scope from now on, and the focus is put on the right hand side of the instrument, both body and mechanics.

7. INTERNAL MECHANISM

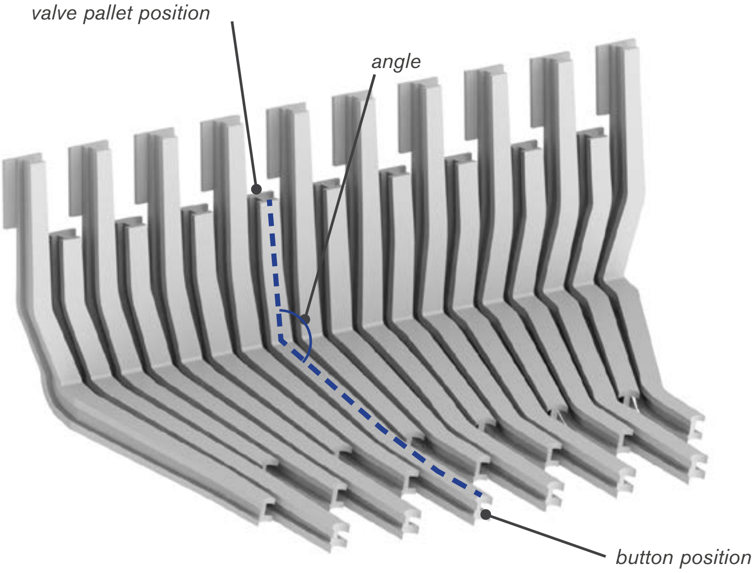
The internal mechanism consists of all parts in the body that form the connection between the button and the valve. In this chapter, the design of its basic structure is discussed, as well as the method of attachment to the body, the resilience mechanism and the incorporation of a valve pad.

7.1. beam structure dimensions

A conventional internal beam structure consists of angled aluminium bars that are mounted on a steel axis. The bars have been bent into position by hand in order to place all valves and buttons in the correct position. Assembling and bending all beam structure parts is a time-intensive process, approximately 4 hours for the complete right hand side mechanics. Producing all the different beams pre-shaped means that this post processing is not required. Here lies a clear opportunity for additive manufacturing techniques.

DEFINING THE BASIC DIMENSIONS

Since the playing interaction of the instrument should not change, the button positions need to be similar to that of other accordions. Furthermore, the angle in the beam structure is a logical choice. The playing interaction is set: the back of the instrument is resting on the bosom of the user, with the buttons on the front right (user perspective). The reeds are placed under an angle of about 110° from the buttons. This leaves enough room to for the hand of the user, and creates enough area to mount a significant bellow onto the body. These main dimensions of the internal beam structure are similar to that of the traditional accordion.



The basic dimensions of the inner beam structure

BEAM STRUCTURE DIMENSIONS

The mechanical parts should not be larger than necessary and should fit the buttons and reed blocks. This is necessary in order to keep the instrument compact and functional.

The mechanical system fits onto the sound chamber air holes and the buttons. It can not be wider than these components, or higher than the current instrument. Buttons lie 18mm (horizontally) and 15mm (vertically) apart, while the sound hole positions are defined by the sound chamber design.

requirement #18

An early version of the complete beam structure that incorporates all the dimensions as specified.

7.2. beam structure fixation

Currently, all beams are mounted on a bar that functions as a hinging point. When all beams are in place, torsion springs are placed in order to keep the valves closed onto the air holes when no button is pressed. All the springs are placed by hand. One end fits into a tiny hole in the beam, the other end lies in a holder slot on the body on the other.

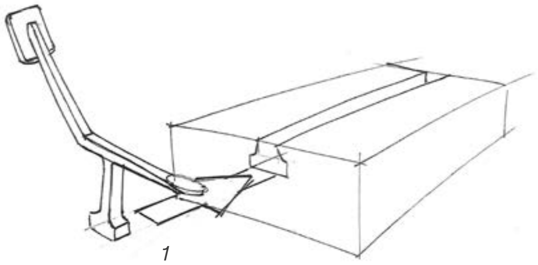
A SNAP FIT FIXATION

If a part of the internal beam structure breaks down, it will need to be replaced. If for instance (part of) a beam is damaged, all beams and springs need to be disassembled in order to reach the part. Only then, the complete beam structure with springs can be reassembled. For an instrument this size, this can take up to an hour.

Although the current beam fixation on an axis forms a reliable and secure connection, an alternative solution is desirable. This should enable easy maintenance to the beam structure of the instrument.

The design, dimensions and materials of the instrument in this project will be different from the traditional accordion. Flaws might come to the surface over time, and this means that being able to replace certain parts easily is extra important.

There are multiple options for an alternative beam structure fixation. This includes a slot that the beams slide into, the beam structure as a separate part mounted inside the body, an axis mound with a different spring, and multiple snap fit systems.



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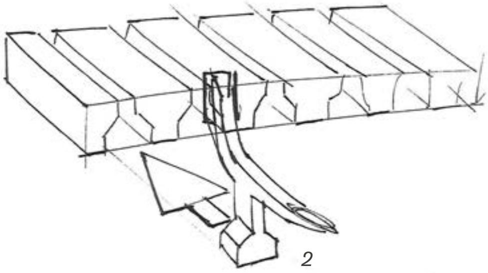

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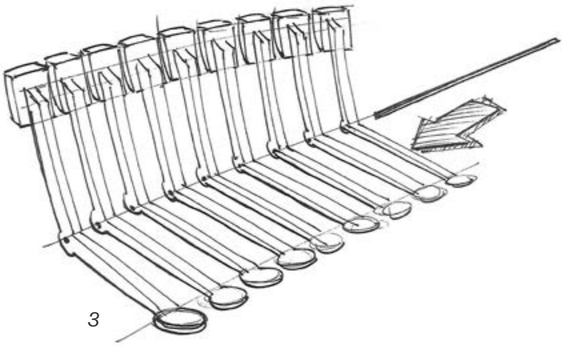

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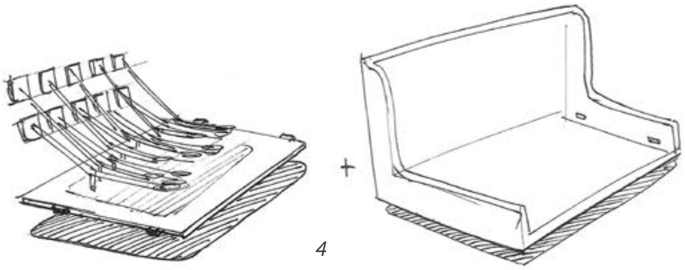

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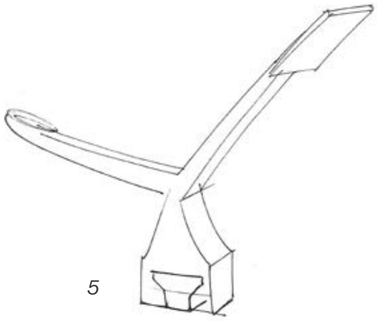


5

Ideation drawings for a slot for the full mechanism (1), single snap fit slots (2), a conventional rod mount (3), a separate mechanical system print (4) and a different type of snap fit system (5) .

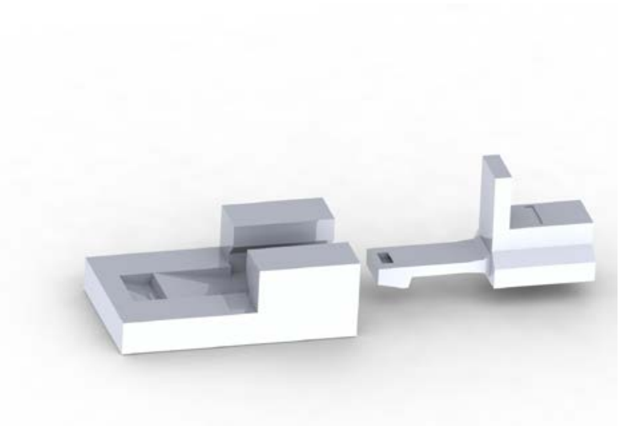
EASY (DIS)ASSEMBLY

Mechanics can be disassembled when a certain part requires repair. Especially for a new product like this, unexpected repairs might take place. Currently, all the mechanical parts are mounted on one bar, so everything has to be taken apart in order to repair one part. This can be made more efficient.

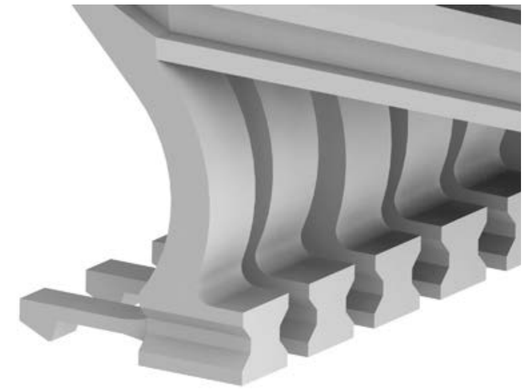
The time to remove a single beam should be under 1 minute. With 19 arms on the right hand side, this enables repair on the right hand side mechanic within 40 minutes (excl. repairing components), the time it would also cost with the current MiniMouse.

requirement #19

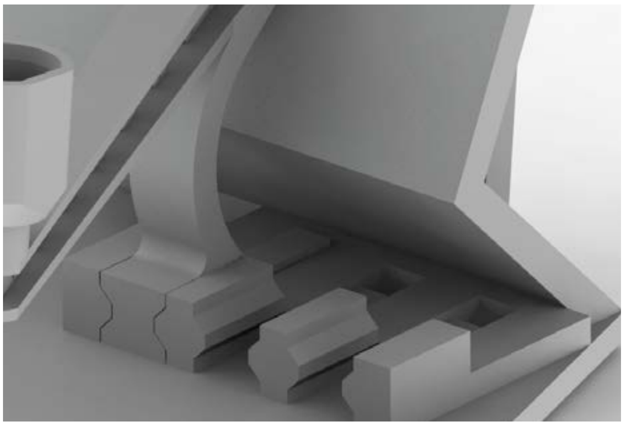
The choice is made to fixate each beam with a separate snap-fit. Since the snap fit can be printed along with the rest of the beam structure, no extra parts are required. The beams can be assembled one by one, making placement and eventual replacement relatively easy.
The choice for a snap fit is combined with the choice for a printed spring, replacing the original torsion spring. The printed spring forms a connector between the snap fit and the beam itself.



The first version of the snap fit mechanism



The second version of the snap fit mechanism



The third version of the snap fit mechanism, where the snap placement is problematic

SNAP FIT DESIGN

The snap fit system consists of a block that slides into a slot. This slot secures the block in two directions. The third direction is secured by the snap fit. Its male side is placed on the front side of the block. Since this is the part of a snap fit that breaks most easily, it is logical to place it on the block, and not on the instrument body. If the part would break, it is more desirable to replace a single beam than it is to replace the whole instrument body.

During normal use, there are not many forces acting on the snap fit that can detach it. The button will be moving inside certain boundaries, resulting in an up- and downward direction rather than backwards, which would detach the snap fit. Therefore the chance of accidental detachment is relatively small.

The first version of the snap fit is a 10mm long part that slides over a cavity in the body of the instrument. The angles of the snap fit are 13° and 60°. Calculations give a mating and pull-off force of respectively 0,9 and 18,3N (BASF Corporation, 2007). It features a tiny hole in order to lift the snap when removing it does not go smoothly.

A test print shows that the basic system works, but the parts only snap into place with a lot of force.
This is due to the design of the snap fit itself and the tolerances during printing (making the fit tighter than expected). Also, the tiny hole does not prove functional because it is too small to handle easily.
The upper side of the first version is smaller than its bottom. This means there is less width available to place a spring on. This is resolved in a second version, where a new profile for the snap fit base is created. The base now fits into the slot well when printed with a 0,2mm width reduction on each side. If printing errors occur (e.g. a slight warp), material can be removed manually. Because of the vertical surface in the middle, this is not a satisfactory process. A knife blade can not follow this contour, since it is obstructed by the part itself. Therefore, the design is updated, resulting in a triangular cutout. This shape can, if necessary, easily be optimised using a knife, since the blade can trace the profile without obstructions.

There are more problems that need to be addressed. One of these is the length of the snap, which is obstructing the instrument body and therefore leaving less space for the reeds to be placed.

Since the snap that is blocking the wall would result in an unnecessarily large instrument, the snap fit is shortened to 8mm. This does, however, increase the chance of failure: shortening the snap fit will increase the stresses at its base. Still, the snap almost touches the body. It could be smaller, simpler and more trustworthy in terms of material failure. Although the calculated strain at the base ($1.5/(8^2*1.3) = 18$MPa) does not exceed the yield strength, multiple test prints have broken. This may be due to the strength of the printed material.

The snap is completely redesigned to tackle all problems. It is moved to the top of the base, and works by snapping over a ledge. Its length is reduced once more, to 6mm.

Because no clear model for calculating the mating force is available, test prints have to indicate if the design is correct. After multiple iterations, the snap fit fits well into place.

In order to make the loosening of a snap easier, a ring-shaped structure is added to the back of the base. Using a custom tool, the user can now easily reach the snap and loosen it, without being obstructed by the other part of the mechanical structure.

CONCLUSION

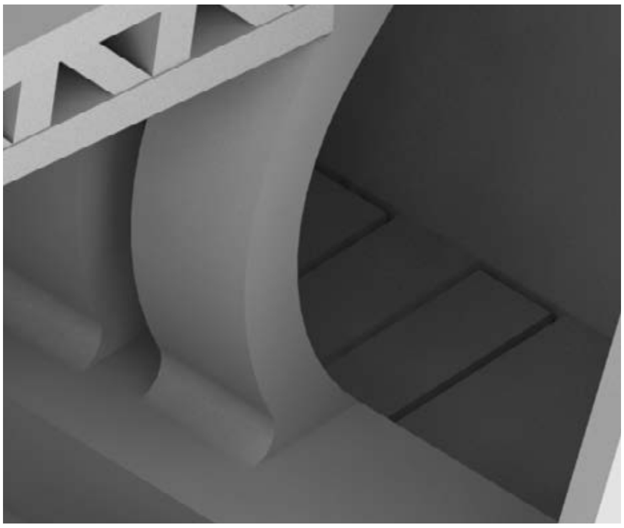
During a process of many iterations, the initial choice for a snap fit mechanism is optimised for multiple aspects. The snap fit needs to be easy to place and position, and needs to stay into place until it is deliberately removed. This is made possible by printing the snap fit and its base with precisely correct dimensions. A ring-shape on the back of the snap fit base makes it easy to loosen using a tool.

SNAP FIT FORCE

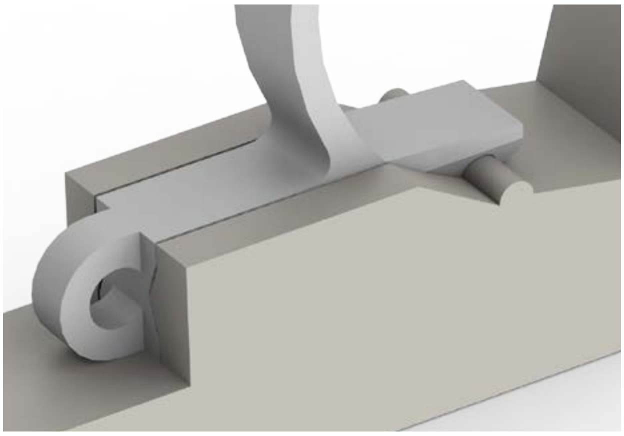
The snap fit can be placed and replaced by a human, eventually with tool. The snap fit should not open during use. When placing the snap fit, user feedback should indicate that the snap fit is well connected.

The maximum snap fit push and pull force is 50N.

requirement #20



The snap dimensions are adjusted so that it does not form an obstruction for other parts



A fully redesigned snap fit proves more functional

SNAP FIT CLEARANCE

Any clearance would make it easier for the snap fit to loosen. It is not desirable for the user either. The snap fit should not have a noticeable clearance. This can be verified by moving the snap fit mount by hand.

requirement #21

7.3. resilience mechanism

Some sort of resilient mechanism is required in order to move the button and valve to their original position when the button is released. Conventionally, this is done via torsion springs at the base of the internal mechanism.

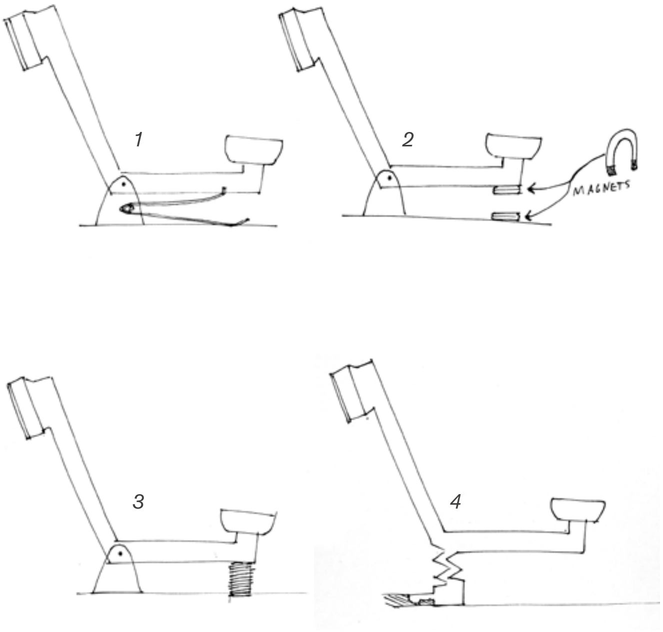
TYPE OF MECHANISM

There are four different concepts to create resilience in the mechanism: using a conventional torsion spring (1), using a compression spring (2), using magnets (3) and using a completely printed spring (4), where the beam is placed under pretension using the material properties of deforming resilient plastic.

The first three concepts use an axis mount for the beam structure, similar to the conventional system. The fourth concept does not require an axis as the arms can move on their printed sprint. The advantage of such a concept is that there are no additional axis and spring that needs to be assembled.

Since the compression and torsion spring are known concepts, only the magnet and printed spring are subjected to further research. A quick and dirty test indicates that neodymium magnets can provide an amount of pressure on the valve that feels realistic. While a printed spring is the best option in terms of assembly, the magnets provide a good alternative. Placing a magnet by sliding it into a slot takes little time.

A digital model for a first printed spring is created, and a force of 1,5N on the button is simulated. The button moves down 8,5mm with high stresses in the spring: up to 47MPa.



A torsion spring, magnet, compression spring or a printed spring can be used to create resilience

A quick model to test the feel of a magnet system

SPRING-BUTTON FORCE

The button force required to fully open the valve is similar to that of a conventional accordion. Accordionists are used to a certain force when pressing a button. The redesign needs to adapt to the previous experiences of the user.

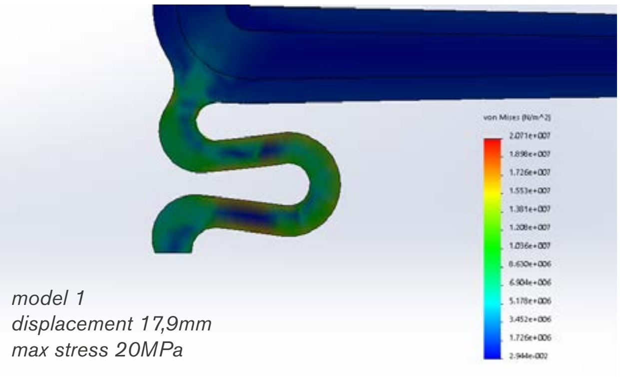
The current MiniMouse has button forces ranging from 0,8N (first row) to 1,7N (third row). Values for the redesign need to be in between these values.

requirement #22

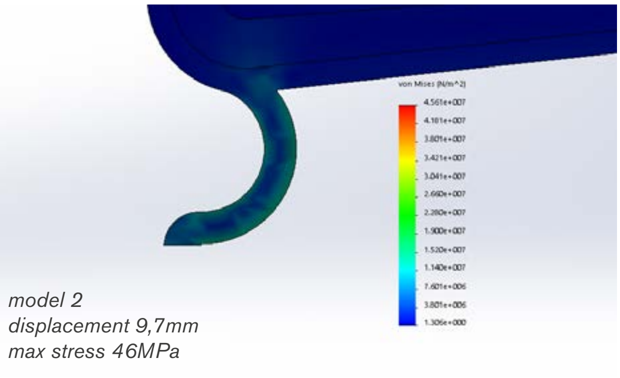
In order to lower both the button displacement and the stresses in the spring, the design is updated. Three more versions are simulated in the computer.
The third model has the lowest button displacement and internal stresses. It indicates that the spring will hold with no plastic deformation. This is the model that is selected for testing.

Multiple test prints are created for the printed spring and the magnet system. The printed spring can be placed under different pretension by varying its distance to the vertical surface. A configuration is found where the model feels good and the required force for full displacement (5,5mm) lies around 1,2N.

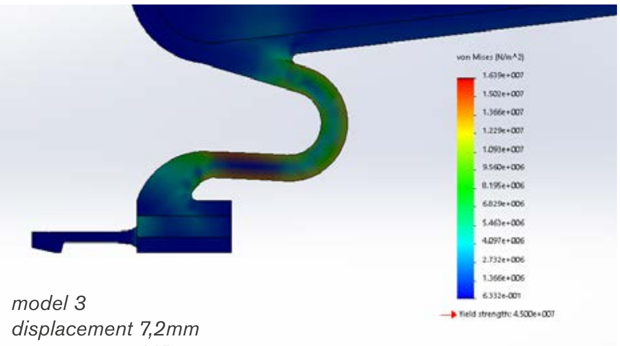
The magnet model proves to be more problematic: it is based on two magnets that repel each other. The problem here is that the sides of the magnets are attracted to each other, so that the arm tends to move sidewards and snap to the bottom magnet. A guidance system does solve this problem, and forces of 1,1N for full displacement are found. The guidance system does cause a noticeable interference, which is not desirable for the design. Because of this, the choice is made to focus on the printed spring further on.



model 1
displacement 17,9mm
max stress 20MPa



model 2
displacement 9,7mm
max stress 46MPa

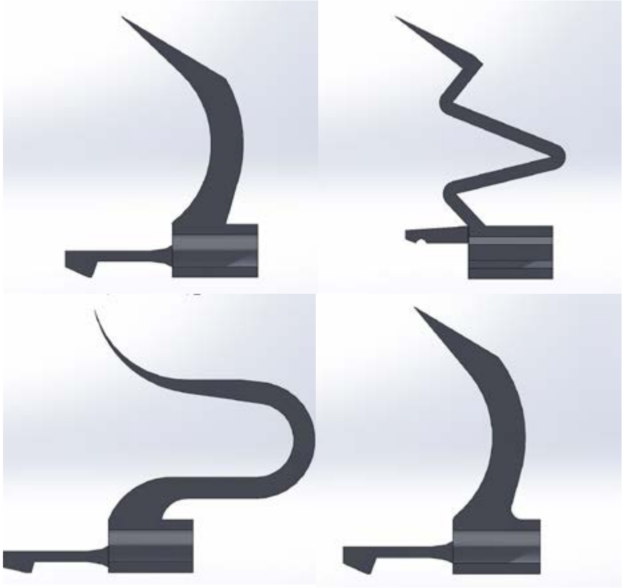


model 3
displacement 7,2mm
max stress 16MPa

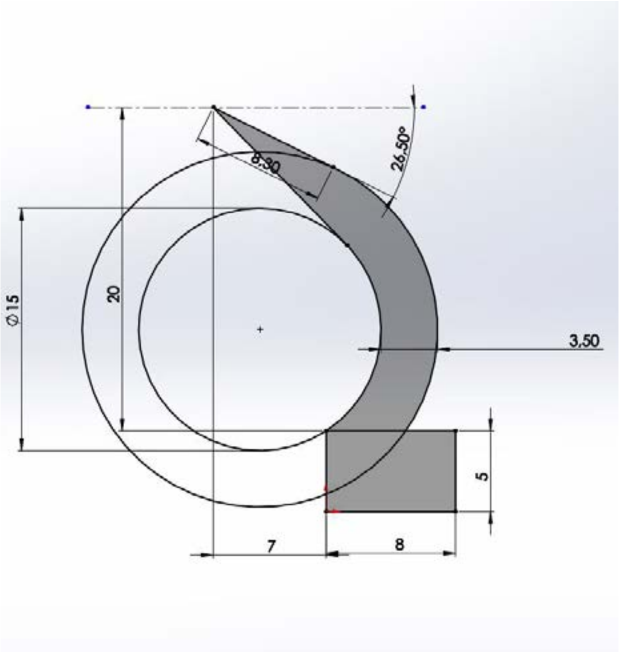
This model indicates the magnet system is suboptimal because of guiding problems. The printed spring designs perform well.

More iterations on the design of the spring reveal that the design based on a circle performs best in terms of displacement and stresses. Small alterations of this design are made in order to improve the stress distribution in the material. The design is made in triplicate: each beam length has a specific spring thickness in order to keep button pushing forces equal for each row of buttons.

The result is a spring with a rather equal stress distribution. There are still some small stress concentrations on the base and top of the spring. These are hard to eliminate without affecting spring performance. In the spring stress simulations, the stresses on the curved survace of the spring are not uniform. This is due to the fact that the arm that is used is not straight, as it is on the side of the mechanical structure. This causes a torque in the spring.



Using digital simulations, many spring designs are analysed on their stress and resilience performance



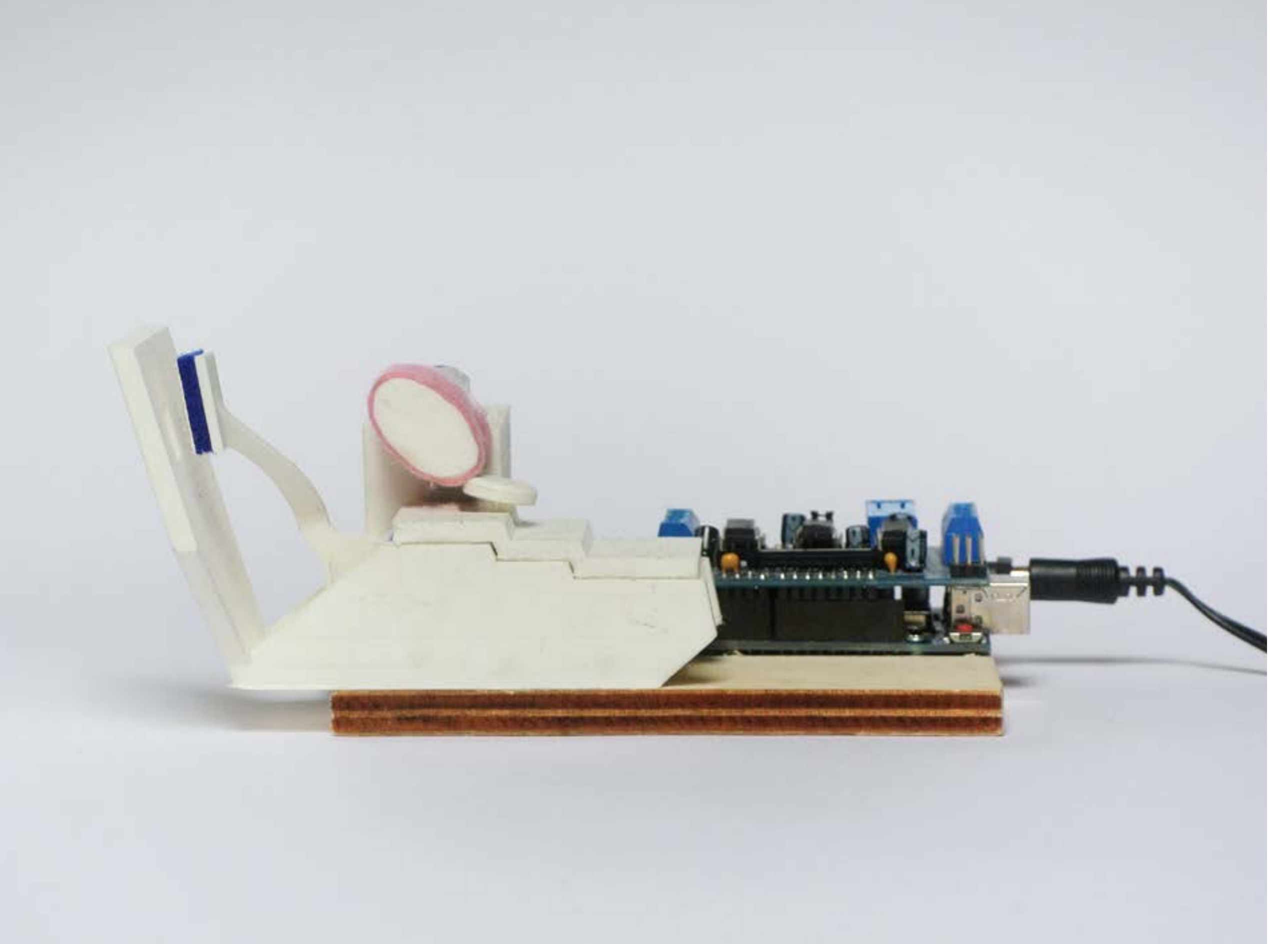
The construction of the final spring is based on a circle

SPRING LIFETIME

The springs in the instrument can endure 10 years of playing. Pigini users are used to such a quality for their instruments.

Suppose an accordionist plays the instrument for 30 minutes a day (since it is a small instrument, intensive playing is not very likely). Some tones will be used more often than others, depending largely on the music that is being played. In this case, we state that the accordionist plays scales only, consisting of 8 tones. If the tempo is moderato and the notes are crotchets, this means 110 tones per minute. In 10 years time, a button will be pressed 365,25 * 10 * 30 * 110 / 8 times, which is about 1.500.000 pressing cycles.

requirement #23



Using a microprocessor and a motor with a transmission, buttons are pressed at least 1.500.000 times

SPRING DURABILITY

It is possible that the spring fails during use due to fatigue. To find out if this happens, a rough estimation of the pressings of a button is made.
A reasonable lifetime for the spring would be 10 years. This is equivalent to 1.500.000 spring load cycles, as explained in requirement 23 on page 56.

An SN-curve can be used to determine if the spring will fail during 1.500.000 load cycles. However, these are not widely available for FDM-based materials. Fischer & Schöppner (2016) present an SN-curve for Ultem 9085 material. This is a very strong plastic with a tensile strengh around 70MPa when built in the X-direction and 47MPa in the Z-direction.
With the current spring stress (~10MPa), this material can resist between 10^5-10^6 load cycles in X-direction and 10^4-10^5 load cycles in Z-direction. After this point, the material will break. When printed in the right orientation, it is likely that using PC-ABS (tensile strength 41MPa XZ) gives results in the same order of magnitude as the Ultem Z-direction.

Besides material failure, creep is another potential problem: due to the stress on the spring, plastic strain can occur. This can make the pretension in the spring less effective. It can eventually cause air leaks as the valves need to be closed under tension against eventual air pressure.

Stress relaxation is another factor that can affect the spring and its pretension. If the instrument is not used, there are still stresses in the spring due to the pretension. This can create a permanent set of the spring: a decreased tendency to return to its original position when unloaded. This makes the stress in the spring decrease, making the pretension less effective.

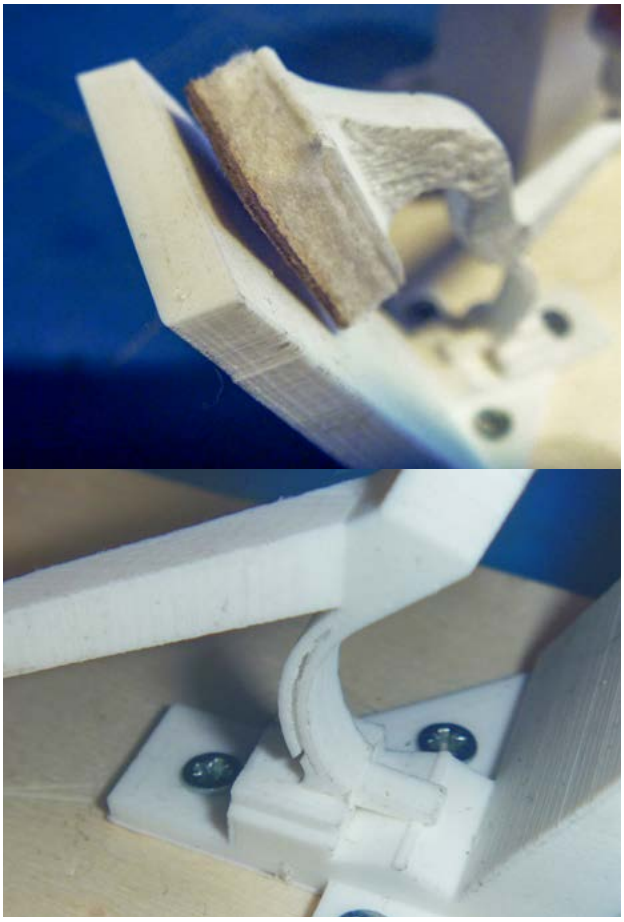
Material failure, strain and loss of stress can be problematic in the design. In order to validate the concept, a fatigue test is set up. A single printed arm is installed against a wall with a sound hole, just like in an accordion. The spring and valve are all included in the print, and felt and leather are added onto the valve in order to make the setup as realistic as possible. The parts were printed in PLA (tensile strength 45MPa XZ). This material does not have a comparable yield strength with PC-ABS, but its Young's modulus is in the same range (1900 vs 2500 MPa). A cylinder-like shape is mounted onto a geared DC motor that is connected to an Arduino. Because the shape is a elliptical, it presses the button 5,5mm downwards when rotating.

In the first test, the short arm is tested for over 1.500.000 cycles. The button was pressed 186 times every minute, at room temperature. This is a realistic tempo for playing a note, while not taking too long for all the cycles (5,7 days). After 400.000 cycles, the required button force has dropped from 1,5N to 0,5N. The valve does not fully close anymore. After 1.500.000 cycles, the required force dropped under 0,5N, and one layer of printed material has come off of the spring. The spring did not fully break.

A second test is set up with the same arm on a thicker spring to find out what this does to the required force. The required force at start was 2,5N. However, a little over 500.000 cycles, the spring completely broke down at the top.

A third test, similar to the first one but faster (316 cycles per minute) presses the button over 2.300.000 times - roughly 15 years of playing. This is done to verify the results of the first test. The outcome is similar: the spring does not tear or break, but the separate print paths come loose. The spring in this test ends up with pretension and pressure problems similar to that in the first test.

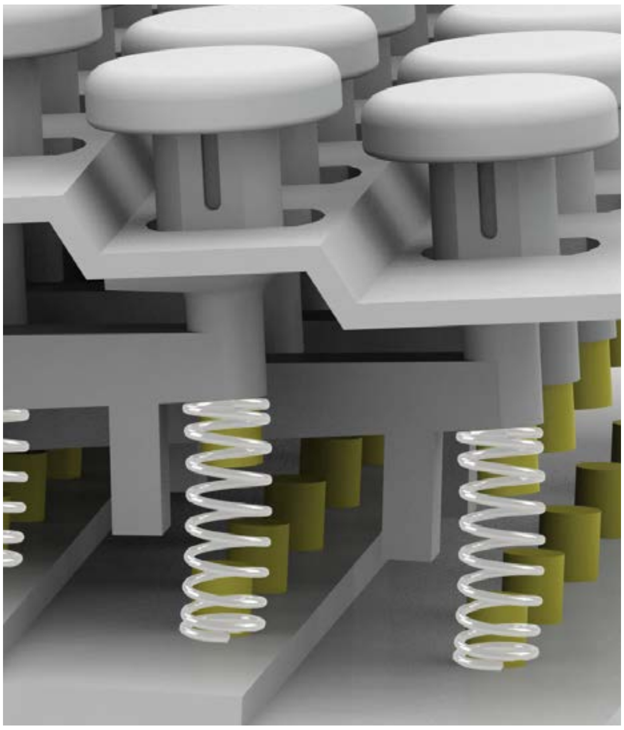
The fatigue test shows us that the concept of a printed spring is a bit too optimistic. The fact that the thinner spring does not break after millions of cycles does provide the opportunity to make use of the separate arms and clicking mechanism, which is valuable during assembly and maintenance. The resilience of the buttons, however, needs to be created by another component.



The result of test 1: a damaged spring and displaced valve

The result of test 2: a completely destroyed spring

The result of test 3: another damaged spring and displaced valve



Early design for spring placement

The new spring position, placed here on a impractical plateau

FINDING A NEW SPRING

The spring test clearly indicates that using a printed spring for the spring force in the instrument is not an option. Since the thin spring does not break after many pressings, it is still possible to use the printed spring as a connector between the snap fit system and the beam. This means no axis is required to fixate the beam structure inside the instrument body.

The design is updated with a compression spring (Fabory DIN2095 0,5x4,5x12) that can facilitate the required spring force. The pretension of the valve and the spring resistance when a button is pressed will come from this component. The compression springs are placed over printed plugs. One plug is directly under the button, the other is on the instrument body. This means the pressing force for each button will still be equal. However, the springs prove to be too strong, and mounting a spring can take up to 30 seconds as the spring needs to be between two components.

A redesign is made where the spring is not placed between the body and the beam, but on the separate beam part only. It is still placed over plugs, directly behind the printed spring. This means the springs can be placed inside the mechanical structure before the separate beams are connected to the body. Placing the springs now only takes a few seconds per beam.

A beam with the final spring design is subjected to the same test in order to test its lifetime. After 1.500.000 pressings, all parts are still intact. The button force has dropped from 1,4N to 1,3N. This small difference is acceptable, as it stays within the required range. Furthermore, the valve still closes airtight with a pushing force of 0,5N.

The test is continued onto 7.500.000 pressings, equivalent to a lifetime of 50 years. Still, the parts are intact. The button force at this point has dropped to around 1N. The valve closing force has dropped from 0,7N to 0,4N. The printed spring performs better than previous versions due to slight changes in its dimensions: it has been made thinner so that it consists of only 3 extrusions of material next to each other.

CONCLUSION

The separate parts of the beam structure are fixated using a snap fit. The parts are positioned by sliding the base into the snap fit slot. On this base, a printed spring is present to enable beam movement. The printed spring does not maintain its material resilience during its lifetime. Adding a compression spring to the design solves this problem. It ensures a lifetime of over 10 years for each button of the accordion. By adjusting the spring pretension length, the button force can be influenced. The compression spring is selected since it is easy to place. An update to the design of the mechanical system makes it possible to place the springs before assembly of the beam structure into the body.

7.4 beam profile selection

A polymer-based beam structure will behave different from the original aluminium structure in terms of deflection. The beams are not mounted on an axis, so their shape will have to be redefined. The goal is to create a product that is material and cost efficient, while meeting the mechanical requirements.

Material theory learns that an I-profiled beam can be strong and material efficient when forces are acting on it in the vertical direction. A topology optimisation verifies this result for our particular situation of an angled beam. Therefore, this beam profile is chosen as a starting point for the design.

The result of the topology optimisation

BEAM TORSION

Torque in the mechanics should not obstruct playing of the instrument. Some mechanical components are subject to torque. They should not touch each other as a result of torsion, since that would obstruct the functioning of the instrument. Furthermore, the user should not notice any influences created by the torque, e.g. no skewing buttons.

requirement #24

BEAM DEFLECTION

The beams in the mechanics will deflect when a button is pressed. This is a result of the pretension in the system, that needs to be relieved before the mechanics will start moving. This deflection of parts in the mechanics does not result in plastic deformation of the material, is not larger than 1,1mm at the button (20% of button pressing), and neither does it obstruct the playing of the instrument in any other way.

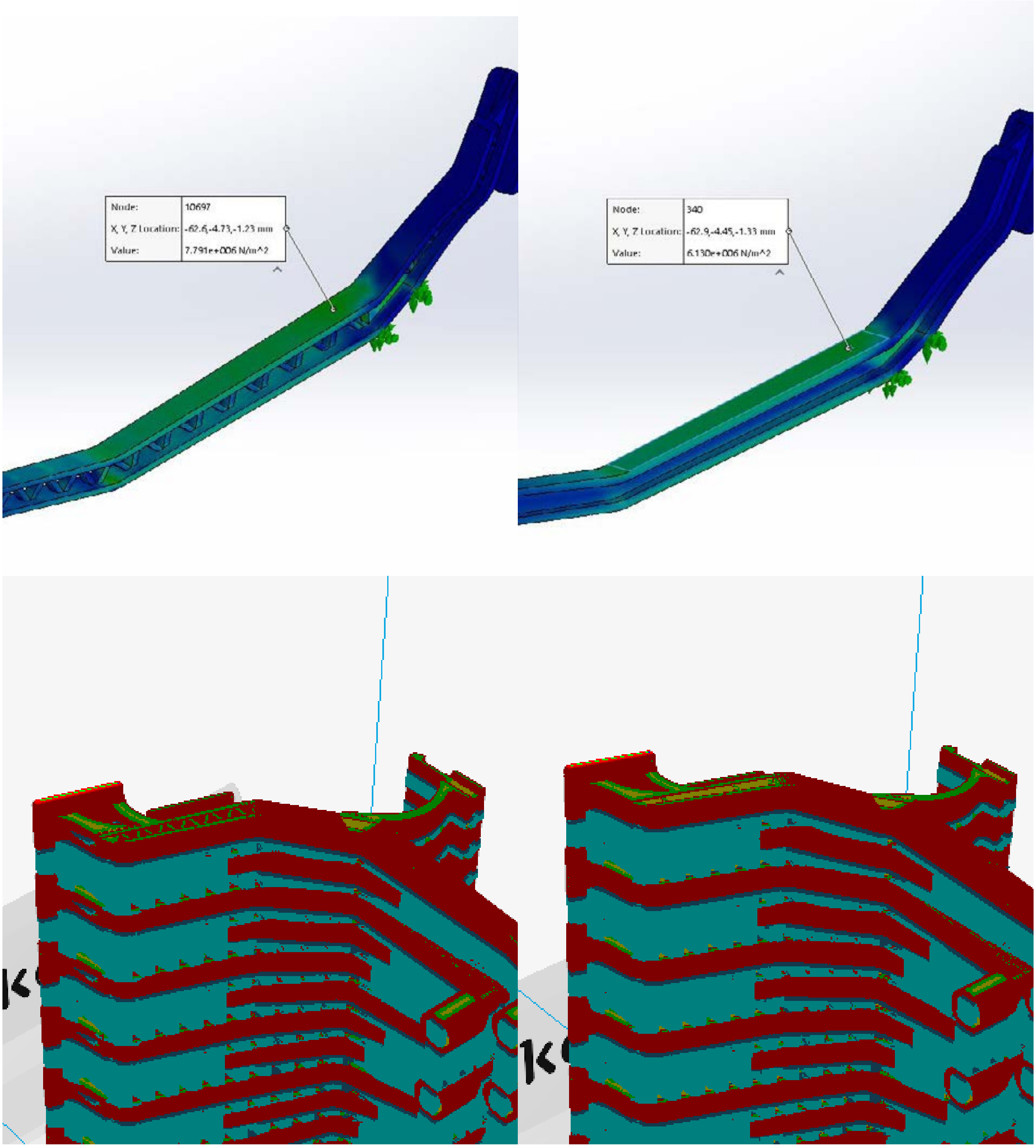
For a PC-ABS material sample the material strength is 41MPa in XZ orientation (Stratasys, 2016). Depending on the print orientation, the stresses should not exceed this value, using a safety factor of 2. This means the material stresses need to lie under 20MPa.

requirement #25

The basis of the I-profile at the center is a rectangle of 5,5x8mm. The width of 5,5mm for each beam is defined by the space available. There is a 2,5mm clearance between each beam. At the end of the profile, its width and height become smaller, because lower stresses occur in these positions.

In order to decrease material usage, the profile can be outfitted with a triangular cut pattern. This can reduce its weight up to 25%, but it will also increase internal stresses and deflection with ~25%.

However, when printing this, the amount of material required is almost equal for a model with triangle cut-outs and a square model (112 vs 115g). This happens because triangles require extra walls to be printed. Printing with triangle cut-outs takes about 8% longer, because the printer head needs to make more complex movements. A regular rectangular profile is therefore the best option.



Node: 10697
X, Y, Z Location: -62.6,-4.73,-1.23 mm
Value: 7.791e+006 N/m^2

Node: 340
X, Y, Z Location: -62.9,-4.45,-1.33 mm
Value: 6.130e+006 N/m^2

Stress simulation and printer setup for an arm with and without cutouts. As the cutouts require support material and obstruct the model infill, only a minimal amount of material is saved, and print time increases.

CALCULATING BEAM DEFLECTION

The deflection of the beam half from the button up to the spring connection needs to be calculated, as this is the part of the beam that is affected when a button force is applied.

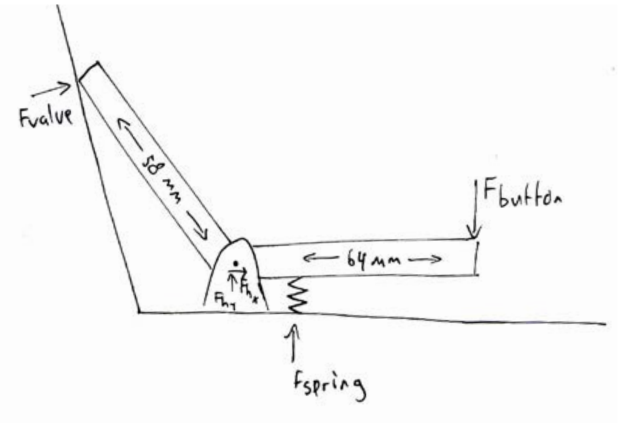
In order to press a button downward, the moment caused by the spring needs to be neutralised by a force on the button. This causes a beam deflection.

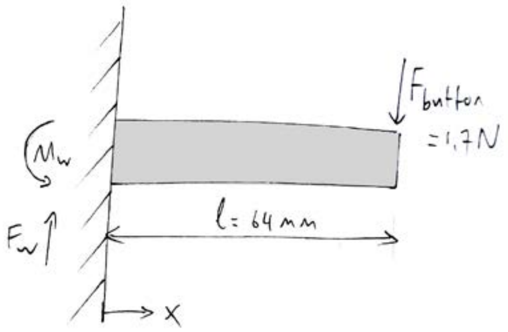
Although the pressing of a button is a dynamic situation, we can model this in a static form. Before the valve starts moving, there is a spring force (F_{spring}), a button force (F_{button}), and reaction forces on the valve (F_{valve}) and hinge (F_h). When the button is being pressed down, there is only F_{spring} and F_{button}. With the landing of the button, a vertical reaction force on the floor will occur. As the beam is fixed against the floor, this force does not deflect it.

The maximum force required to fully press a button is known to be max. 1,7N (requirement 22). This occurs at the end of the pressing (because of Hooke's law). This maximum value will be used for the calculations, combined with the longest beam length, which is 64mm.

The deflection of the beam from hinge to button needs to be calculated. This situation can be simplified to a static model of a single beam that has a fixed end where the hinge would normally be. When the button is almost fully pressed and held still, this situation will occur. The spring force is located close to the hinge and will therefore cause very little deflection. Thus, the direct impact of this force on beam deflection can be neglected.

The accordion beam model with varying dimensions is simplified as a 5x5x64mm beam. The deflection can be calculated for a square, circular, I-profile and triangular beam. A 3D printer would not print these beams solid, and its infill is neglected in these calculations. The beams are considered hollow, with a wall thickness of 1,5mm.





Free body diagram of a single arm, calculating deflection

The calculations give the following deflection values:

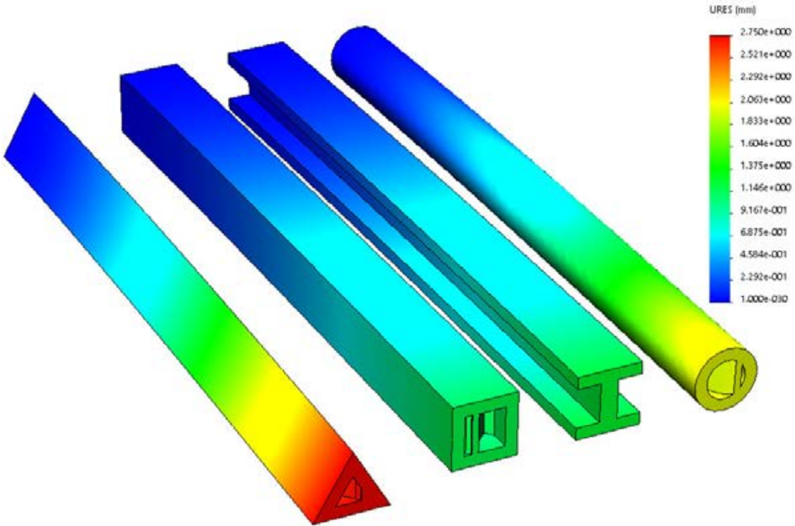
Square profile	1,2mm
Circular profile	2,1mm
I-shaped profile	1,2mm
Triangular profile	3,6mm

The I-shaped and square profile perform best in terms of deflection. Therefore, one of those profiles will be used in the internal mechanism.

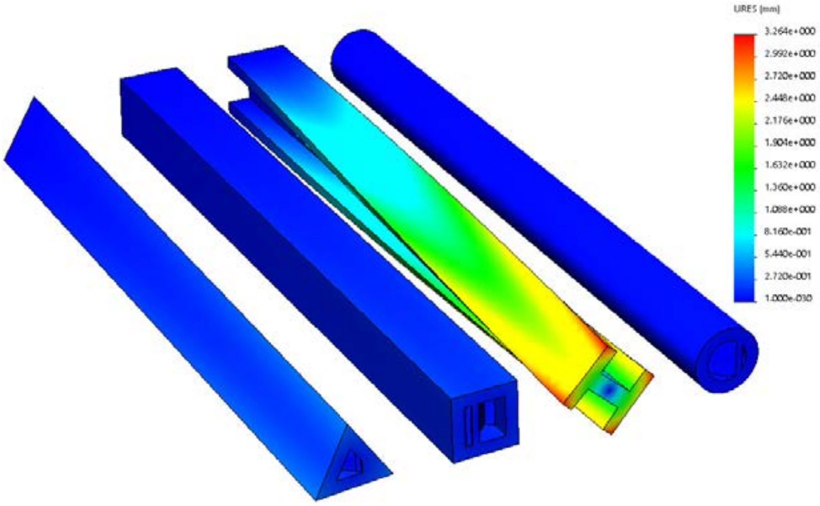
The earlier neglected infill of the beams might reduce beam deflection. The situation is simulated in a finite element method, and a 25% FDM print infill is modelled inside of it. Results show that the infill does have an effect, but the decrease of deflection is less than 10% for each beam.

Some beams are subject to torque. The torque will be the greatest for the mechanical components where the force on the arms is the furthest from the spring (x-direction). This means the arms on the side will be most affected by torsion. For the long arm, the force furthest away lies about 10mm from the spring. This creates a torque of 0,01*1,5=0,015Nm.
The torque is modelled using the same simulation as for the deflection. The result is an overview of the torsion, including the displacement and stress distribution. The method of modelling the beams straight is chosen in order to be able to see an isolated rendering of the impact of torque. This provides useful information when choosing a beam profile. It is advisable to choose a profile that does not displace too much because of torsion, since this can effect the touch of the buttons or cause interference. Since the I-shaped and square profile score almost similar in terms of deflection, the torque analysis is used to select the profile. As the square profile with infill clearly has a better torque resistance than the I-shaped profile, this profile is used in the design.

The modeled infill, seen in a 50% transparancy



beam deflection simulation (results scale 1:1)

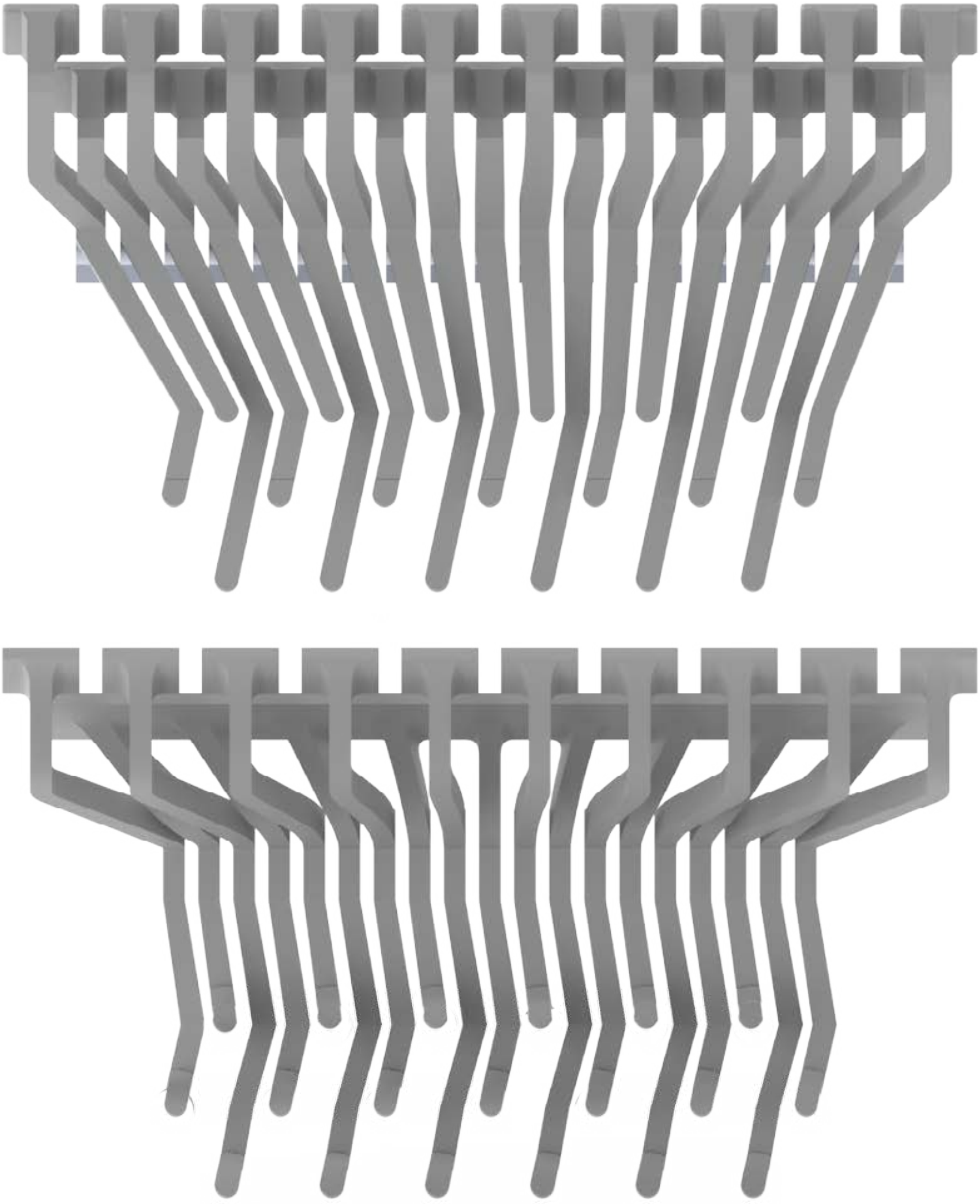


beam torsion simulation (results scale 1:1)

The selection of a metal spring makes the design of the arms inefficient. Since the spring needs to be placed vertically, a connection part with overhang is attached to the base of the arms. The model is updated so that the arms do not have an angle at the spring position. This enables a simple mount for each spring, without obstructing other arms. This adjustment does leave less width for each arm: their 5,5x6mm profile is changed to 4x6mm. As this has proven not to provide any torque problems, it is an acceptable adjustment.

CONCLUSION

A printed square profile beam appears to be a time and material efficient way of producing the inner mechanic system. The parts can be printed with an infill, reducing the amount of material required. Based on the forces applied on the beams, the space available and the strength of the material, the beam height is defined. Furthermore, beam geometry is optimised in order to make the beams fit the spring connection.



The old (top) and rebuilt model (bottom), with updated geometry so that all springs can be placed direcly onto their base. For reference, see the top right image on page 59: here, the spring has to be placed on a custom holder.

7.5. valve pads

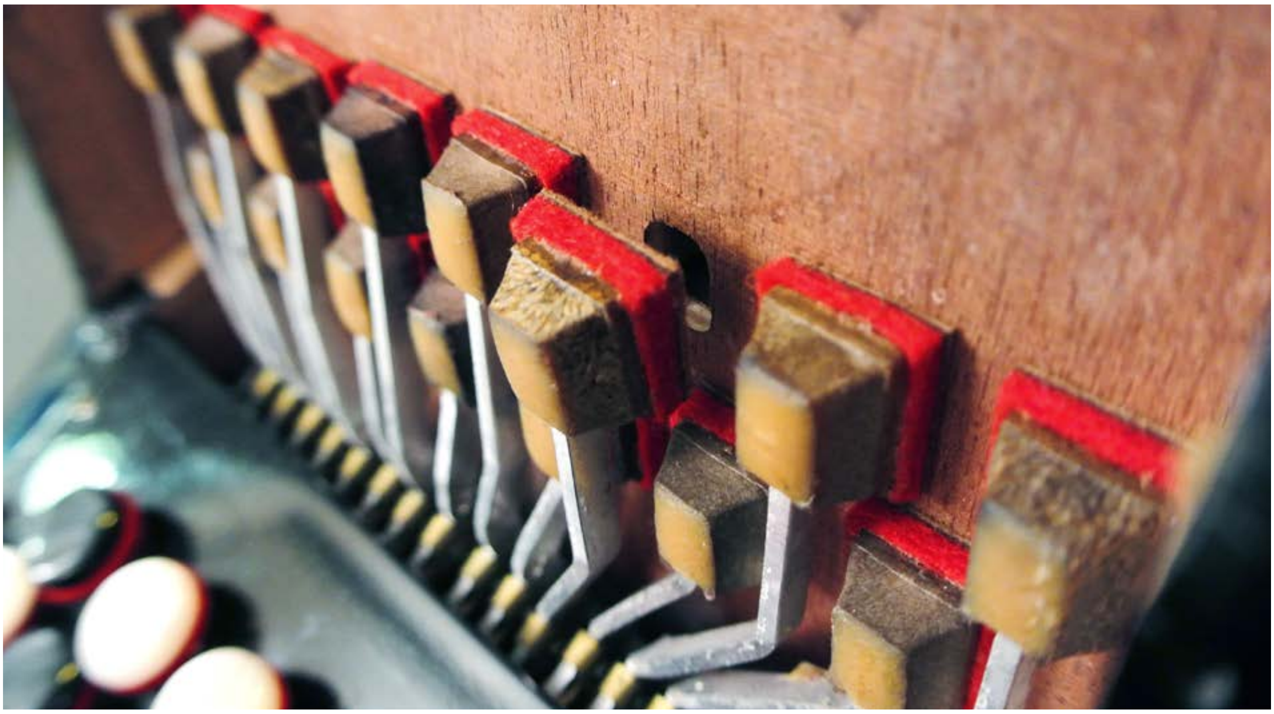
The valve pads block any air from entering the sound chamber until a button is pressed. They vary in size for different accordions and reeds. The current accordion that Pigini produces has valves measuring 12x15mm. They consist of a wooden base with a layer of felt and leather glued onto it and are pressed onto the body with a closing force of 0,7-1,5N, varying for different arm lengths.

The valves form an airtight closure on the holes. They also accommodate some damping when fully lifting a button, as the felt slightly decompresses during landing. Because this system influences the playing interaction, it is chosen to keep the felt and leather in place. The wooden base will be replaced by a printed one that is attached to the rest of the model. The shape of the valve is dependent on the shape of the sound hole, that is part of the reed block concept.

The first design of the valve pads is a plate that was placed directly onto the beams. The concept of felt and leather for closing the airholes is adapted from the conventional accordion.

The first valve pad design measures 10x16mm. In the second version, this is 11x16mm. Still, this is rather small: a proper airhole will be around 9mm wide. This would leave only 1mm of space for the leather valve on each side of the hole. A minor tolerance flaw could cause leakage. This is especially a problem since the beams cannot be manually bent, as is the case with the conventional aluminium beams. Also, there is too little space between the valve and the beam next to it: only 1,3mm.

The first design of the valve pads is dimensionally suboptimal

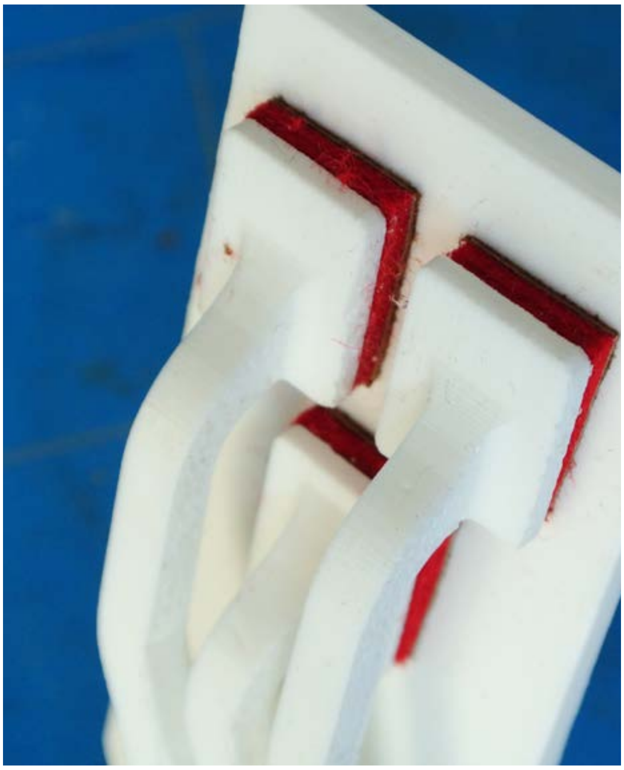


Valves in a conventional instrument, consisting of wooden blocks with felt and leather on top.

FALSE AIR

A small air leakage through a valve causes an airflow through the reed. Especially for smaller reeds, this can make the reed produce a sound. Eventual false air around the valves and through the reeds should not cause any reed to play unwantedly.

requirement #34

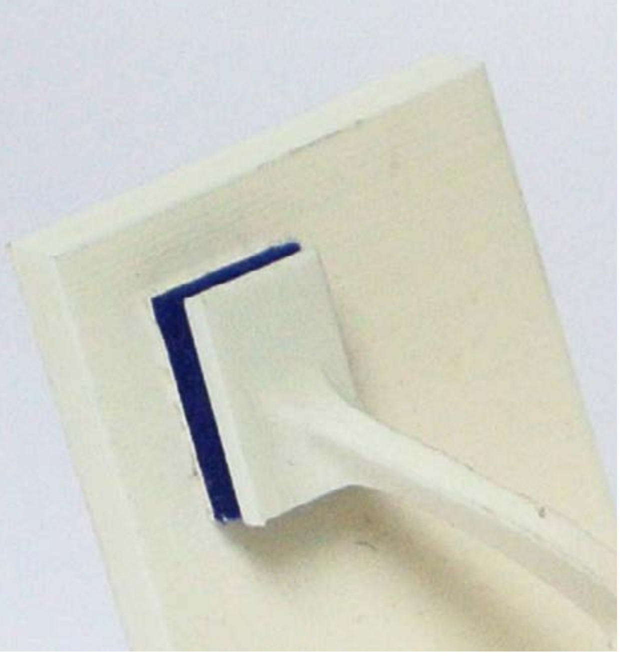


The second valve pad design incorporates a distance holder. Later on, the valve pad thickness is increased to prevent printing errors.

The spacing problem is solved by placing the valve pads on a distance holder. They are now located 8mm away from the beam, making those parts unable to interfere. This also allows for a further increase of the valve size to 12x18mm. The design with cut-outs for weight reduction is updated to a more simple design and the final valve pad size is once more increased to 12x19mm. To make printing errors less likely, the valve pad thickness is increased from 1 to 2,5mm. In the final version, the connection to the arm is adjusted in order to create more clearance between the arms.

CONCLUSION

The valve pad dimensions have been optimised for the print, so that they block as much surface as possible without interference. This is made possible by placing them on a distance holder. Their thickness is updated as well, resulting in a trustworthy airlock.



The third generation of valves has a location efficient connection that is more organically shaped

AIR LEAKAGE OF FULL INSTRUMENT

Only a small amount of air leakage is allowed for the full instrument. This leakage comes mostly from the bellow and the reed valves. Any significant air leakage will cause serious troubles for the playing of the instrument, because this means less air is available for the reeds to sound and the user will have to work harder to play the same note. The maximum air leakage for the full instrument is 25cm^3/s for each Newton of bellow pulling force.

requirement #11

SOFT VALVE CLOSURE

The closing of a valve should not produce a loud noise when a button is released rapidly. Furthermore, it should not feel harsh for the user. Both the feel and sound of the valve closure need to be similar that in a conventional instrument.

requirement #35

8. BUTTON ATTACHMENT

Conventional buttons are attached onto a plastic cylinder using glue. This requires them to be manually aligned. If a part of the mechanics breaks down, all buttons have to be broken off in order to remove the underlying cover and access the components beneath. Afterwards, the buttons need to be glued on again. This problem needs to be addressed by making them detachable.

The buttons on a conventional instrument, with felt glued onto the bottom

IMPROVING ACCESS TO MECHANICS

To provide easier acces to the parts under the button cover, there are two options. Either the cover needs to be removable with the buttons still in place or the buttons need to be detachable. The first option would mean increasing the hole size in the cover, so that the buttons fit completely through the hole, or splitting it in parts. Aesthetically, this is not desirable, and more dust wil be ablel enter the instrument because of this.

It is therefore is chosen to change the button and not the cover as a means of simplifying component access. The problem of manually aligning buttons can be solved simultaneously, as automatic alignment of buttons can be incorporated in the detachment system that is to be designed.

MAX. BUTTON ATTACHMENT FORCE

No extra tools should be required for attaching a button. This means the snap fit can be attached by hand by at least 95% of all users. Therefore, the maximum button push force is 50N (Department of Trade and Industry, 2002).

requirement #27

BUTTON FIXATION

Buttons can be detached from their base and put back on. If something is wrong with the inner mechanics of the instrument, all buttons need to be broken off in the current situation. Only then the protective cover that is under the buttons can be removed.

Detachment is not required very often. A lifetime of 10 button detachments is sufficient.

requirement #26

Ideas for button attachment

Different types of fastening mechanisms have been taken into account, and the concept of snap fits seems the most logical choice. This type of connection can be made out of one material, while fastening the button in all directions and enabling multiple detachments. It is very unlikely that a well-designed snap fit comes loose accidentally, which would be unacceptable as conventional instruments do not have such problems.

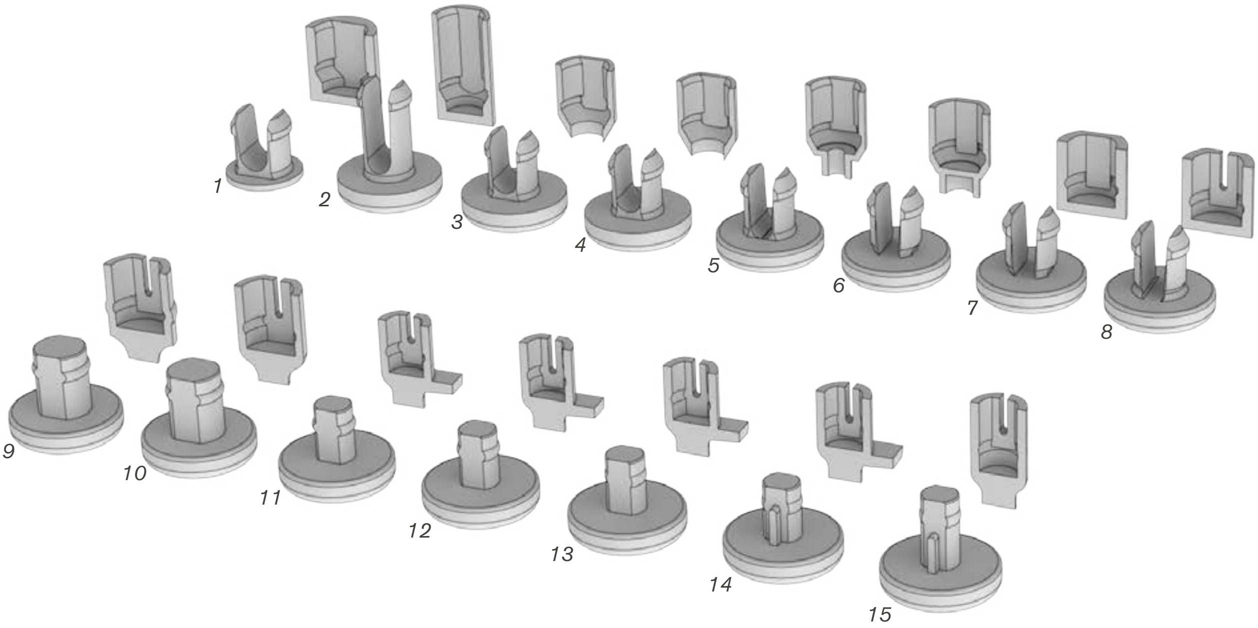
MAX. BUTTON DETACHMENT FORCE

No extra tools should be required for detaching a button. This means the snap fit can be detached by hand by at least95% of all users. Therefore, the maximum button pull force is 40N (Department of Trade and Industry, 2002).

requirement #28

The first test print of the button snap fit

Early designs tend to break at their snap base



An overview of snap fit design iterations

SNAP FIT ITERATIONS

A test print of the first model (no. 1) was made with a design based on the BASF Plastics Snap-Fit Design Manual. Because the snaps proved to be fragile and could break during a fast attachment, it was elongated (no. 2). Since this would make the buttons unnecessarily high, changes were made to the design of the snap fit with its original height (no. 3, 4).

To avoid interference with the beam structure, an extra and thinner part is added on the bottom of the female part (no. 5). Because the snap fits kept breaking, more dimensional changes are made especially to the base of the snap (no. 6, no. 7, no. 8). The female part proves fragile as well, but an added slot (no. 8) lowers the stresses in the material and prevents the part from breaking.

When the changes to the base proved unsuccessful, the design of two snaps is changed to a single bar with straight edges. A ledge on this bar forms the snap fit to secure the button (no. 9). After a test print, the shape of the female part is optimised (no. 10).

The width of the male snap fit is reduced from 7 to 5 millimetres to give it a less bumpy look (no. 11). This did not prove to be a problem for the button clearance or force. Along with this, a platform is added to the female part, enabling the detachment of the button without damaging the system. The platform is pulled against the cover when a button is detached, so that only the button will come off. The shape of the ledge is optimised for the attachment and detachment forces (no. 12, 13) and the height of the button is increased in order to prevent interference with the instrument body (no. 14).

A counterpart for the slot is added so that the parts look more like a whole, and dirt cannot amass in the slots. Dimensions are updated in order to meet tolerance requirements (no. 15). Because of the felt and cover plate thickness, the height is updated once more. The platform is not visible here, because the female part and platform are now fully integrated into the design of the arm.

Subtle dimensional variations of snap fit design are used to determinde the correct fit

The snap fit tolerances have been analysed by varying both the dimensions of the snap base and the ledge of the final design. The dimensions of the female part are varied as well.

Out of 28 dimensional variations, a button without a noticeable clearance, and with acceptable attachment/detachment forces is selected. It requires 20N to attach, and 23N to detach. These values vary slightly for every print, due to the tolerances of the printing process.

BUTTON FEATURES

The movement of the buttons needs to feel like it does in a conventional accordion. Besides the clearance of the button snap fit itself (which should not be present), there is a clearance of the total button system. The beam that supports the button can not only move up and down, but sideward as well. This clearance should be kept as small as possible, without causing any interference.

CLEARANCE OF BUTTON ATTACHMENT

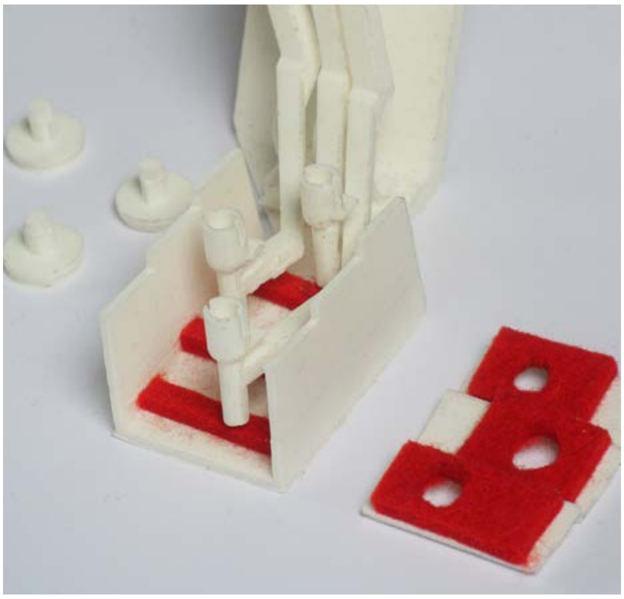
Button snap fits have no noticeable clearance: they should feel stuck to the rest of the mechanic, like in the current accordion.

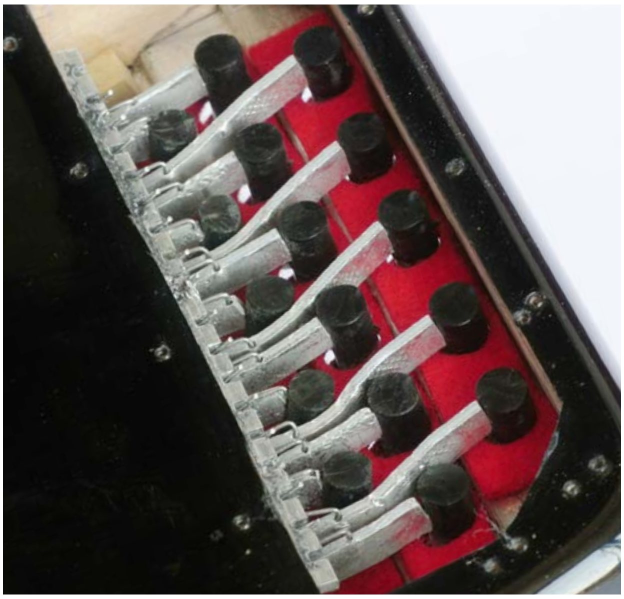
requirement #29

CLEARANCE OF BUTTON SYSTEM

Buttons can have only a small clearance. When a button on the current instrument is pushed to the left or right, a clearance of about 1mm is easily made without too much force, but the button should go no further. For the redesign, a max. clearance of 1mm both left and right is acceptable. Within this range, any type of movement is acceptable for the scope of this project, including partly rotational movements.

requirement #30


Felt is placed on the bottom of the button cover


A similar system is sometimes used in conventional instruments

The clearance is controlled by the dimensions of the holes in the cover. They leave less than 1mm of space for the button to move sideward. A layer of felt on the bottom of the button cover prevents the buttons from having a noticeable interference with the cover. An early cover design had non-round button bases and therefore non-round holes. This would require custom tools to make the holes in the felt. The button base and holes have been updated to a round design, so that the holes can easily be punched with regular tools. Each strip of felt is placed in a custom 3D-printed die, making it easy to punch the holes in the desired locations. A similar layer of felt is used in conventional instruments.

The landing of the button is another point of attention. In a conventional accordion, a soft landing is accommodated by a layer of on the bottom of the button. This makes the buttons land softly onto the button cover.
Although the felt can be bought pre-shaped, this requires the user to attach a separate piece of felt on each button. By moving the felt from the buttons to the instrument body, this is reduced from 19 to 3 pieces. Each beam has a cylindrical part on its bottom that makes it land on the felt when a button is pressed 5,5mm. This means that the button hoovers above the button cover plate at all times. This also benefits button attachment, because the male part needs a steady female part in order to click into place.

SMOOTH BUTTON MOVEMENT

The buttons move smooth when pressed down. For the user, it is not convenient if there is a clear interference between parts when pushing the button. A noticeable rough interference should therefore not be present.

requirement #31

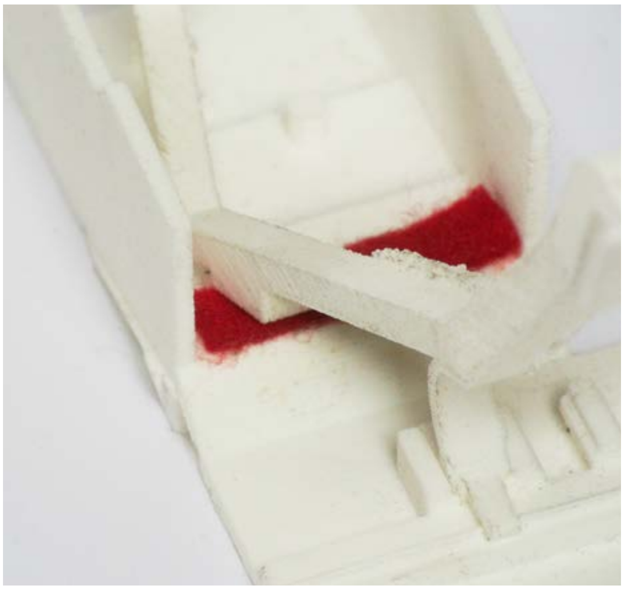
BUTTON DIMENSIONS

The button dimensions are similar to those of the current instrument. Accordionists are used to a certain button configuration and size. The redesign needs to adopt to the previous experiences of the user. Buttons are 18mm apart from each other and are 14mm in diameter. They have rounded corners and can be pressed 5 to 6mm.

requirement #32

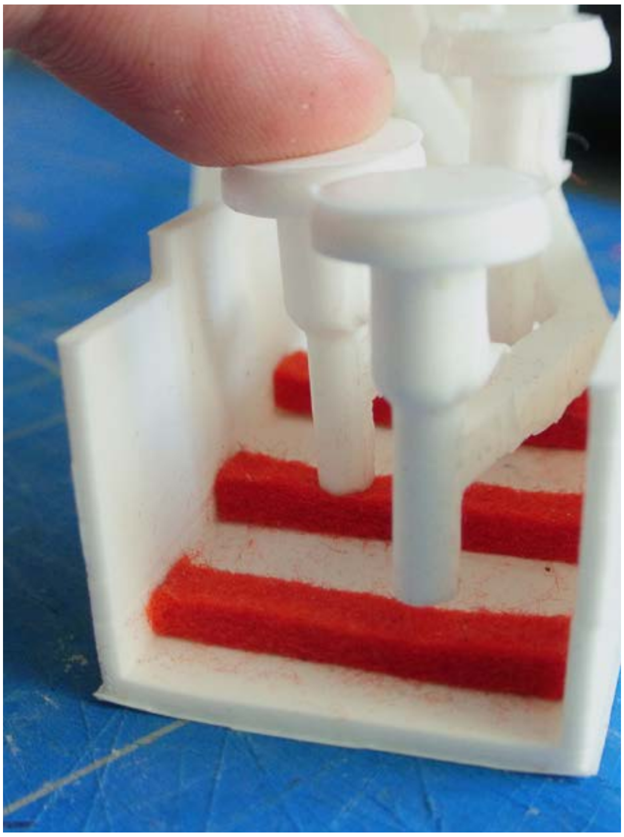
The initial idea was to have one strip of felt, on which all buttons would land. For the longer beams, this creates a dead area where the button can still be pressed due to elastic deformation of the beam, while nothing happens in terms of valve movement. Two extra layers of felt are added, so that every row of buttons has a landing point near the button.

The end result of the button system is a snap fit with attachment and detachment forces of 20 and 23N. There is no noticeable clearance on this snap fit.
Its design is the result of many tests with different geometries and, most important, printing tolerances. In the end, the right combination is found to create a button that stays in place, while it is still possible to place and replace it.
The landing of the button is accommodated by a layer of felt directly under the button. A bar on the arm ensures the button lands after being pressed down 5mm. Placing this landing felt further away from the button does not work, which is why every row of buttons has its own strip of felt.
Another layer of felt, located under the button cover, keeps the buttons in place and prevents interference between the plate and the button. Alltogether, these factors facilitate the user interaction of pressing a button smoothly.


Placing the felt far away from the button creates a problematic dead area in the button pressing, caused by beam deflection

SOFT BUTTON LANDING
When pressed down fully, the buttons land softly. The landing of the buttons should not make a noticeable sound for the user, and should feel like it does on the current instrument.

requirement #33


The landing felt is relocated to a position directly under each button

CONCLUSION

A snap fit system makes easy assembly and disassembly of the buttons possible. The system has been designed to match the desired button forces. The conventional landing felt under buttons is replaced by three strips of felt inside the instrument body. This requires less assembly steps than glueing felt to each button separately.
Three strips of felt are placed under the button cover as well. These strips form a guidance for the button and prevent them from interfering with the button cover. The felt has holes for the buttons which are easy to punch using a custom die.


Custom felt die and tools for punching holes

9. BODY & REEDS

The design of the instrument body is closely related to the reeds and their tonal properties. In order to find the correct dimensions for the sound chambers in the body, research has been conducted
Further body elements include the attachment of the reeds, grille and button cover.

9.1. reed mount

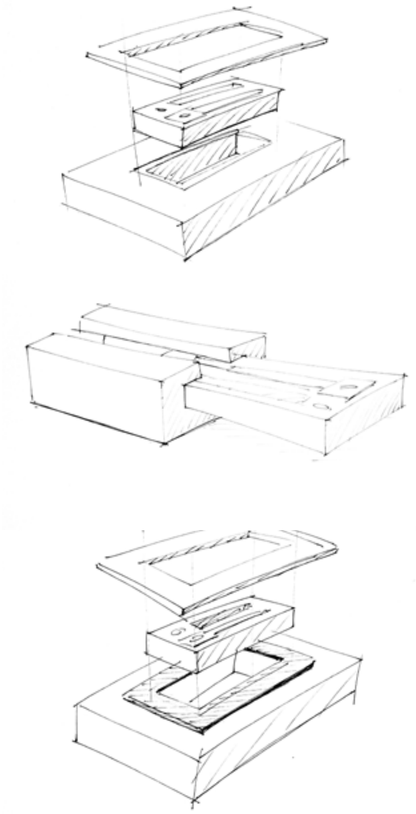
A conventional reed block is a wooden block where reeds are mounted on using wax. It incorporates multiple sound chambers with custom dimensions for each reed. Most accordions have reed blocks that can be taken out of the instrument, but for smaller instruments, the reeds can also be mounted flat, as is the case with the current MiniMouse accordion and the accordion in this project. The right hand side of the accordion for this project requires 19 reeds, ranging from A#3 (220 Hz) to E5 (~659 Hz).

AIRTIGHT CONNECTION

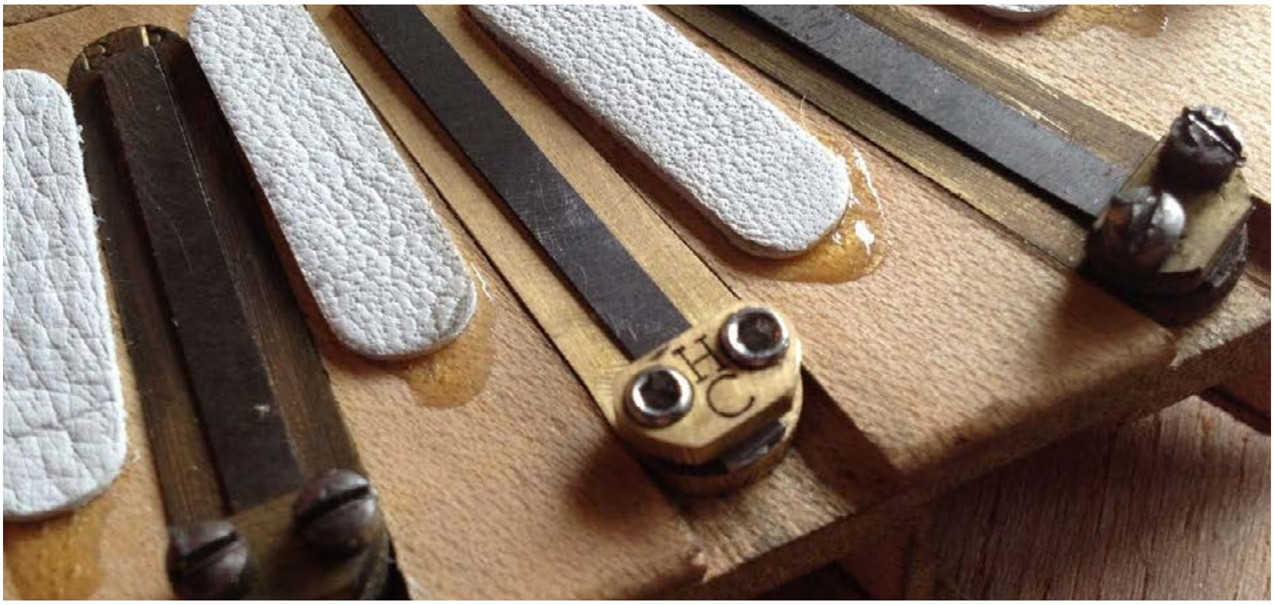
It is important to seal the reed airtight onto the reed block. The current system that uses wax is suboptimal from a production/repair point of view. Applying the wax takes effort, and removing it is a real hassle.

An alternative for the wax can seriously reduce reed block assembly time, which currently takes up to two hours for the right hand side. Attaching and detaching a reed should be easy, while still creating an airtight seal. The solution can not take up too much space, because the array of reeds defines the dimension of the bellow and therefore that of the whole instrument.

Three concepts are analysed. Two of them press the reed directly onto the print: the concept sketched on top presses the reeds fiercely onto the plastic with a separate part that is screwed on top. The middle concept slides the reeds in a trench and closes it with form closure. This is the same principle as for instance the reeds of a concertina. The bottom concept is the same principle as the first, but with the use of a gasket in between the reeds and the print.



Concepts for a reed mount using a clamping, sliding and gasket system



Concertina reeds, mounted in a slot using a form closure

EASY REED (UN)MOUNT

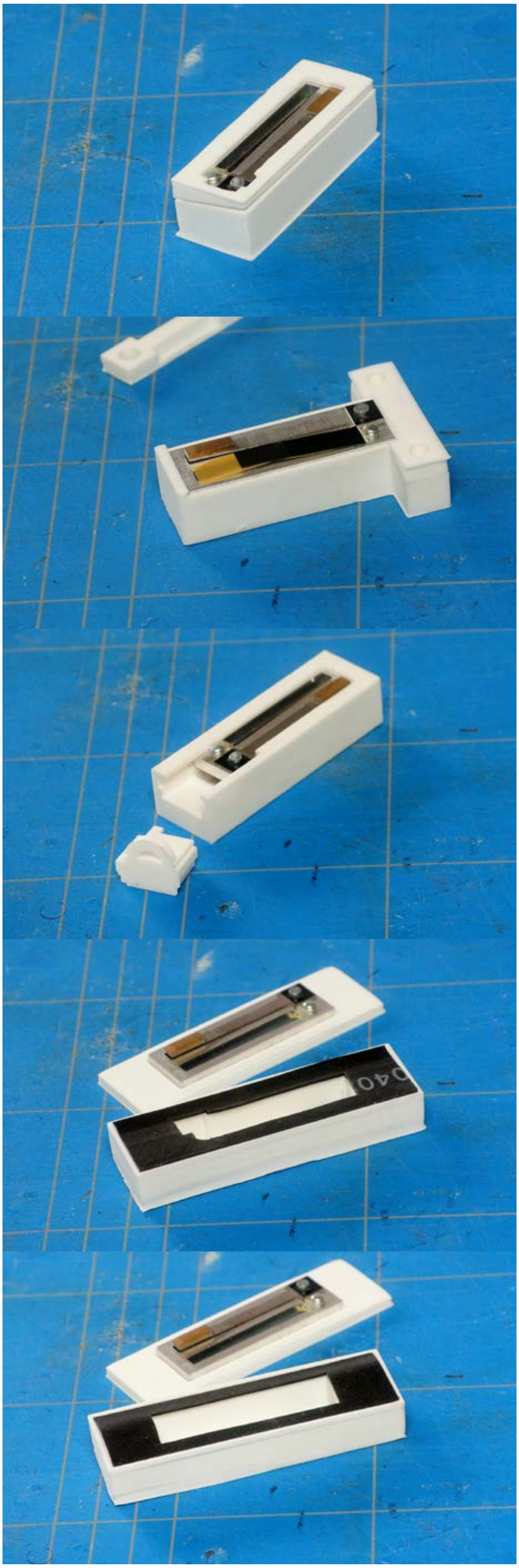
The current waxing system is inconvenient, especially when the wax has to be taken off (for instance when replacing a valve). This should be made easier in order to save man hours for production and repair. Therefore, reed mount time needs to be under 30 minutes for mounting or remounting right hand side.

requirement #36

All three concepts were tested using a print that accommodates one reed. This reed is made airtight using tape, so that any leakage along the reed can easily be found. It turns out that direct fixation on the print is not an option, because there are surface irregularities in both parts. In the print, these are caused by the extrusion paths of print material. In the reed, these are tiny surface variations emerged during production or in a later phase. Sliding the reed in a trench is subject to the same problem. Because the sides of the reed have a rough material quality, the trench does not provide an extra air seal on the side of the reed.

The concept with a gasket does create an airtight reed seal. This is not the most desirable concept, because it requires an extra production part (the gasket) and its influence on the sound is unknown. Pigini currently uses thin chamois leather as a gasket material for larger reeds in some instruments. This indicates that it is possible to incorporate a gasket while maintaining a good sound quality.

It is possible to print the top layer of the reed block in a different, flexible material. This would be similar to a separate gasket without the effort of placing it. However, this does require an extra nozzle on the printer and it is unclear if it will be stable enough over time. The reed is pressed onto the material fiercely, and if the flexible material breaks down, a whole new instrument body would need to be produced. This is an unacceptable risk when compared to the production of a new gasket.



The test prints for the reed chamber concepts, with multiple variations for concept 1 and 3.

An accordion reed. The roughness of its surface can clearly be seen.

CLAMPING THE REEDS

Placing and clamping the reed is not an easy task. First of all, the gasket should fit the reed dimensions. The reed itself and the reed valve can not be obstructed by the gasket. At the top of the reed, this leaves less than 1mm of space for the airtight gasket.

NBR rubber is chosen as a material for the gasket. It is a common material for gasket since it is durable, airtight and inexpensive. It can be lasercut precisely and quick, making it fit onto the reed. A first version of the gasket used all the surface available. This can result in the reed touching the gasket, since every reed is slightly different. In order to prevent such errors, a rectangle shape is used in later designs.

Every hole in the gasket and underlying sound chamber is created for a specific reed dimension. The reed is clamped into a tight slot on one side, pressing it onto the gasket. On the other side, it is roughly clamped behind a pin in horizontal direction. This prevents the reed from sliding out of the slot during assembly. To finalise the reed placement, it is pressed by a plastic bar. Both sides are now tightly pressed onto the gasket.

Usage tests indicate that it can be problematic to align and fixate more than five parallel reeds at the same time. Therefore, the 19 reeds are fixated using 5 different fixation bars. These bars are fixated using M3 bolts and insert nuts. The nuts are simply pressed into the instrument body, and the bolt pulls the fixation bar towards the body.

On some places, the gasket is only a few millimeters wide. This makes it flexible at these locations, and can cause it to move into the sound chamber during assembly. This can obstruct the reed from sounding. It is therefore advisable to glue the gasket to the instrument body. When using a glue that does not harden fully when drying, this is a reversible process.

REED REACHABILITY

When the bellow is taken off, the reeds can be tuned. However, both reeds on the aluminium base will need to be tuned. When one side is accessible, the reed on the other side can be pulled out using a special tool. As at least one side of the reed should be fully accessible for tuning, no direct obstructions perpendicular to the reed surface are allowed.

requirement #37

CONCLUSION

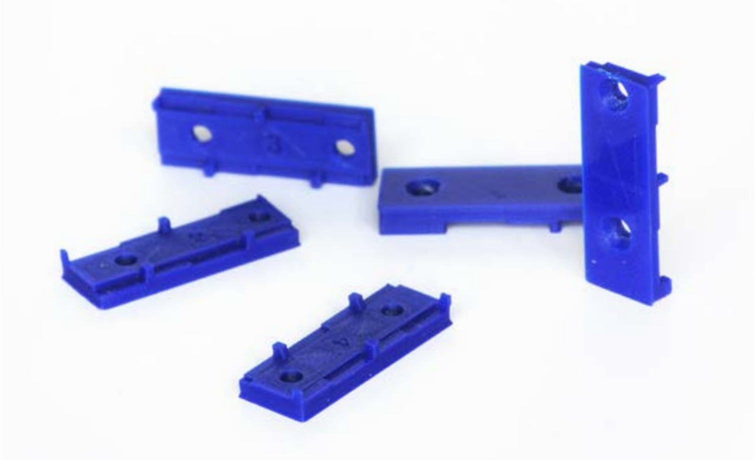
Clamping a reed airtight directly onto a printed material turns out to be impossible, no matter clamping method that is used. This is the reason for the use of a gasket. NBR rubber is chosen as a material, because it is durable, it can easily be produced via lasercutting, and, most importantly, it is airtight. Each reed is clamped under a ridge on one side, and secured using a mounting bar on the other side. This bar is attached to the body using bolts and insert nuts. Five fixation bars are used to fixate all 19 reeds. They are placed using countersunk M3 bolts. As the reeds need to be aligned well, clamping five reeds at the time was found to be a convenient configuration during prototyping.
The clamping mechanism turns out to work well, and mounts the reeds airtight. With only 1,5mm distance between two reeds (16,2mm wide), it is a space efficient solution.

REED BLOCK DIMENSIONS

The width of the reeds influences the size of the instrument as a whole. In order to keep the instrument compact, there should not be more space between the reeds than necessary. The reed block length and width should remain under 110% of the total reed length and width. (This is extra important for the length, since this is most critical for printer dimensions.)

For conventional waxing techniques, the space between the reeds (~16mm in width) is about 2mm per reed.

requirement #38



The reed mounting clamps are numbered to prevent assembly errors.

Early impression of the reed block with a single mounting bar in the middle. This is the same basic principle as in the final design, although the mounting bar has been split up into pieces and the chamber dimensions have changed.

9.2. reed chamber design

The reed chambers of a conventional accordion differ in size for each reed. Their width and height is defined by the reed itself, and the depth increases when the tone lowers. Values for the depth lie between ~3 to ~15mm. Using sound research, the dimensions for the chambers are defined.

REED CHAMBER INFLUENCE

The accordion in this project differs in many ways from a conventional accordion. Several factors will influence the resonance of the instrument itself, as well as the resonance of the air inside the sound chamber. The main differences are:

- The printed plastic material and different wood types used for accordion construction are both orthotropic materials, but in a completely different way. The layered FDM material will react differently to sound pressure waves than the polar orthotrope cell structure of the wood material.

- The FDM infill pattern creates spaces filled with air inside the body. It is unclear how this influences the resonance.

- The rubber gasket itself will resonate in a different way than the conventional wax does. Furthermore, the attachment of the reed onto the body is different. More damping may be present, since the rubber appears to be softer than hardened wax.

- The FDM process creates a layered surface structure inside the sound chambers. This differs from the smoothly sanded wood surface found in conventional accordions and will affect the reverberation of the sound pressure waves.

- The FDM body is printed in one part (consisting of bonded layers), while a conventional instrument body consists of different wooden parts that form a rigid connection using glue and celluloid. Potentially, an FDM body will be more rigid

- Two reeds never produce exactly the same tone. Tuning is an influence here. Ventiles on the reed can be made out of plastic or leather, also influencing the sound.

It is beyond the scope of this project to determine the precise influence of each of these factors. We can however analyse the sound spectrum of both a conventional and an FDM instrument.

Since we expect the spectrum of both instruments to be different, two tones of an printed prototype are compared with different sound chamber dimensions. By varying the depth, we can select the dimensions that create the most similar sound.

Tonon (2009) indicates that the reed cavity air vibration can become large enough to influence the self-excitation mechanism of the reed. This happens when a partial of the reed vibration frequency lies close to the cavity mode resonant frequency. This cavity resonance can assist or interfere with the reed vibration. The lower the partial that resonates, the higher the influence of this effect will be.

The chamber can be approached as a Helmholtz or a quarter wave resonator (Tonon, 2009; Cottingham, 2013). Using the pitch of the reed, its dimensions and the dimensions of the aperture, we can calculate the required sound chamber depth to make each partial resonate.

A model with seven different chambers indicates there is a large difference between chambers.

An early model with a variable sound chamber depth

TEST MODEL LAYOUT

To find the best chamber dimensions for a printed instrument, several chambers are compared. Early tests indicate that both low and high-pitched reeds perform well with a sound chamber larger than that in a conventional instrument. It is found that for the higher tones, the Helmholtz model can have an influence. Relatively low partials resonate for these tones with acceptable sound chamber dimensions. Therefore, a test setup is made with the F#4 (~349 Hz) and A4 (440 Hz). These reeds have been selected based on their expected performance, but also because they both fit the same test model.

The model of Tonon (2009) indicates that a cavity with a depth of 14,5mm forms a Helmholtz resonator for 5th partial of the F#4. A cavity with a depth of 9,5mm resonates with the 5th partial of the A4 tone and the 6th partial of the F#4. Besides this, cavities of 12,0mm and 7,0mm put to test. The three deepest cavities are also tested in a variation with an angled bottom surface of 6°. These dimensions come from earlier experience with sound chamber tests and conventional chamber dimensions, and are not based upon resonance theory.

The assembly used for the sound analysis

For the test, a full accordion is mimicked as well as possible. The valve has influence on the airflow, and is therefore incorporated. In order to prevent air loss due to the state of the model, tape is used to close unwanted holes. This mimicks the closed valves that would normally be in place.

The sound of the F#4 and A4 reed mounted on each chamber is recorded using a callibrated microphone, as well as a reference tone from a conventional instrument. The recording are subsequently compared to each other.

PAIRWISE COMPARISON

A two-second sample is taken for each different tone-chamber combination. This sample is taken from the sustain of the tone, the main sequence of the signal. As the key is already being pressed and not being released in this area, the amplitude of the signal is rather constant in this area for our samples.

The samples are presented in a pairwise comparison test for each tone. This means that all different samples are compared against each other in sets of two. With 8 samples per tone (7 printed and 1 reference chamber), this results in 28 sample groups for each tone. The total number of comparisons for the two tones then lies at 56.

The reeds are mounted on a different sound chamber for each recording

SETUP

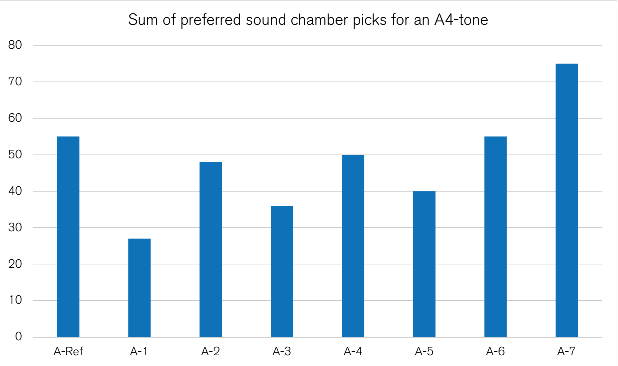
Participants of the pairwise comparison study indicate their preference for each pair of sounds. 14 Persons participated in the study. These are all adults in the age of 20 to 60. This group represents the potential buyer of the instrument, as it will most likely be bought by an adult to be used by a child. None of the participants suffers have hearing problems. Their musical experience differs, but none of them are professionals or highly acquainted with the accordion.

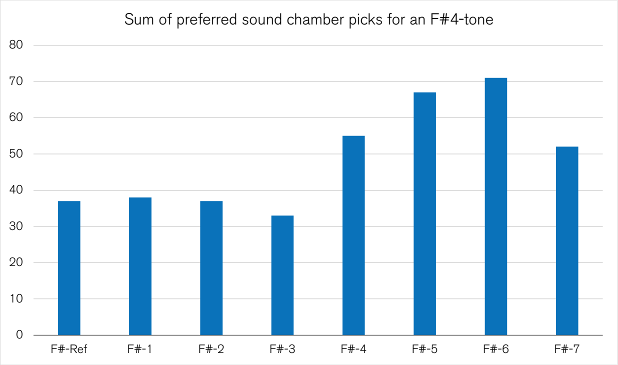
The lossless .wav sound samples were played from a MAX software patch. The order of the samples and the position of the order of each pair is randomised to prevent them from influencing the results.
All sessions were conducted with constant audio volume using the same laptop and high performance headphones.

RESULTS

The sound ranking is the result of the total number each sound is picked as a preferred sound. For the A4 tone, there is a clear preference for sound chamber no. 7. This chamber is 9,5mm deep, with a 6 degree angular bottom surface. Out of the 98 times this sound chamber was presented to participants, it was picked as the preferred option 75 times, a total of 77 percent.
For the F#4 tone, the preference is less clear. Both chamber 5 (14,5mm - angled surface) and chamber 6 (12mm - angled surface) are preferred by the participants. They were picked respectively 67 and 71 times, or 68 and 72 percent.
Compared F#4 chamber 5 and 6 directly to each other, 10 out of 14 participants have a preference for chamber 6.

Both for the A4 and F#4 tone, the conventional instrument's tone is not the first choice. This indicates opportunities for 3D printed sound chambers. The most preferred sound chambers/samples are no. 7 for the A4 tone, and no. 6 for the F#4 tone. The least preferred samples are respectively no. 1 and no. 3.

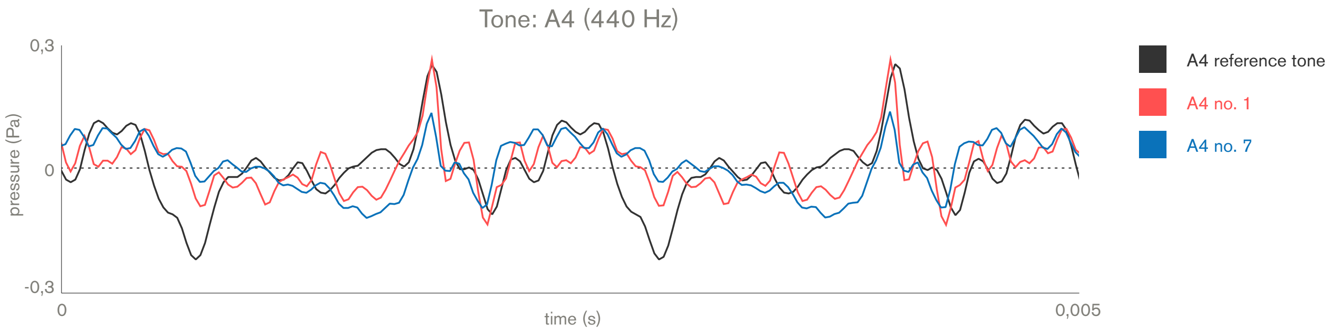




These graphs illustrate the total preference for each sample

LIMITATIONS

There are several factors that may have a negative impact on the results. First of all, the 3D printed part is not fully similar to the conventinal accordion, as it is not a complete accordion. Important parts, such as valves and shell material are missing. Most importantly, it has only one reed mounted onto it, while the conventional accordion has 16. This influences the resonance of the instrument.
The sound holes in the test model are dimensionally similar to that of the conventional instrument, but they are not positioned exactly the same.
The instrument is played by hand. It is impossible to play every tone with the same bellow pressure. (The same pressure can create a different loudness for different chambers, hence afterward signal manipulation is not desirable.) There are also slight variations in pressure during playing; the bellow shivers. Due to this, the recordings are not of continuous loudness.
There are also limiatations in the pairwise comparison. The high amount of pairs (56) requires participants to focus for about 15 minutes. This can cause loss of focus and leave participants indifferent, influencing the results.
Taking a sample from the sustain of the tone results in equal samples. However, unique characteristics that lie in the attack, decay and release time of the tone are neglected in this method, making the sample sound more artificial than the full recording would have done. As all tones are treated this way, this is considered acceptable.



The waveform of the A4 reference (black), most preferred (blue) and least preferred (red) sample

SPECTRUM ANALYSIS

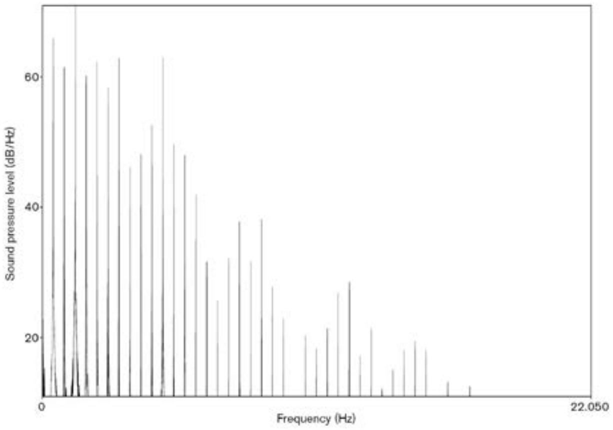
Looking at the spectrum of the most and least appreciated reed chambers gives us insight in their influence on the sound of the reed. The audio samples are compared using Praat software. The peaks in the graphs are frequencies where the sound is loudest. This occurs at the key-note frequency (e.g. 440Hz) and its overtones (e.g. 880Hz, 1320Hz, etcetera).

The clearest difference between the reference tone and the printed sound chambers is the resonance of the higher frequencies. This can be seen in both the A4 and F#4 samples.
In the reference tone, the first overtones resonate loudly, but the amplitude drops quickly for the tones above ~5000Hz. For the printed sound chambers, the graph is less steep, with larger amplitudes for the high overtones. The printed chambers give a more shrill sound, while the reference tone sounds more muffled. This difference in timbre is caused by the difference in high-frequency overtone resonance.

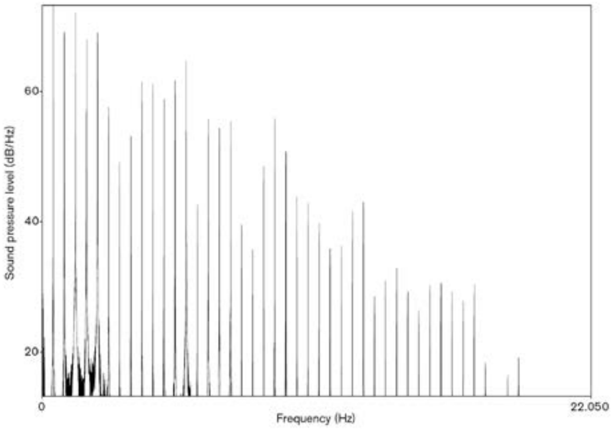
Another noticeable difference is the noise in the lower frequencies. The reference tone does not have much noise in this area, and neither does the preferred sample. In the graphs of the least preferred samples (A chamber no. 1, F# chamber no. 3), there is a lot more noise in this area. This distorts the key-note and makes the sound more impure. It should be noted that the influence of this noise on the sound is not particularly large, as its intensity does not exceed 20dB.

The F#4 tone has two highly preferred samples, sound chamber no. 5 and no. 6. As we see in the spectrum (next page), chamber no. 5 resonates a bit more in the overtones. This results in a slightly sharper sound. This can be a cause for the participant preference for chamber no. 6.

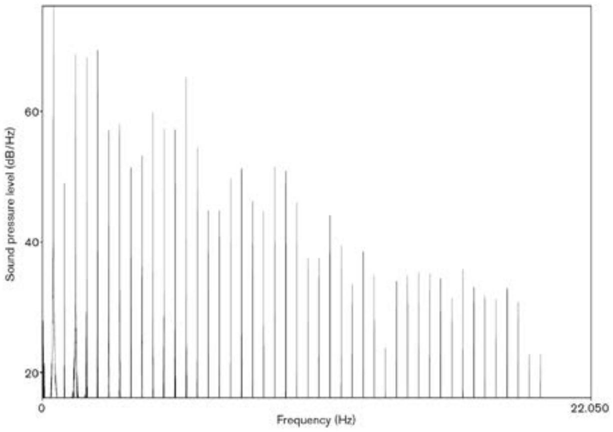
The expected Helmholtz resonance of 5th and 6th partials for the sound chambers mentioned earlier is not taking place. The graph values for these partials are similar for most sound chambers. Subtle volume differences (e.g. in the gasket thickness, printing margins etcetera) are the most likely cause of this.



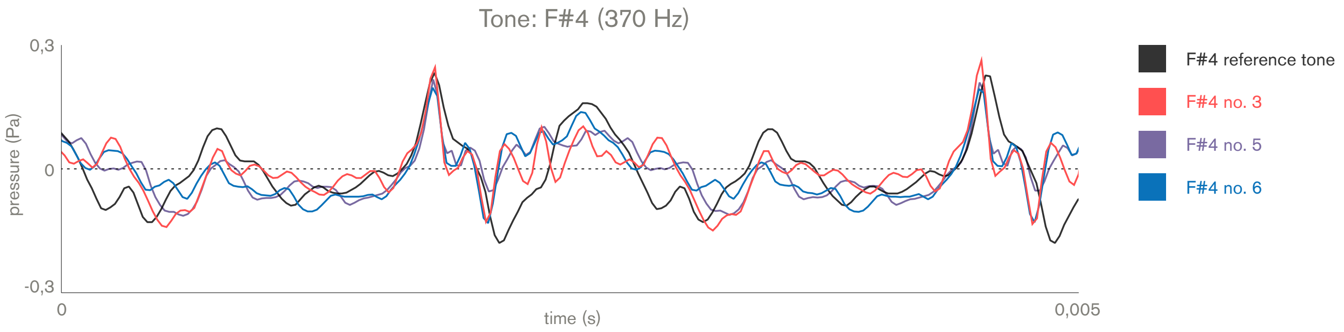
Spectrum of the A4 reference sample



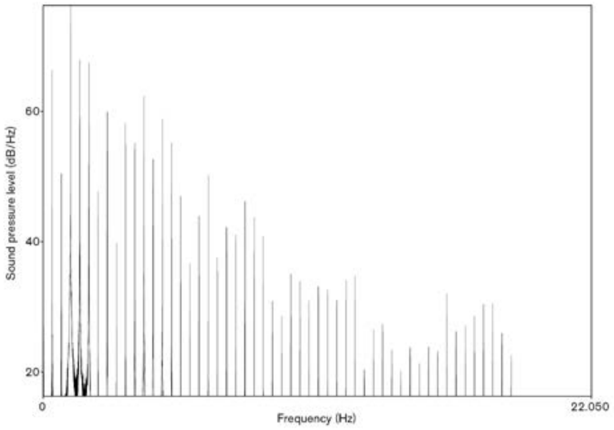
Spectrum of the A4 least preferred sample (chamber no. 1)



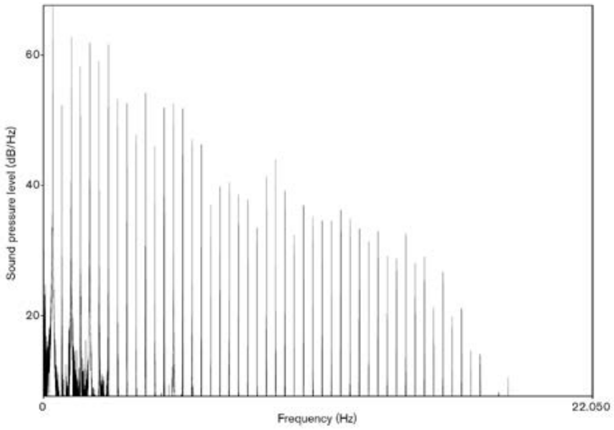
Spectrum of the A4 most preferred sample (chamber no. 7)



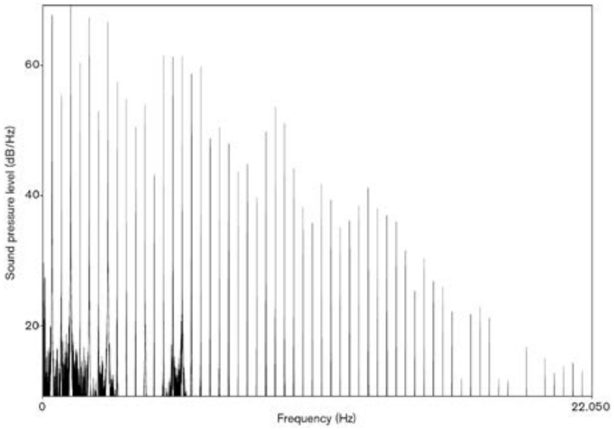
The waveform of the F#4 reference (black), most preferred (blue), second most preferred (purple) and least preferred (red) sample



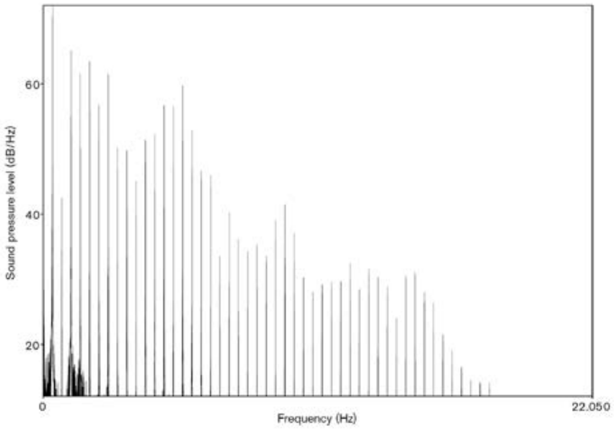
Spectrum of the F#4 reference sample



Spectrum of the F#4 second most preferred sample (chamber 5)



Spectrum of the F#4 least preferred sample (chamber 3)



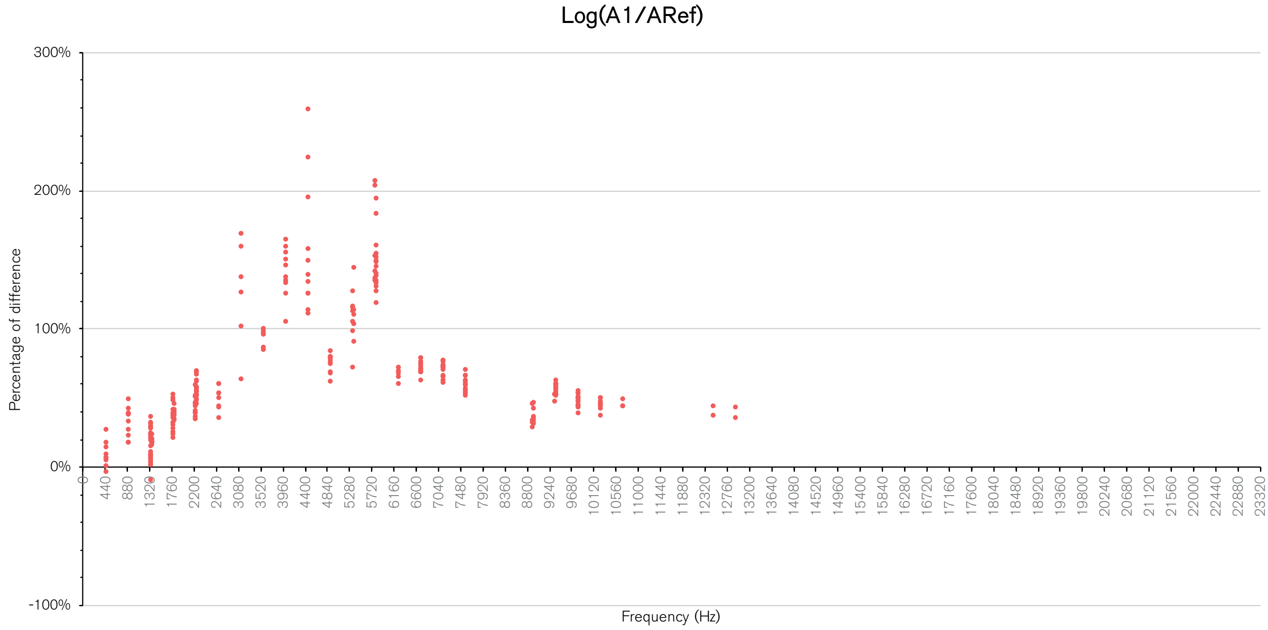
Spectrum of the F#4 most preferred sample (chamber 6)

The sound wave can be seen as the sum of all different frequency waves that the tone is composed of. Since the resonance is harmonic, the waveform consists of a complex but repeating pattern.

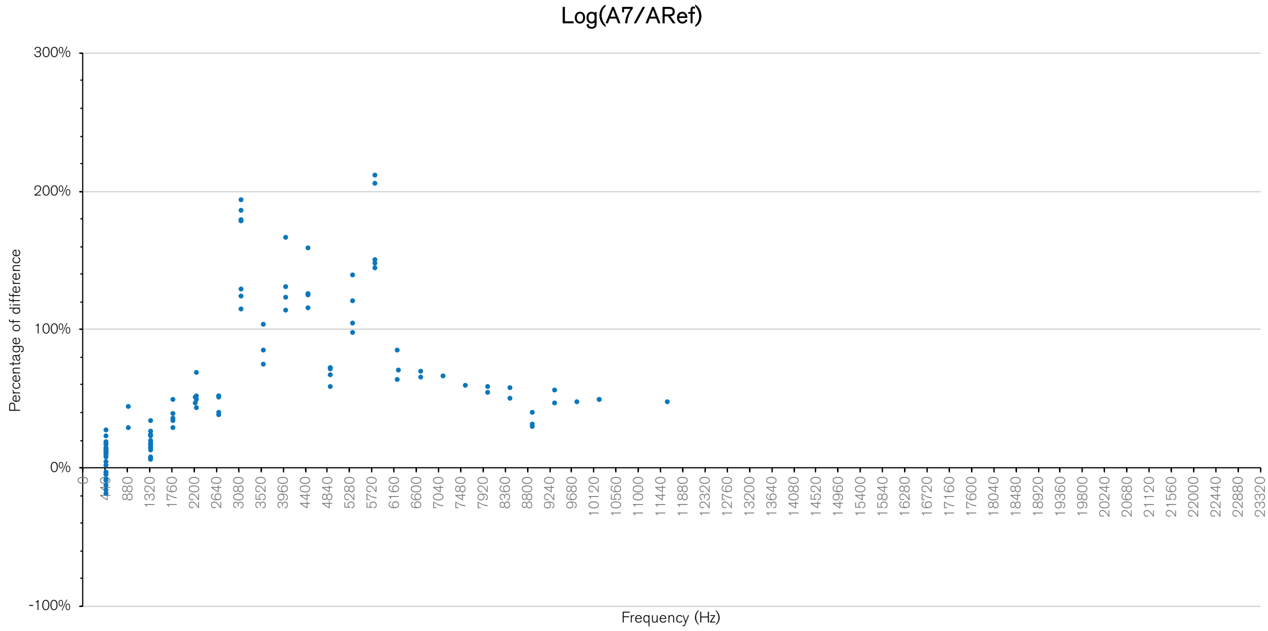
The black waveform is that of the reference tone. As it does not have the exact same frequency as the other tones, its pattern is a bit longer.
The red and blue waveforms are respectively the least and most preferred sound chambers. Their overall waveform roughly follows the shape of the reference tone, but is more jagged. This is due to the more intense resonance of higher frequencies.

For both tones, the red waveform has the highest and sharpest peak, where the highest peak of the blue waveform stays under that of the black one. The red peak is very sharp, while the blue one is more fluid. This effect can also be seen in the smaller peaks of the waveform.

A fluid waveform results in a more smooth sound - for example, compare sine and a triangular waveform. Appearently, this is preferred by the user.



Signal difference between the A4 least preferred sample (chamber no. 1) and the A4 reference sample. Threshold: 40dB

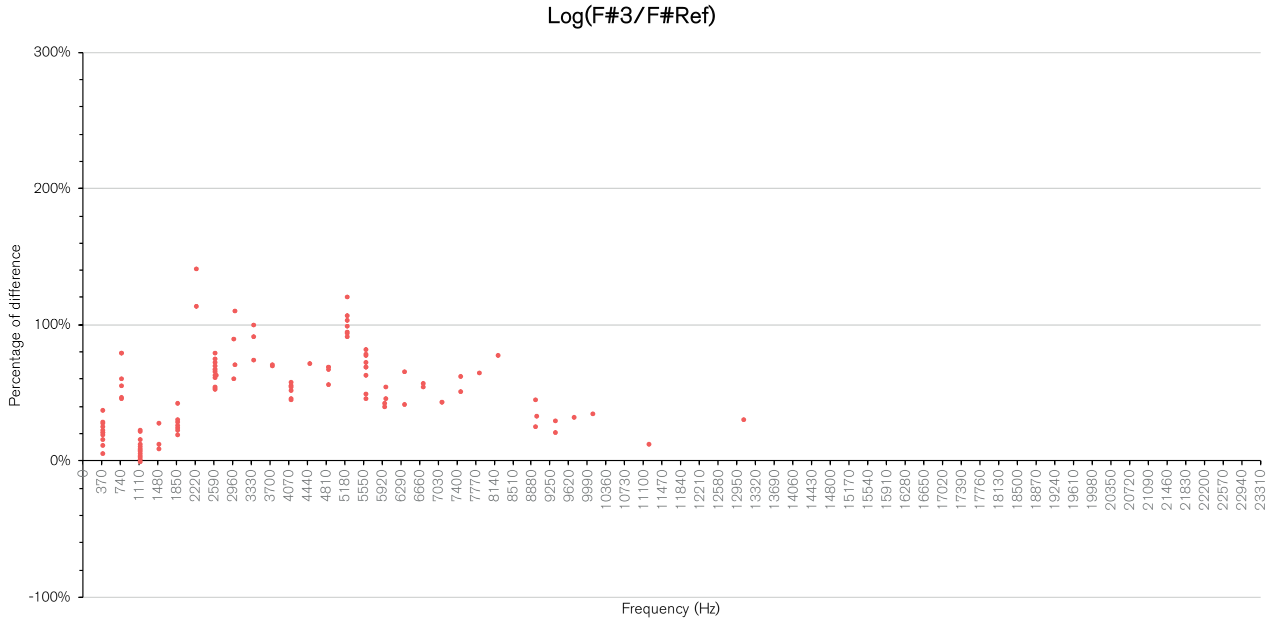


Signal difference between the A4 most preferred sample (chamber no. 7) and the A4 reference sample. Threshold: 40dB

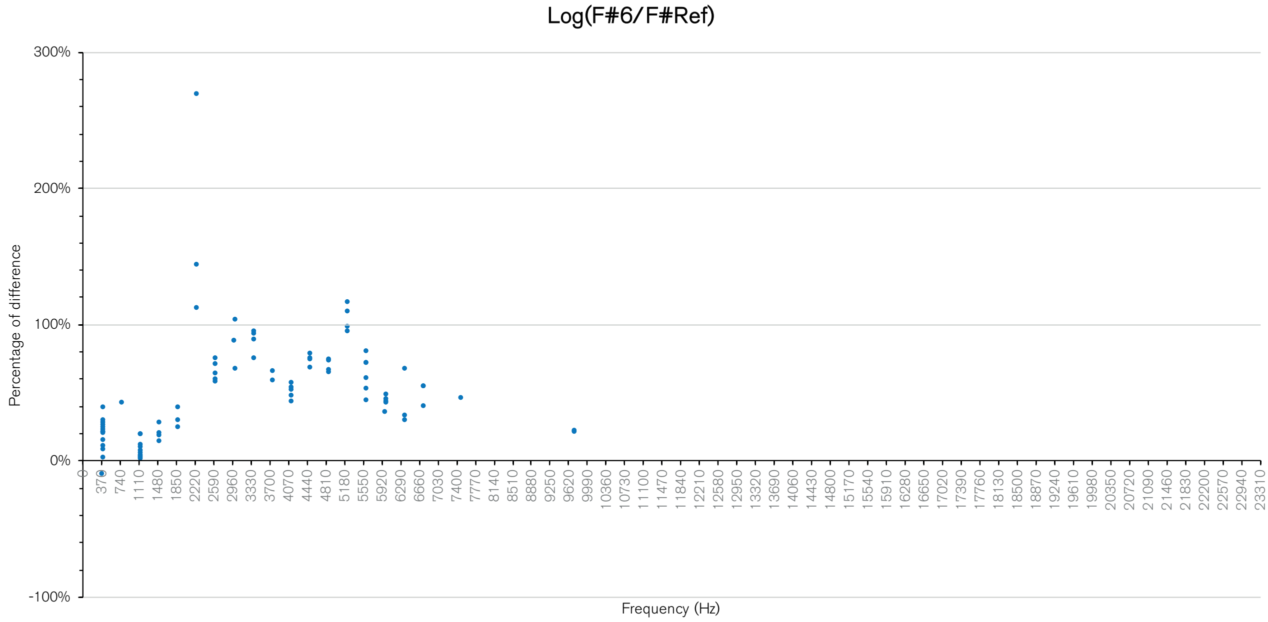
The graphs on these pages showcase the difference between samples. The least and most preferred samples are compared to the reference sample in terms of sound intensity. Since the decibel scale is logarithmic, an (absolute) log function is used to obtain the intensity difference in percentage:
$log_{10}(dB\_print/dB\_reference)$

A problem with this view is that it takes the difference for all frequencies without regarding their initial intensities. For instance, a frequency sounding at 25dB in the printed chamber that is only 10dB in the reference tone results in a difference of 40%. This is a valid outcome, but it does not provide very useful information, as a frequency of 25dB within the complete signal will barely be noticeable by ear. A threshold value is used to solve this problem. Only frequencies that sound at 40dB or more (in the printed chamber sample) are taken into account. 40dB is equal to the sound in a quiet living room (Alpine, n.d.). and is therefore considered a reasonable threshold value.

Note that the reference tones are tuned at 440 and 370Hz. The reeds on the printed chambers sound a bit higher: 444 and 373Hz. This slightly affects the graph, as the peaks in the spectrum do not fully overlap and thus have a natural difference. This effect is the same for all data in the graph, so the comparison of these graphs is still valid.



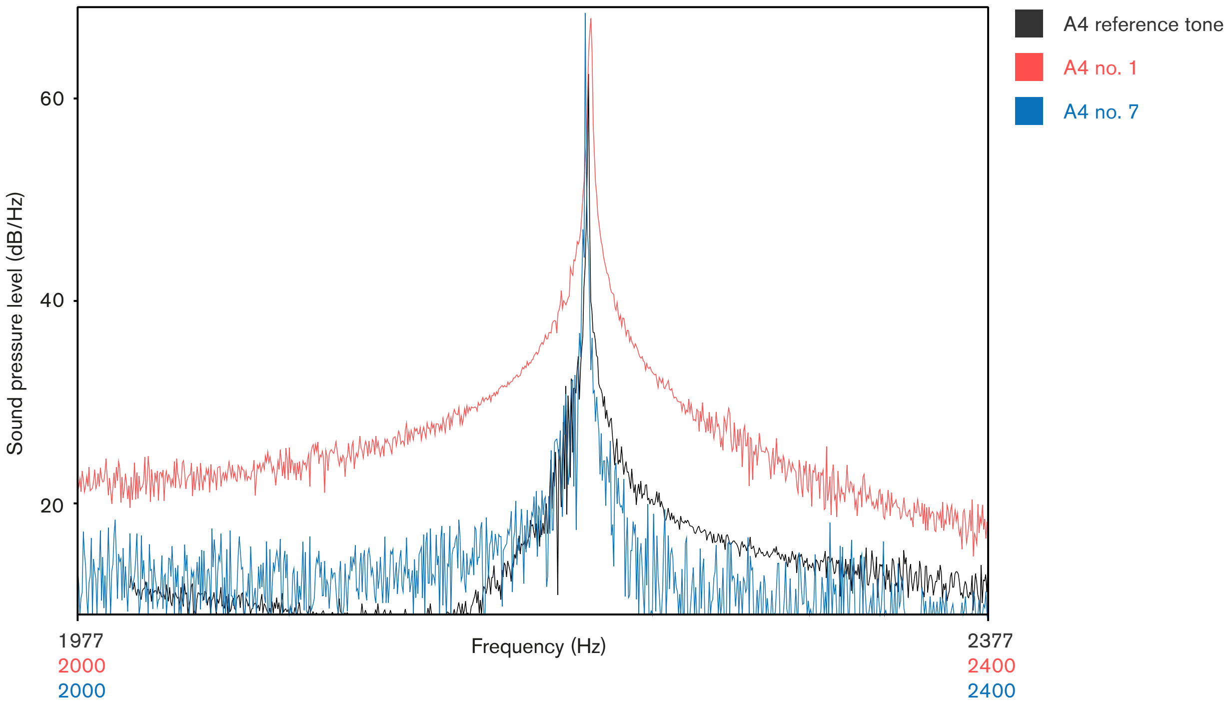
Signal difference between the F#4 least preferred sample (chamber no. 3) and the F#4 reference sample. Threshold: 40dB



Signal difference between the F#4 most preferred sample (chamber no. 6) and the F#4 reference sample. Threshold: 40dB

The differences for the key note are relatively small. For higher overtones, the difference increases. The largest difference between the printed chambers and the reference tone is found between 3000 and 6000Hz. For the A tone, these differences are up to twice as large as for the F# (except for a single outlier). Appearently, some A tone partials in this range resonate well in the printed chamber. The precise reason for this is unclear.

Besides this difference between the A and F# tone, these graphs show us that the most preferred and least preferred sample both differ from the reference tone in a similar way. The graphs for both samples have a very similar shape. The main difference between them is the number of data points: the least preferred tone has more of them. All in all, this means that the least preferred tone has a greater difference from the reference tone than the most preferred tone does.



Zoomed-in spectrum of the fifth partial of the A4 tone samples

The number of data points in the graphs can be explained when we zoom in on the spectrum. Here, this is done for the A tone frequencies between 2000 and 2400 Hz. The fifth partial, around 2200 Hz, is one of the points where the sample no. 1 has more data points than sample no. 7 (as seen on the last page).

To improve the graph readability, the difference in reed tuning has been compensated by overlapping the graph peaks. This results in different x axis values for the reference sample. This why the x axis values are shown for each sample separately.

Besides a difference in intensity of this partial, the graph shape is a major difference. The peak of sample no. 1 is much broader than the other two and its intensity remains around 20dB for non-harmonic frequencies. The broad peak is what leads to the higher number of data points that we saw earlier. In other words, the no. 1 sample consists of relatively less pure harmonics.

The graph for the reference tone and sample no. 7 look rather similar, especially in the peak. The printed chamber has lot more variation in the non-harmonic frequencies (e.g. sharper peaks). As the intensity here is very low, this does not influence the sound much.

CONCLUSION

The main insights from the sound analysis are that for the reference tone, the higher partials have a relatively low resonance. In the least preferred tones, this resonance is higher, making their timbre more sharp. The partial resonance of the preferred tones is more similar to that of the reference tone.
The least preferred tones have broader frequency peaks and more noise, rendering their sound less pure. The preferred samples have a more pure resonance, just like the reference tone. For both the A4 and F#4 tone, the preferred sound chamber has an angular bottom surface. The precise relation between sound chamber dimensions and frequency resonance is not clear.

The preferred chamber dimensions for the A4 and F#4 reed have been implicated in the design. The chamber height changes linearly through all sound chambers. This is a method also used in conventional instruments. For the A4, the final chamber dimensions are similar to that of the test (9,5mm depth, angular).

Early tests with a variable sound chamber indicate that the lowest reed (A#3) creates a warm and deep timbre with a sound chamber depth around 14mm. Increasing the depth further does not create a noticeable difference. For the F#4, the preferred depth of 12mm has been decreased with 0,5mm in the final model. This reduces the slope of the depth increase, so that the A#3 chamber stays within acceptable proportions - a depth of 14,5mm. To do so, this small depth reduction of the F#4 chamber is necessary.

9.3. outer body design

The body accomodates the attachment of the mechanical system. The reed mount is integrated within the body. The body defines the appearance of the product, since this is one of the parts that the user will clearly see.

BASIC SHAPE & AESTHETICS

The instrument itself is rather innovative: it makes use of progressive production technologies in a conservative market. The shape of the instrument body should indicate this. Still, the instrument needs to be recognisable as an object that feels and sounds like a conventional accordion. The user should be able to trust the instrument performance based on its aesthetics and his or her previous experience with the instrument. Therefore, it is not possible to diverge from Pigini's aesthetics too much.

The body follows the shape of a conventional accordion, but with angled details to showcase its innovative production background. Some conventional accordions look rather hefty, which should be avoided for this modern instrument. This is accomplished by using little perpendicular surfaces, and curving surfaces to make the whole look more sleek.

A blue filament colour is chosen for the proof of concept. This is not necessarily the colour for a production instrument: these can come come in a broade range of colours, considering the target group of both children and adults.

The model is 5mm thick, with a shell of 1,05mm. Test prints (20% infill) indicate this results in a rigid product. The body, or parts of it, are not noticeably moving when being pulled back and forth by hand.

ARCHETYPICAL SHAPE

The user needs to easily recognise the instrument as an accordion. This can be accomplished by the archetypical shape of an accordion, that is defined by the components housed inside.

requirement #39

MODEST APPEARANCE

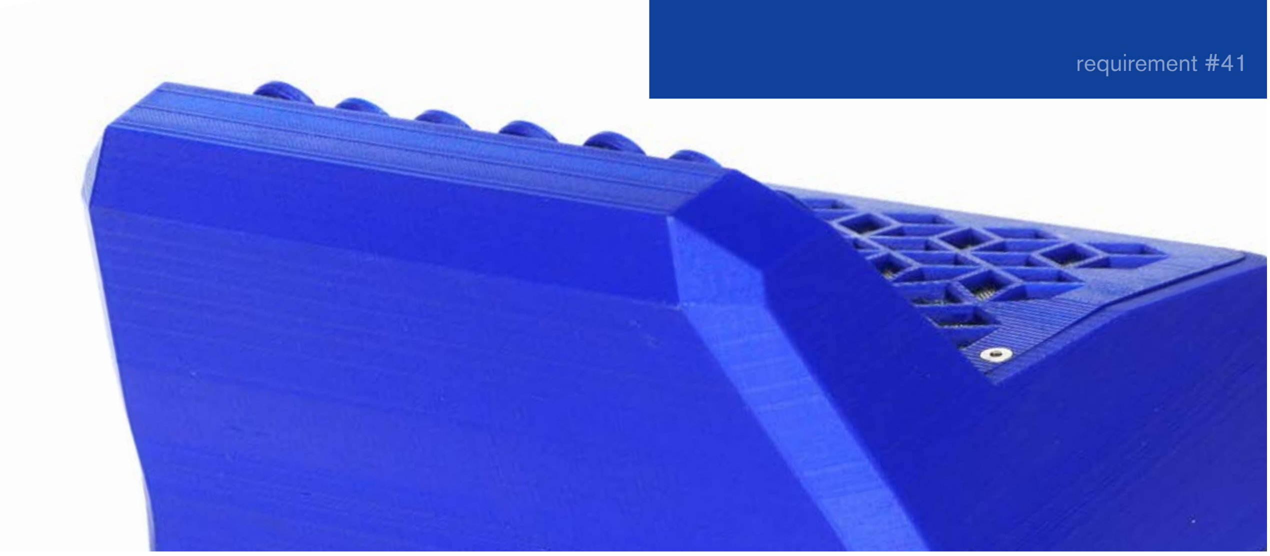
As the instrument combines modern production techniques in a tradional instrument, it is desirable to have both progressive and conservative elements in the design of the body.

requirement #40

RIGID BODY

The user should not feel any movement between parts of the body structure when handling the instrument. This ensures product stability to the user and is beneficial to the sound of the instrument.

requirement #41



The body has an archetypical accordion shape. Its detailing of angled surfaces is unconventional.

VALVE SURFACE

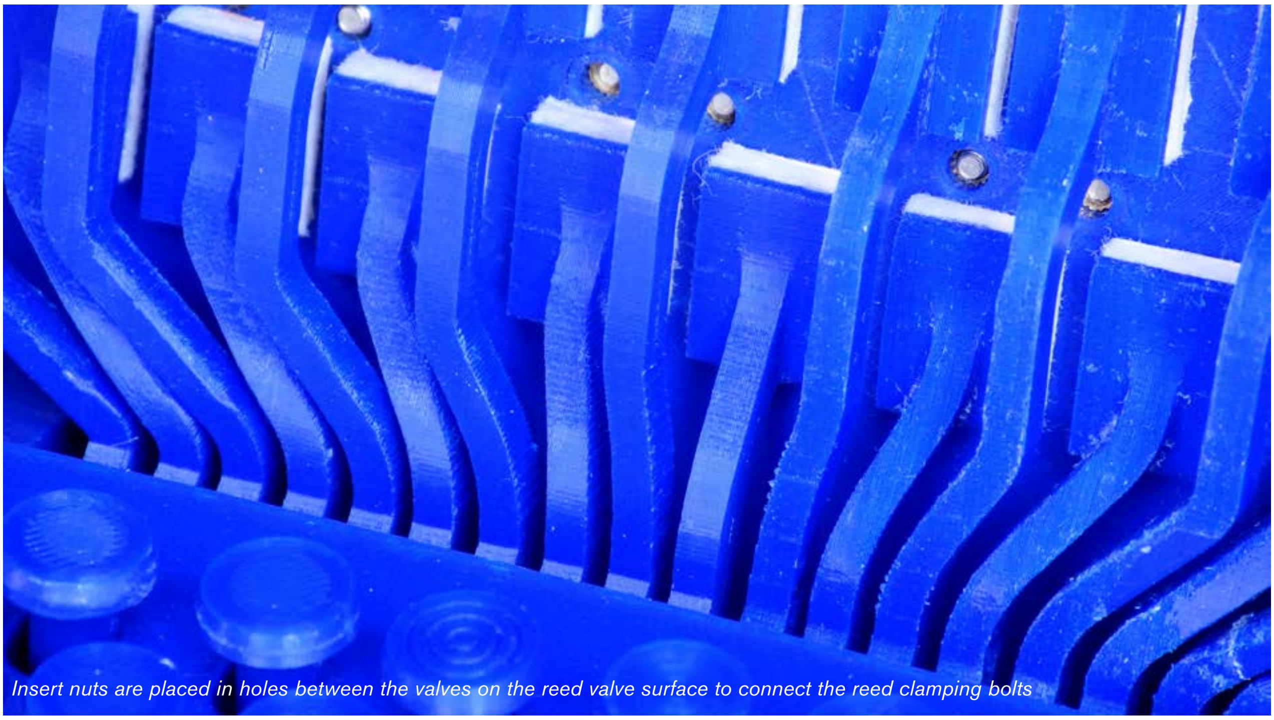
The reed chamber height decreases as the reed pitch increases. This means that the reed mount surface is angular compared to the reed valve surface. For printing, the reed valve surface is placed parallel to the buildplate, so that a smooth surface is created for the valves.

In the middle of the reed valve surface, M3 insert nuts for the reed attachment bolts are placed. Because of the angular surface, each nut lies at a different depth, and matches a bolt of a different length. This is to prevent them from protruding from the reed valve surface, which would cause interference with the valves.

EASY REED (UN)MOUNT

The reed mount time of a redesign needs to be under 30 minutes for mounting or remounting right hand side in order to make it more convenient than the traditional waxing process.

requirement #36



Insert nuts are placed in holes between the valves on the reed valve surface to connect the reed clamping bolts

REED BLOCK DIMENSION

The width of the reeds influences the size of the instrument as a whole. In order to keep the instrument compact, there should not be more space between the reeds than necessary. The reed block length and width should remain under 110% of the total reed length and width. This is extra important for the length, since this is most critical for printer dimensions.

requirement #

REED REACHABILITY

No direct obstructions perpendicular to the reed surface are allowed. This makes the reeds reachable for tuning. If necessary, reed blocks can be taken out of the instrument before tuning.

requirement #

BELLOW CONNECTION

A separate flange is printed and glued onto the bellow. This part needs to be attached to the body with an airtight connection. To do so, conventional foam-like gasket strips are used.

Conventionally, the parts are attached using four pins on the front and back of the instrument. For this instrument, this has been reduced to two pins on the bottom, which is aesthetically more desirable according to Pigini. The connection on the other side is made using a printed bulge that falls into a slot on the inside of the body.

STRAP CONNECTION

The printing of the body allows for new methods to attach the straps. Normally, this is done via a steel hooked part that is screwed onto the body. Pigini Nederland dislikes how this looks on small instruments, and placing the hooks requires manual placement. The additive manufacturing process allows us to redesign the connection and incorporate it into the body.

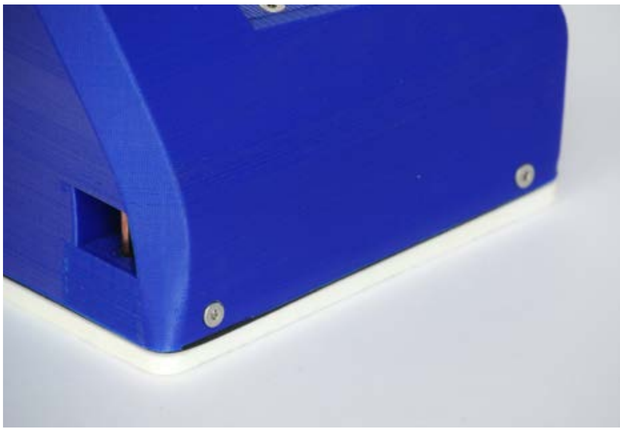
A cutout is made in the body where the straps need to be placed. A 3mm steel bar slides into a slot and forms the connection point for the straps. This bar is secured by the bellow flange, that covers the hole and prevents it from sliding out.

BUTTON COVER

The button cover is more than just an aesthetic closure on the body. The button holes fixate the buttons in the sideway directions.

Each row of buttons has a different height, which affects the cover design. The plateaus in the cover are designed in such a way that there is enough horizontal bottom surface to attach the felt to.

The cover is fixated by sliding it under a ridge on the front side of the instrument. On the other side, it is clamped down by the grille. This attachment method requires no additional fasteners, which are undesirable in terms of assembly and aesthetics.



The button cover as seen from the top

The bellow and strap connectors of the conventional and new instrument

GRILLE

The grille is a separate part with a pattern of holes where the sound can leave the instrument body. Its basic shape is defined by the shape of the body. The shape of the hole cutout gives each instrument a certain character. It usually consists of a pattern of decorative elements, ranging from geometric shapes to more exuberant ornaments. The grille of most instruments looks traditional, with little basic shape variation over the last decades. Pigini's Nova model has a grille with a more modern line pattern cutout, giving the instrument a modern look.

As stated before, the aesthetics of the body should not diverge too much to that of an conventional instrument, as this could deter users from trying the instrument. Therefore, the grille is outfitted with a traditional geometric pattern. Meanwhile, there is a modern twist to the design. The cube-like shapes in this pattern are a subtle reference to the solid 3D geometry that is used to create the instrument.

On the top side, the grille is fitted under a ridge, similar to the button cover. On the bottom, two bolts are used to fasten it. These two bolts are the only visible connectors on the front of the body. For conventional instruments, this can be a lot more.

CONCLUSION

The outer body has been designed to look like a conventional instrument with a modern twist. This can be seen in the archetypical but angular instrument body shape, as well as the pattern of the grille. Some components are connected to it via insert nuts and bolts. These are the reed clamps, the grille and the bellow flange. As visible connectors are considered not to be beneficial to the aesthetics of the instrument, they have been reduced to a minimum. Only two grille bolts are visible on the front, and two for the bellow flange on the bottom. The bolts of the reed clamps are housed behind the grille and do not influence the aesthetics of the instrument.

The grille of the final design, the Pigini Studio B2, Pigini Nòva and Pigini Preludio P30

10. PRINTING PARAMETERS

The digital design can only be translated into a product if it is succesfully 3D printed. To do so, using the correct printing parameters is essential. Changing parameters may cause printing errors or assembly problems later in the process. The most important parameters are discussed here.

PRINTER

Test prints have been created on Ultimaker 2+ and Ultimaker 3 printers. For future printing, Pigini will need to set up its own printing facilities. As the current prototype has been designed to be produced on an Ultimaker, a high-end consumer (prosumer) printer will be sufficient for Pigini. This is preferred over outsourcing the printing, enabling a more flexible production and planning.

For accordion production, the printer reliability is very important. A high quality and stable end result is required. Since the parts are large, printing defects can have a great impact, with misprints causing a lot of material and time to be wasted. Other printer qualities, such as ease of use and initial cost, are inferior to this.

The current design makes use of two printing nozzles and a heated bed. It barely fits on the Ultimaker 3 print bed, so a reliable dual extruder printer with a large build volume is required. A full enclosure is desirable, but not necessary.

Printers that meet these requirements are for instance the BCN3D Sigma, Raise3D N2 or Ultimaker S5. They are known to be reliable, and with a price around 3000 euros, these machines are affordable.

SLICER/PRINTER SETTINGS

The print files are set up using Cura 3.2.1. To ensure the print quality, the following settings need to be taken into account:

- *Layer height*
  For most parts of the design, a large layer height would not be a problem. However, especially the snap fit connections require enough detail in order to function properly. A layer height above 0,15mm is therefore undesirable. The body is currently printed at 0,12mm layer height, the other parts at 0,1mm.

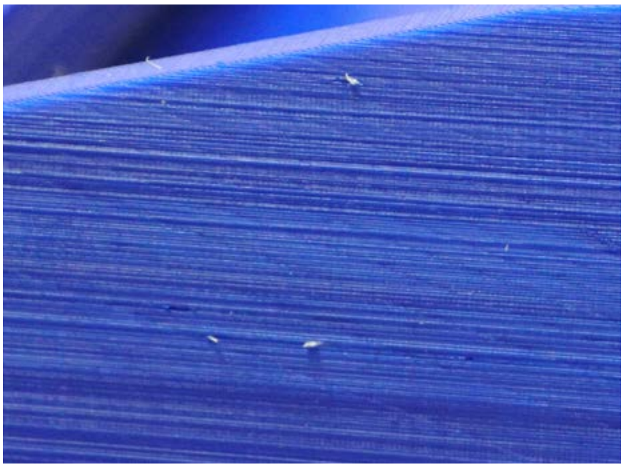
- *Support*
  The model can be printed with a support density of 15%. It is advisable to use extruder 1 for larger support parts, and use extruder 2 (PVA) for the layers connecting the support to the model only. The use of a support interface is advisable, so that for instance the spring snap fit dimensions do not deviate too much. An interface of 0,6mm is used for current prints.

- *Infill*
  It is not clear what the influence of infill percentage is on the acoustics of the instrument. In terms of product feel and strength, a 25% infill with a wall line count of 3 is more than sufficient.

- *Build plate adhesion*
  Since the model is rather large for an FDM printer, especially warping can become an issue. Build plate adhesion of the first layers should be monitored carefully so that any defects are spotted right away. Of course, depending on the precise material, but plate adhesion improvement methods such as using glue need to be applied where possible. Using a raft can also help, since it reduces the model surface on the buildplate.

- *Temperature*
  A heated print bed is required for the type of materials that will be printed with. The precise temperature of the bed and nozzles depends on the precise type of filament.

- *Prime tower*
  The prints were created without making use of a prime tower. This reduces printing time, and eliminates the chance of the primer tower falling over. This is a serious risk for parts such as the body, a print of 122m height. For this print, a prime tower can only be placed in the corner. Here, the build platform is usually lower, increasing the risk of falling over even more.
  Not using a prime tower can cause oozing and wipe problems. In the printed instrument body, tiny parts of PVA are in between the print layer, leaving unattractive little holes in the surface. This effect can be reduced by using an ooze shield. However, because of the size of the body, this was not a serious option for all prints on the Ultimaker 3.



PVA filament has ended up between layers of the model

PRINT ORIENTATION

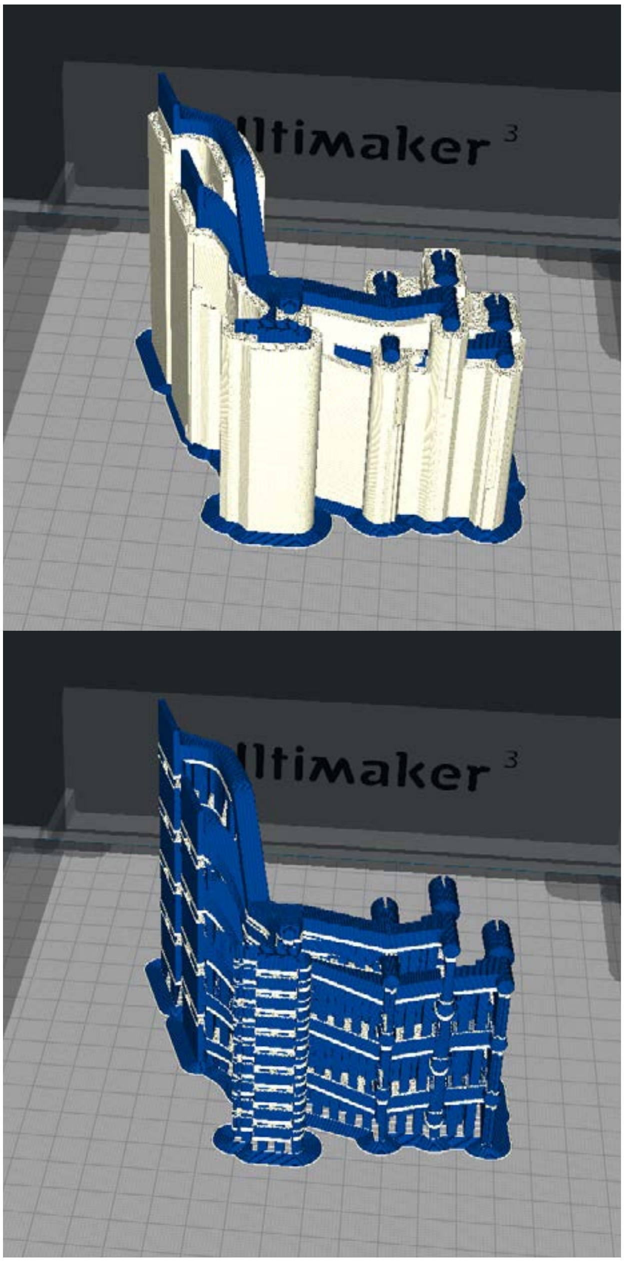
The orientation of the print is crucial for some parts, because of the material strength and surface qualities.

The printed springs are the most important: they need to be printed in a flat orientation, so that the nozzle follows the shape of the spring. If the spring would be printed in a standing position, the material would easily tear between two layers.

The spring snap fit system has been printed in multiple orientation without causing problems, as well as the button snap fit system.

The body can be printed with the sound chambers directed towards the build plate. This is the most efficient use of material, and ensures a somewhat uniform surface for the valves to attach to. For the gasket, the surface is under a slight angle, making it more rough. Keep in mind that for larger layer heights, this can cause problems.

The printed buttons require a good touch for the user, if no post-processing such as a pearlescent top is chosen. A bit of roughness is not a big problem, as long as it is equal along the surface. This is the case for a perfect print. However, a print usually has tiny layer defects that can be felt by the user.
In order to minimise misprints and enhance the button aesthetics, it is advised to print the buttons top-down onto the build plate. This creates a shiny top surface, so post-processing is not necessary. The strength of the snap fit should however be considered: the layers are perpendicular to the movement of the snap fit, which may cause the button to break. In order to prevent this, the buttons are printed with a wall line count of 4 instead of 3.



Changing the support infill material in this print results in 16+54 grams of PVA & PLA usage, instead of 78+41 grams. Printing time decreases from 35h to 23h.

In terms of aesthetics, it is advisable to print the grille with its top surface horizontally. Currently, this is done under a slight angle, resulting in a clearly visible layer structure. This is unneccessary and undesirable.

Besides part orientation, the build plate part layout is of importance. Although parts for multiple accordions can be printed at the same time, it should be noted that the build platform should not be too full. A larger print increases the chance of failure, and if a larger print fails, more material is wasted at once.

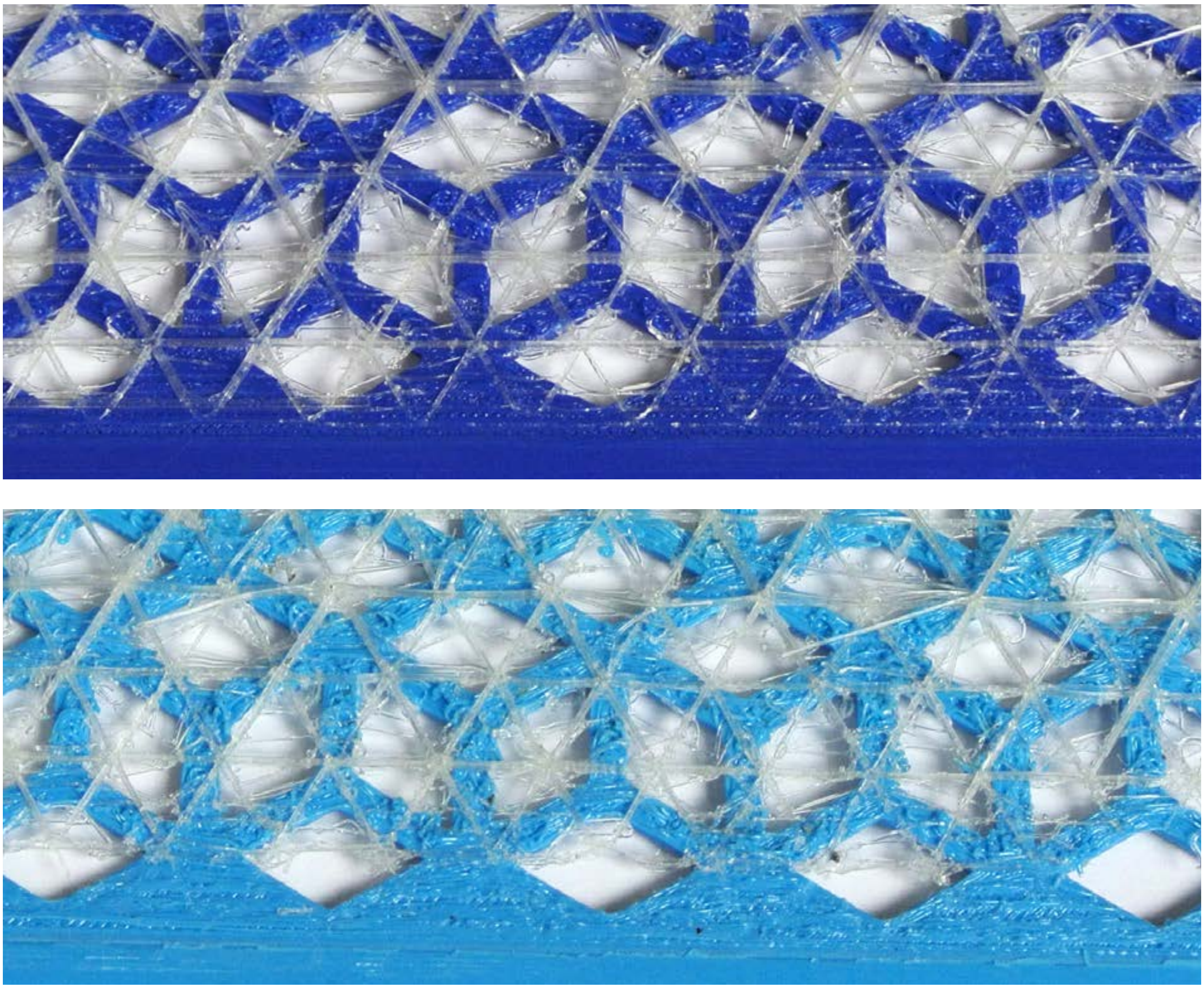
PRINTING MATERIALS

The original choice of material for the print is Ultimaker CPE. During test prints, the PVA support did not bond well to this material, resulting in print complications. According to the manufacturer, these materials should be compatible, but there was not enough time to find a workable print setup. Therefore, Ultimaker PLA material was used for the current prototype. This material was selected mainly for its printability, and is not desirable for the production of end product instruments. Certain post-processing processes can enhance its mechanical properties and UV stability, however, a high-end material is required to ensure the product lifetime.

For the prototype, the complete support structure consists of PVA. As this is usually more expensive than the main build material, the price can be decreased by printing the infill of the support in the main build material. This reduces PVA usage up to 80% and can reduce printing time due to a lower support infill percentage. Furthermore, the support horizontal expansion can be decreased in order to save material.

CONCLUSION

AM techniques proves to be useful for producing accordion parts. The basic settings for printing turn out to be well. A proof of concept has been produced using an Ultimaker 3. For some parts, print orientation is important as it ensures part strength and durability. There are several options for improving the print in terms of material usage and printing time. These have yet to be worked out. It is also necessary to do more testing with high-end materials in order to ensure the lifetime of the final products.



This print with minimal support structure showcases the difference between PLA (top) and CPE (bottom) filament

11. DESIGN EVALUATION

The final step of this project is to verify whether the final design matches the project requirements. The goal of the project is to simplify accordion production using additive manufacturing techniques. This should enable Pigini Nederland to sell a small batch of instruments under the current price of 999 euros.

EVALUATION OF DESIGN REQUIREMENTS

This evaluation is based on the design requirements as communicated earlier in this report. The numbers match the number of the requirement for reference.

1. Cost

The material/machine cost for the printed instrument are similar to that of a conventional instrument. For details, please see appendix B. A 20% reduction in total labour can be established for the design in its current state. A quick overview of this can be seen in the figure below. Combined with the material costs, the total cost reduction is roughly 15%. This means that if the hourly rate for human labour is kept the same as for the MiniMouse (price: 999 euros), the complete instrument in its current state can be sold for 850 euros. This is less expensive than the MiniMouse, so the requirement is met. Details can be found in appendix B.

2. Means of production

All core parts are produced using FDM techniques, except for the reeds. On some places, additional materials (felt, leather, springs) are used. FDM can be seen as the main production method for the instrument.

3. Production logistics

The design can be produced on a semi-professional benchtop FDM printer. This means of production is suitable for use within Pigini Nederland's current facilities, as desired by the client.

4. Dimensions

The dimensions of the printed right hand side body are 195x135x125mm (LxWxH), while the original MiniMouse measures respectively 190x140x140. This makes both instruments similar in size.

5. Tonal range

The reeds in the instrument range from A#3 (220 Hz) to E5 (~659 Hz), as originally planned.

6. Product lifetime

The durability test of the spring indicates that a lifetime of 10 years usage (30min/day) is no problem for the moving mechanism inside the instrument. If parts of this mechanism fail for other reasons, they can easily be replaced.

The current PLA prototype is not expected to last 10 years without a reduction of quality. This material can lose its mechanical properties over time, and is sensitive to e.g. UV light (Ultimaker, 2018).

If a more stable material is used, no functional problems are expected in a normal use scenario. Scratching may occur on the body, which is one of the reasons why applying a coating should be considered.

7. Use environment

The product needs to be used in both in indoor and outdoor conditions, with temperatures up to 50°C and exposure to normal levels of outdoor UV light.

As stated before, this is a problem for the current prototype, PLA having a glass transition temperature of 50°C (Ultimaker, 2017).

For high-end materials such as CPE (glass transition trempерature 82°C) or PC-ABS (glass transition temperature 125°C) these requirements do not form a problem, since they have been selected based on these properties.

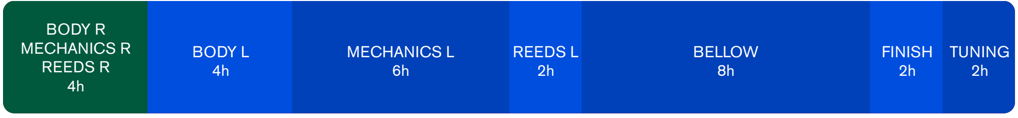
The impact of UV radiation can vary for different filament colours: pigments can absorb UV, reducing weathering effects (Osswald, 2011:49).

8. User interaction

Component configuration and tone production technique have not been changed from a conventional instrument, so the interaction with the instrument while playing music has not changed.

Conventional accordion production in the Netherlands - ca. 35 hours

Partly printed accordion production in the Netherlands - ca. 28 hours



Indication of man hours required to produce a conventional accordion and an accordion with printed right hand side. Green parts indicate the labour on the right hand side of the instrument.

9. Sound perception

15 Accordionists have listened to the sound of the prototype. None of them perceived the sound as unpleasant. Most of them indicated the instrument to sound better than expected. For example, the reaction “it does not sound like plastic at all” is a positive outcome, although it also indicates that expectations are different than they are for a conventional instrument.

Another given note is that the sound lacks a certain fullness when compared to a full-fledged instrument. This can be due to the design, but probably the size of the instrument also plays a role here.

In general, the user sound perception is acceptable, while improvements can be made to make the instrument sound more like a full-fledged accordion.

10. Production time

If not in stock, all parts can be printed successively within 8 days. A shorter print time is possible by changing printing variables, but the effect on print errors and product quality needs to be researched. Mechanical properties vary for different printer settings, e.g. layer height (Aliheidari, Christ, Ameli, Tripuraneni, & Nadimpalli, 2017).

The requirement of producing an instrument within two weeks after an order can easily be met, as this currently leaves a minimum of four working days to assemble the instrument after printing.

t11. Instrument air leakage

The air leakage of the instrument is measured using the bellow and left hand side of a Pigini Nederland’s previous printed prototype. No custom bellow is available for testing, so this bellow is connected to the print using tape, as it is slightly larger than the instrument body.

An air leakage of 27cm^3/s/N is measured. This is unacceptable, as the maximum value was set at 25cm^3/s/N. The left hand side Pigni prototype used for testing has serious air leaks. This contributes to the air leakage of the system. It is therefore not fully clear to what extent this air leakage is caused by the print of this project. Air leakage may occur at the valves, but it is also possible that due to tiny print defects, the body itself is not fully airtight. This should be researched further.

12-17. Bellow requirements

As the initial requirements could not be met by a printed bellow, the choice was made to use a conventional bellow. The properties of this component meet the standard of the insdustry and do not require further evaluation.

18. Dimensions - internal mechanism

The mechanism is kept as compact as possible, and fits the instrument body well.

19. (Dis)Assembly - internal mechanism

Disassembling every single arm in the mechanism takes up to 10 seconds using custom tools. This enables a disassembly time under 5 minutes, compared the the 40 minutes of the conventional instrument. In some situations, it might be more convenient to remove the complete mechanism instead of just one arm (e.g. when an angled arm is obstructed by other arms). This is acceptable since this only requires 5 minutes. Furthermore, removing a single arm is not possible in a conventional instrument.

20. Snap fit force - internal mechanism

Current assembly forces are rather high, around 40N for both assembly and disassembly. This is still within acceptable range, but a lower force is desirable. This accounts especially for the assembly force in order to improve user convenience.

The high force has to do with printing tolerances, as a change of body layer height from 0,1 to 0,12mm has influenced the dimensions of the prototype.

The snap fit itself is not the problem, as the extra friction is caused by the tight fit of the snap fit base. Lowering the force can easily be done by adjusting the parametric margin in the 3D model.

21. Snap fit clearance - internal mechanism

There is no noticeable clearance in the snap fit of the internal mechanism. As mentioned above, the fit of the snap fit base is rather tight.

22. Spring-button force

The current MiniMouse has button forces ranging from 0,8N (first row) to 1,7N (third row). Values for the redesign range from 0,8N to 1,3N and are therefore within the acceptable range, but there is room for improvement.

23. Spring Lifetime - internal mechanism

The latest design of the spring can easily endure 1.500.000 cycles, and up to five times as much, as indicated in several tests.

24. Beam Torsion - internal mechanism

Beam torsion does not cause any mechanical problems, and users indicated not to feel a clear torque effect when pressing a button. The valves open and close as they are supposed to do. It should however be noted that the arms on the left and right of the mechanism show signs of torque when inspecting them during a button press. The design can be altered in order to make these arms stronger.

25. Beam Deflection - internal mechanism

The beams of the mechanical system do deflect a little when cancelling the spring pretension, but this does not result in plastic deformation of the material. Their deflection is barely noticeable: there is no dead zone when pressing a button. Neither does this effect obstruct the playing of the instrument in any other way.

26. Button fixation

A snap fit system fixates the buttons well, and makes them detachable over 10 times.

27-28. Max. button attachment/detachment force

The buttons can easily be placed by hand. Requiring 20N and 23N for attaching and detaching, they are far below the maximum button push and pull forces of 50N and 40N.

29. Clearance in button attachment

Via the use of the right printer margins, the button snap fits have no noticeable clearance.

30. Clearance in button system

The button pad is designed so that the max. clearance cannot exceed the maximum value of 1mm to the left and right. The felt under the button pad makes the actual clearance even lower, as its material resistance fixates the button.

31. Smooth button movement

The layer of felt mentioned above also regulates a smooth button path, so that they feel smooth when pressed.

32. Dimensions - buttons

The required button dimensions have been implemented in the design. The last two rows of buttons can be pressed 5mm, but the first row can only be pressed ~4mm. This is on the edge of what is acceptable (between 4 and 6 mm). The design flaw is caused by uncorrect 3D model adjustments. This can and should be repaired.

33. Landing properties - buttons

The button landing system is similar to that of a conventional instrument. This provides a soft feel for the user, and prevents the button from creating a loud sound when landing.

34. False air - valves

The amount of air that flows around the air valves through the reed is low enough not to sound any reeds unwantedly. This remains the same when pulling the bellow fiercely without playing a tone.

35. Soft closure - valves

The closure method for the valves is the same as in a conventional instrument. Felt and leather create a soft closure that does not produce a loud sound. This meets the requirement for this part.

36. Easy reed (un)mount

The gasket and reeds can be mounted within 10 minutes, using only temporary connections (e.g. no glue on the gasket required). This is far below the maximum of 30 minutes to make the process more convenient than waxing. Unmounting the reeds takes about the same time.

37. Reed reachability

The reeds are reachable for tuning. The largest obstruction takes place at the bottom of the reed, which is clamped under a ridge. This does not influence the reachability, as there are no obstructions perpendicular to the functional components (the steel reed itself and the leather valve). This means that the tuning process is similar to that of convenional instruments with this reed orientation.

38. Dimensions - reed blocks

The set of reeds has a total length and width of 162,5 and 96,4mm when all reeds are placed in their correct orientation. The reed block dimensions should remain under 110% of these values. The functional surface reed block measures 178,7x105,4mm. This is just within the acceptable range (110% and 109%). Note that there is some extra space on the edges of the reedblock, as the full surface measures 185x115mm. This is done on purpose, so that an eventual left hand side of the instrument (which has bigger reeds) will fit the bellow. This extra space is not regarded part of the reedblock in this calculation.

39. Archetypical shape

The basic shape of the instrument remains unchanged from that of a conventional instrument. This ensures the instrument to be recognised as an accordion, which proved not to be a problem for anyone looking at the design.

40. Modest appearance

A more progressive angular body finishing is combined with for instance a traditional-looking grille. Therefore, both progressive and conservative elements are present in the design.

41. Rigid body

When handling the instrument (body), no movement within parts can be detected. The instrument is therefore rigid enough for the user to feel safe.

12. CONCLUSION

The end result of this project is far from a finished product. What future steps are desirable for further development of the current product?

12.1. assignment reflection

The original assignment is to find out how additive manufacturing technologies can be used to simplify production of a small accordion. The proof of concept provides insight for answering this question.

THE BOTTOM LINE

In its current state, the design consists of a functioning accordion that performs well on most aspects. Minor technical design adjustments are required to make the product meet all requirements.

It has become clear that additive manufacturing techniques can be used satisfactory during the acccordion production process. The current proof of concept matches the original purpose of creating an instrument that requires less labour during production. This is not established by producing parts similar to that of a conventional accordion, but by creating a custom design that matches its means of production in terms of geometry, material and performance. The result is a proof of concept with a sound that is users consider to be pleasant.

Some errors and desirable adjustments in the design need to be addressed in order for it to meet all the requirements and improve its functioning. No problems are expected in resolving these recommendations, as the main parts of the design all prove to function as planned.

A cost estimation can be made for the production of this right hand side of the instrument. The production time of roughly four hours for a printed right hand side means that 7 hours are saved. This is a time reduction of 61% for the right hand side. If a conventional instrument is outfitted with a printed right hand side, its total cost (labour and material) will be reduced more than 15%. If the design is extended to the left hand side of the instrument, a further cost reduction may be possible.

Keep in mind that these figures are estimations, and the precise impact of the design on the production process and the labour required will only come to light when the design is being produced in larger numbers. Still, the figures and the proof of concept provide a clear indication that additive manufacturing can be a valuable tool in lowering the engagement threshold for future accordionists.

RECOMMENDATIONS

- The printing material needs to be updated to a high-end FDM material.
- A more thorough air leakage analysis is required with a different bellow and left hand side of the instrument. The source of air leakage needs to be determined and, if the leakage is still unacceptably large, resolved.
- The mechanical parts connecting the first row of buttons to the valve are currently unconvenient to place: their length obstructs the part to fit. The user needs to apply force in order to get the snap fit in place. This issue should be resolved.
- Placing a number on each arm of the inner mechanics increases the ease of use when placing them in the right order.
- There currently is little space for placing the belt straps. The geometry should be updated to create more space for them to be placed.
- The button shape can be optimised in order to find a shape that is more convenient to the touch when playing the instrument.
- Depending on the print material, a coating may need to be applied to protect the instrument from scratching and to improve its aesthetics. This could be a varnish or epoxy coating, or something else.
- The buttons currently have a pressing depth ranging from 4 to 6 mm. This is undesirable, and should be made equal for all buttons (to 5,5mm).
- The buttons currently have pressing forces ranging from 0,8 to 1,3 N. This is undesirable, and should be made equal for all buttons (to 1,2 N). This can be done by adjusting the spring prestress length.
- More space can be created inside the body in order to make it easy to loosen the snap fits on the side of the mechanics. This space is currently filled with unpurposed material.
- A ridge can be created behind the top of the grille, so that it can not be bent/pressed in the direction of the valves.

If all these recommendations are implemented, the product is a well-performing instrument that meets all requirements and showcases the possibilities of additive manufacturing in accordion production.

12.2. future steps

The current design is not an instrument that can be sold on the market, as it consists of only a part of an accordion. What needs to be done to make the design market ready?

When the design is updated according to the recommendations as stated earlier, more steps can be taken for the project as a whole. These steps take the current prototype as a starting point, but their scope is beyond this graduation assignment. The steps will help Pigini Nederland to translate this prototype into a final design that can be produced and sold on the market.

Sound chamber research

The current instrument sound for all notes needs to be analysed via a method similar to the previous sound research.
After this, the effects of multiple sound chamber variables on the sound of the instrument need to be addressed. The sound chambers can then be optimised in order to create a sound closer to the 'normal' Pigini sound.

Custom reeds

The current reeds are not fully satisfactory, as there are some unnecessary limitations. For instance, there is very little space to clamp the reed onto the gasket, due to the measurement of the reed tip. For conventional attachment methods, the dimension of this part is not of great importance, but for this instrument it is. It is therefore advisable to produce custom reeds in the long term.

Overall design improvements

Besides the recommendations as mentioned earlier, some parts might fail unexpectedly and may need to be redesigned. Other parts, such as the attachment of the belt strap, can be integrated into the design better.

Left hand side body

In order to make the product a success, a left hand side is also required for the instrument. A combination of conventional and printed instrument parts is not desirable. It is not yet clear if the complete mechanical system on this side can be created using FDM technologies. If this is not the case, a suitable alternative needs to be sought, since the conventional production method requires a lot of labour. Printing only parts of the mechanism is an option for this side of the instrument.

Bellow

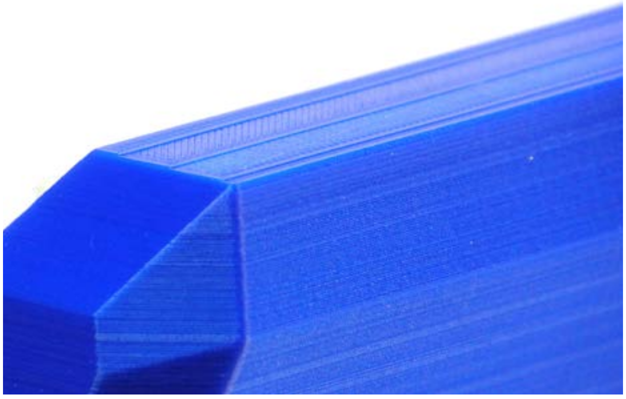
It might be possible to produce a full-fledged bellow using flexible and non-flexible filament. This would require a printer with three nozzles. More tests can be done in this area.

Improving print efficiency & printability

Some parts may be printed more efficiently, e.g. by slightly adjusting dimensions, placing them together on the print bed or adjusting the print settings. Recurring printing implications may surface and need to be resolved.

The print time can be increased by, amongst others, increasing the print speed of the support material and adjusting layer height. In this phase of the project, this is not necessary, but for larger-scale production, further research in improving print speed can be rewarding.

Some surfaces of the body are angled very close to the layer direction. This results in a clear layer visibility on these surfaces, which is not desirable. The design could be adjusted to reduce this effect.



Print layers are clearly visible on the front plane of the instrument

Scaling up

The design can be scaled to larger instruments.
For instance the size of a Pigini Peter Pan, which is a slightly bigger instrument. This brings, besides eventual dimensional limitations, more problems.
For instance, the Peter Pan has four rows of buttons instead of three, leaving less width for each arm in the mechanics system. Its lowest reeds are bigger, and other components such as the button cover may turn out relatively thin. All of this are problems to dive into!

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