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FAKULTA STROJNÍHO INŽENÝRSTVÍ

INSTITUTE OF AEROSPACE ENGINEERING
LETECKÝ ÚSTAV

EXPERIMENTAL VALIDATION OF ACTIVE FLOW CONTROL CONCEPT FOR AUTOMOTIVE APPLICATIONS
EXPERIMENTÁLNÍ OVĚŘENÍ KONCEPTU AKTIVNÍHO ŘÍZENÍ PROUDU V AUTOMOBILNÍ APLIKACI

MASTER'S THESIS
DIPLOMOVÁ PRÁCE

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AUTOR PRÁCE

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VEDOUCÍ PRÁCE

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BRNO UNIVERSITY OF TECHNOLOGY
FACULTY OF MECHANICAL ENGINEERING

Specification Master's Thesis

Department:	Institute of Aerospace Engineering
Student:	**Bc. Vojtěch Sobotka**
Study programme:	Mechanical Engineering
Study field:	Aircraft Design
Leader:	**Ing. Robert Popela, Ph.D.**
Academic year:	2016/17

Pursuant to Act no. 111/1998 concerning universities and the BUT study and examination rules, you have been assigned the following topic by the institute director Master's Thesis:

Experimental validation of active flow control concept for automotive applications

Concise characteristic of the task:

Active flow control is currently very progressive tool for modification of aerodynamic characteristics of bodies in flow. Active flow control principles are studies also at Institute of Aerospace Engineering. After successful numerical modeling there is now possible to perform experimental assessment of concept for passenger car drag reduction. There is necessary to design practical structure and its integration to vehicle.

Goals Master's Thesis:

Design of spoiler for active flow control on rear part of passenger car. Design of pneumatic system for active flow control. Definition of attachment of spoiler and its installation.

Recommended bibliography:

POPELA R., DOUPNÍK P., FRYŠTÁK L.: Active flow control on UP! car, VW AFC project, 2016, internal presentation.

Deadline for submission Master's Thesis is given by the Schedule of the Academic year 2016/17

In Brno,

L. S.

doc. Ing. Jaroslav Juračka, Ph.D. Director of the Institute	doc. Ing. Jaroslav Katolický, Ph.D. FME dean

Abstrakt, klíčová slova/Abstract, key words

Tato diplomová práce obsahuje komplexní návrh systému aktivního řízení proudu instalovaného na osobním voze Škoda Roomster. Tato práce navazuje na výzkum provedený VUT a TUB na vozidle Volkswagen UP! Návrh lze rozdělit na tři základní části - návrh spoileru, návrh závěsů a návrh vyfukovacího systému. V každé z těchto částí je návrh detailně popsán a potřebná výkresová dokumeentace je součástí práce v její příloze. Pro potřeby návrhu vyfukovacího systému bylo provedeno jeho testování. Výsledky testu jsou v této části uvedeny. Práce také obsahuje komplexní popis sestavení celého systému a jeho instalace na automobil.

aktivní řízení proudu, osobní automobil, spoiler, snižování oporu, tlaková láhev, redukční ventil, šroubení, řezání laserem, experiment

This master's thesis contains complex design of active flow control system installed on Škoda Roomster passenger car following previous research done by BUT and TUB on Volkswagen UP! passenger car. There are three main parts of the design found in this thesis - spoiler design, hinge design and blowing system design. In each of these parts the design is described in detail and necessary drawings are then found in thesis appendices. For purposes of blowing system design part system testing was performed. The test results are found in that part. The thesis also contains complex description of system assembly and installation on car.

active flow control, passenger car, spoiler, drag reduction, pressure cylinder, pressure regulator, fittings, laser cutting, experiment

Bibliografická citace/Thesis citation

SOBOTKA, V. Experimentální ověření konceptu aktivního řízení proudu v automobilní aplikaci. Brno: Vysoké učení technické v Brně, Fakulta strojního inženýrství, 2017. 94 s. Vedoucí diplomové práce Ing. Robert Popela, Ph.D..

Prohlášení/Declaration

Prohlašuji, že jsem tuto diplomovou práci zpracoval samostatně pod vedením vedoucího práce, Ing. Roberta Popely, Ph.D. s použitím literatury uvedené v této práci.

I declare that I wrote this master's thesis personally under supervision of my thesis supervisor Ing. Robert Popela, Ph.D. with use of bibliography listed in this thesis.

Brno, 26. 5. 2017

Vojtěch Sobotka

Acknowledgements

I would hereby in the first place like to thank my thesis supervisor, Ing. Robert Popela, Ph.D. , for professional guidance and for his advice and help whenever I needed it. I would also like to thank Ing. Jiří Matějů from IAE for helping me with system test preparation, with the test itself and its output processing. I also thank Mr. Milan Strachoň from Festo company for his assistance with pneumatic component selection and Mrs. Ivana Papírková, also from Festo company, for her willingness in component ordering and delivery. For the same willingness I would like to thank Bc. Alena Dohnalová from Linde Gas company.

Contents

1 Introduction

The active flow control is generally known for its use in aviation in order to improve aerodynamic properties of aircraft for years. The concept itself, however, has much wider area of use than aircraft only. Generally speaking the concept can be used on any object interfering with an airstream where its aerodynamic properties are to be improved.

One of the most promising applications today is automotive industry. With increasing demands on lower fuel consumption using means of active flow control on a car in order to lower its drag appears to be a reasonable decision. In such case a research has to be done proving the viability of the concept taking design difficulties, manufacturing complexity, energy demands and cost of such system into account and comparing and contrasting them to potential benefits.

Such research was started by BUT and TUB and predicted viability of such system on Volkswagen UP! passenger car using CFD simulation and wind tunnel testing on a 1:4 scale model. Therefore it was decided to take the concept to a next level and test it on a real car.

Figure 1.1: Škoda Roomster [Available at: http://skodaroomster.wz.cz/roomster-fresh-1.jpg]

This thesis aims to design an active flow control spoiler installed on a Škoda Roomster passenger car. The design follows the previous research output values and experience and is meant to prove the concept functionality in real conditions.

Using the spoiler designed in this thesis a series of tests will be performed. The car in a certain weight configuration will be accelerated to a certain speed in which the system will be activated. Then the car will be left to decelerate freely until it stops. The time until stopping as well as velocity gradient during deceleration will be then evaluated and used as an indicator of concept's viability.

1.1 Basic design concept

The whole system consists of spoiler, hinges and blowing system. The spoiler will be mounted on car roof's trailing edge as seen in fig. 1.2, will allow slight changes of its angle relative to the roof and will blow air from a slot perpendicularly to the external airstream.

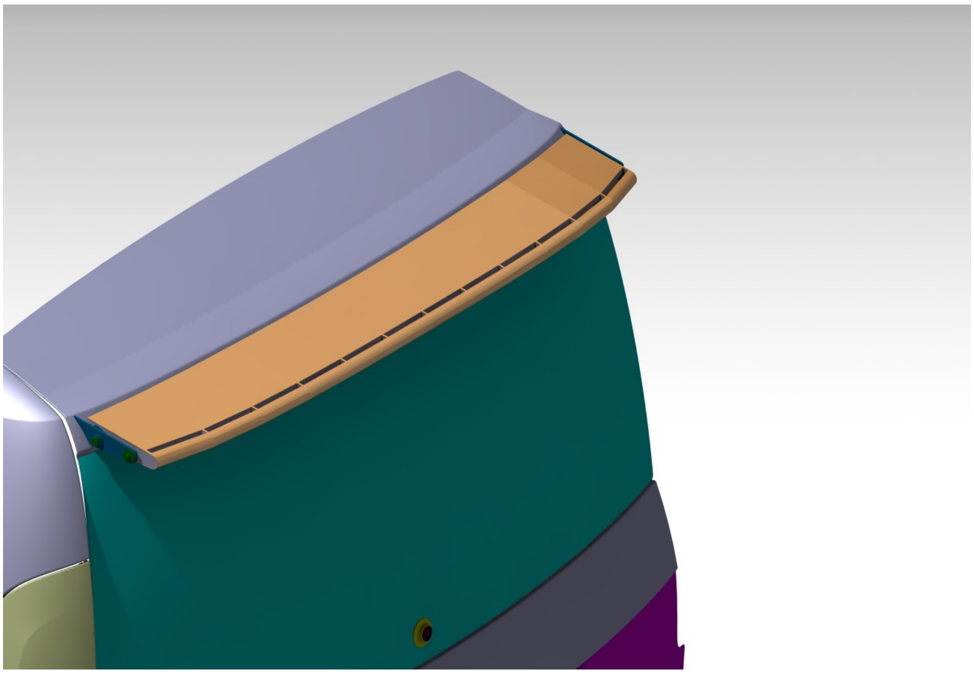


Figure 1.2: spoiler visualisation rendered from 3D model

The blowing system consisting of air supply and air distributing system will be placed inside the car and the distributing system hoses will pass through openings in car body straight into the spoiler. The spoiler itself will be hollow inside and work as a pressure chamber from which the air will blow through the above mentioned slot.

1.2 Design philosophy

The whole design will be adjusted to the fact the final product should serve as a **proof of concept**. It means the spoiler and blowing system should be designed in such a manner the whole product is as simple and cheap as possible and that it allows modifications resulting from the testing phase findings.

The goal is not designing a perfectly shaped, great looking or the most efficient product but designing a product that proves the general functionality of the principle, the concept itself. Only in case the concept is proven the time for development of more perfect and more expensive product comes. This affects not only materials or manufacturing technologies used. It also means that simplification will be applied whenever it is possible. Means and methods used for designing are also selected with respect to the design philosophy. Complex, time consuming and/or expensive methods such as CFD are not adopted while methods like experimental determination are preferred.

This context is then the main principle this thesis is based on and is referred to many times in this thesis whenever it affects the design decisions.

1.3 Definitions

For purposes of this thesis the axis system and views as well as other terms have to be defined. These definitions are presented in fig. 1.3. This figure and terms defined by it are essential for understanding the design as they will be referred to many times. If not specified otherwise, the figures, dimensions and angles are related to **LEFT** side of the spoiler and most often seen from **LEFT** view. The right side is then mirrored.

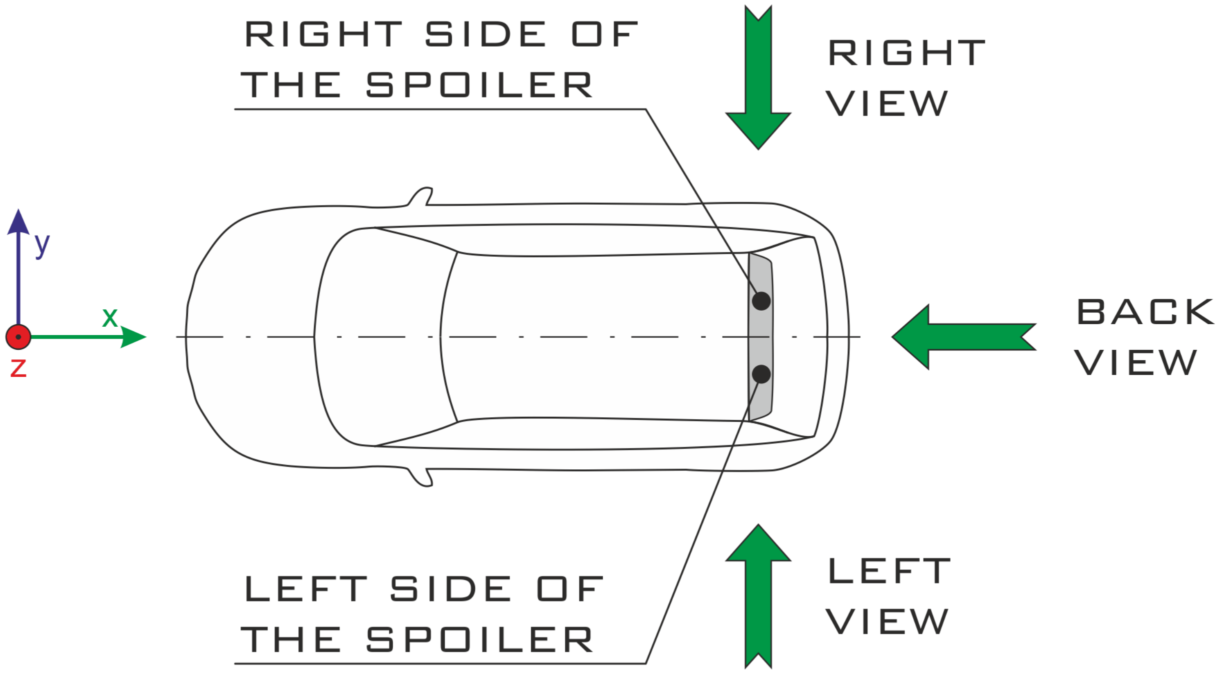


Figure 1.3: definition of axis system, views and other terms

2 Previous research

As mentioned in the previous chapter, this thesis aiming to design an active flow control spoiler mounted on Škoda Roomster passenger car follows previous research done by BUT. It is therefore appropriate to mention the whole chapter and all the information found in it is based on document [1] and so that it will not be specified further on in the text.

The goal of above mentioned research was to prove the influence of active flow control on drag and lift acting on Volkswagen UP! passenger car. The basic principle of BUT's concept is blowing an airstream from inside of spoilers mounted on roof trailing edge and on the sides of the rear part of the vehicle perpendicularly into external freestream.

2.1 Initial CFD prediction

A CFD simulation was performed predicting lift and drag reduction. Blowing speed **25 m/s** was determined as optimal. This blowing speed also means acceptable energy demands on blowing device. Particular values obtained from initial CFD prediction are summed up in tab. 2.1. The effect of blowing speed on lift and drag coefficient is more evident when shown in fig. 2.1.

Blowing velocity [m/s]	$c_{D_{CFD}}$ [-]	$c_{L_{CFD}}$ [-]	Δc_D [%]	Δc_L [%]
Reference geometry	0.4075	0.07	-	-
0	0.4025	0.095	-1.23	35.71
10	0.381	0.055	-6.50	-21.43
20	0.372	0.03	-8.71	-57.14
25	0.368	0.01	-9.69	-85.71
30	0.395	0.05	-3.07	-171.43

Table 2.1: influence of blowing speed on lift and drag coefficient [1]

After initial CFD prediction the concept was to be tested in a wind tunnel using 1:4 scale model. Necessary blowing system parts shown in fig. 2.2 were designed by BUT and manufactured by TUB using rapid prototyping.

During testing it was discovered that the angle of blowing did not correspond with 90 degrees used on CFD model. The real angle was limited to 55 degrees without external flow which was caused by internal slot geometry limitation. Therefore the CFD model had to be modified to correspond with this new discovery. The spoiler geometry used for CFD was also modified as the original one uses continuous slot, whereas the real slot is divided into several sections. After modifying the model the CFD computation was carried out again. The results are presented in tab. 2.2 and fig. 2.3.

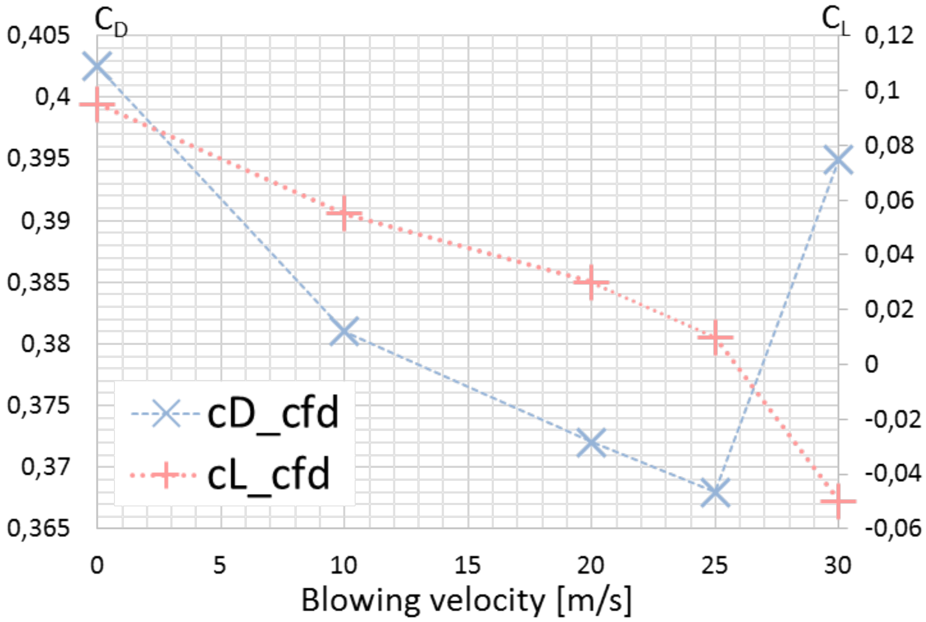
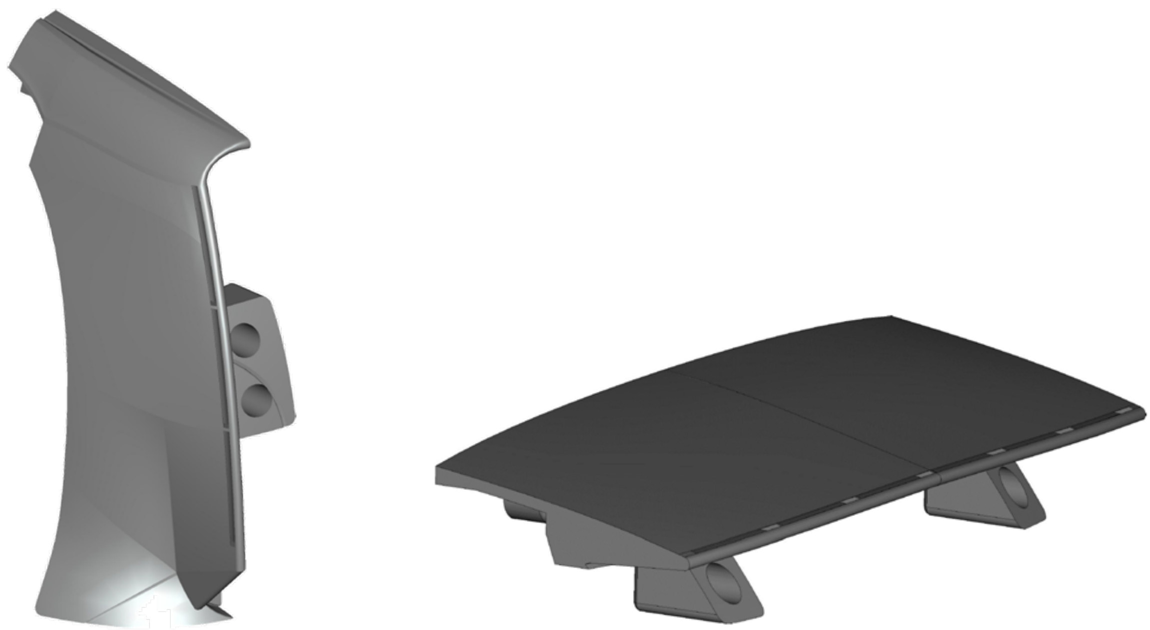


Figure 2.1: influence of blowing speed on lift and drag coefficient [1]



(a) Vertical spoiler (b) Horizontal spoiler

Figure 2.2: manufactured parts [1]

Case [-]	Blowing velocity [m/s]	Angle [deg]	Slot [-]	$c_{D_{CFD}}$ [-]	$c_{L_{CFD}}$ [-]	Δc_D [%]	Δc_L [%]
0	Reference geometry			0.4075	0.07	-	-
1	0	-	-	0.4025	0.095	-1.23	35.71
2	25	90	Continuous	0.368	0.01	-9.69	-85.71
3	25	90	Divided	0.372	0.02	-8.71	-71.43
4	25	70	Divided	0.374	0.04	-8.22	-42.86
5	25	50	Divided	0.38	0.05	-6.75	-28.57

Table 2.2: CFD prediction with modified geometry [1]

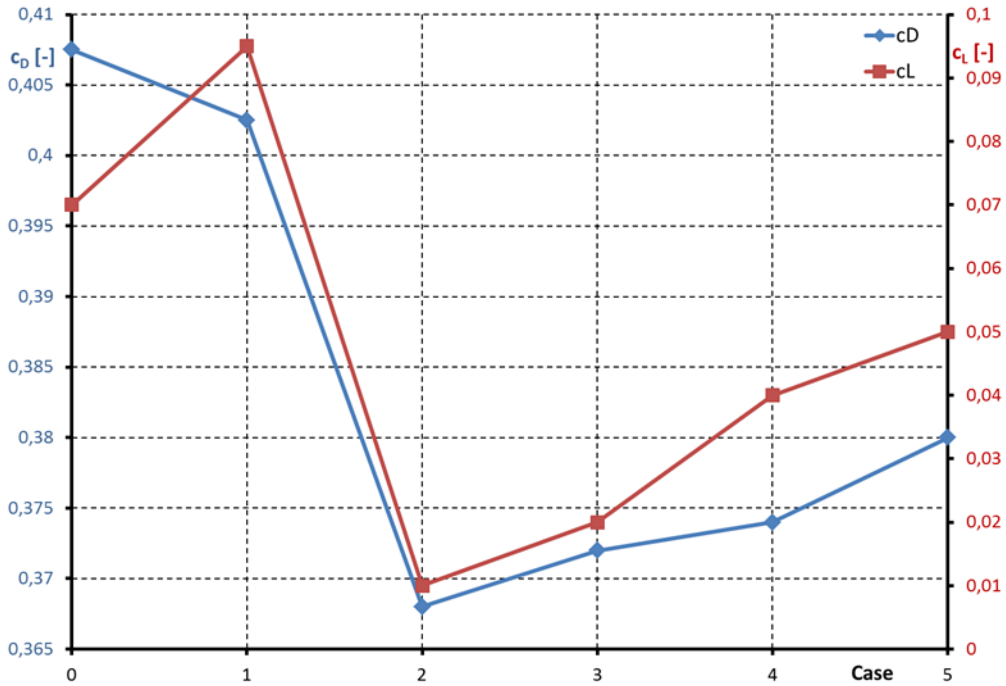


Figure 2.3: CFD prediction with modified geometry [1]

2.2 Wind tunnel testing

After completing the initial CFD prediction wind tunnel testing at TUB was carried out. A 1:4 scale model of Volkswagen UP! passenger car was used with freestream velocity **50 [m/s]**. 6 balance forces were measured and the separate blowing of upper and side parts was controlled by volume frame rate. The car model was placed on a slab with a sharp edge in the front cutting boundary layer off as shown in fig. 2.4. The results of wind tunnel experiment are shown in fig. 2.5.

Figure 2.4: wind tunnel testing scheme [1]

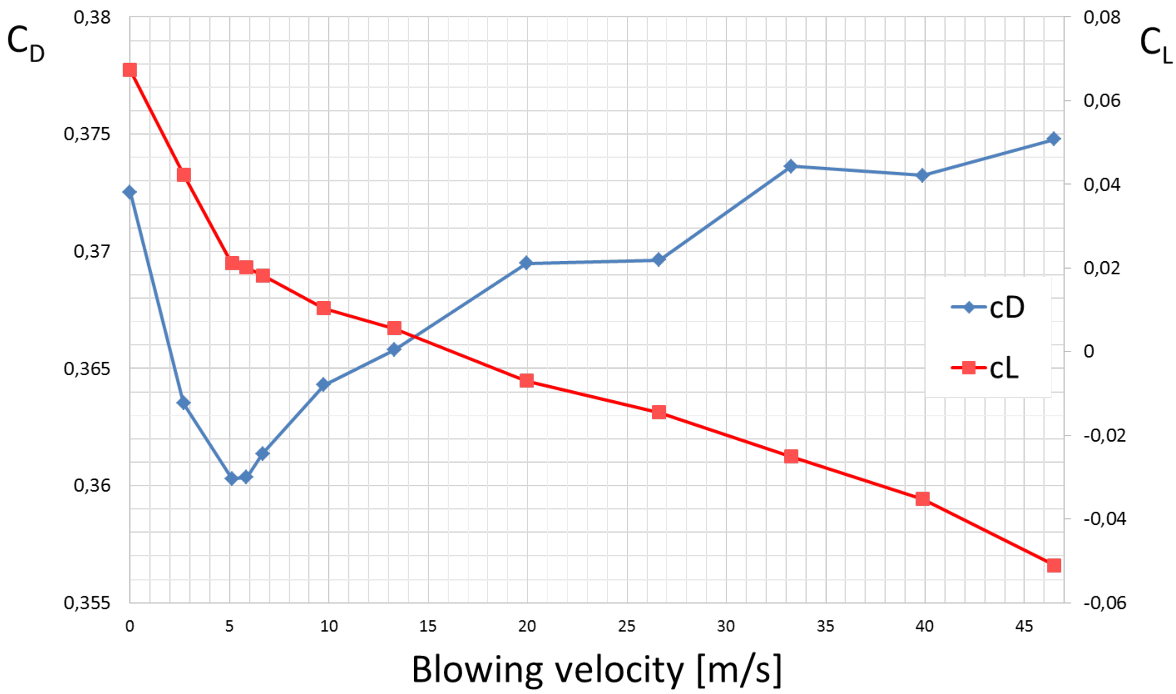


Figure 2.5: wind tunnel testing results [1]

2.3 Comparison and conclusion of initial research

The results obtained from both CFD and wind tunnel testing were compared as shown in fig. 2.6. It is obvious the optimal blowing velocity is much lower than the CFD predicted. The optimal velocity determined from wind tunnel testing results is **5 [m/s]**. This fact is very advantageous as the lower velocity means lower energy demands on blowing device.

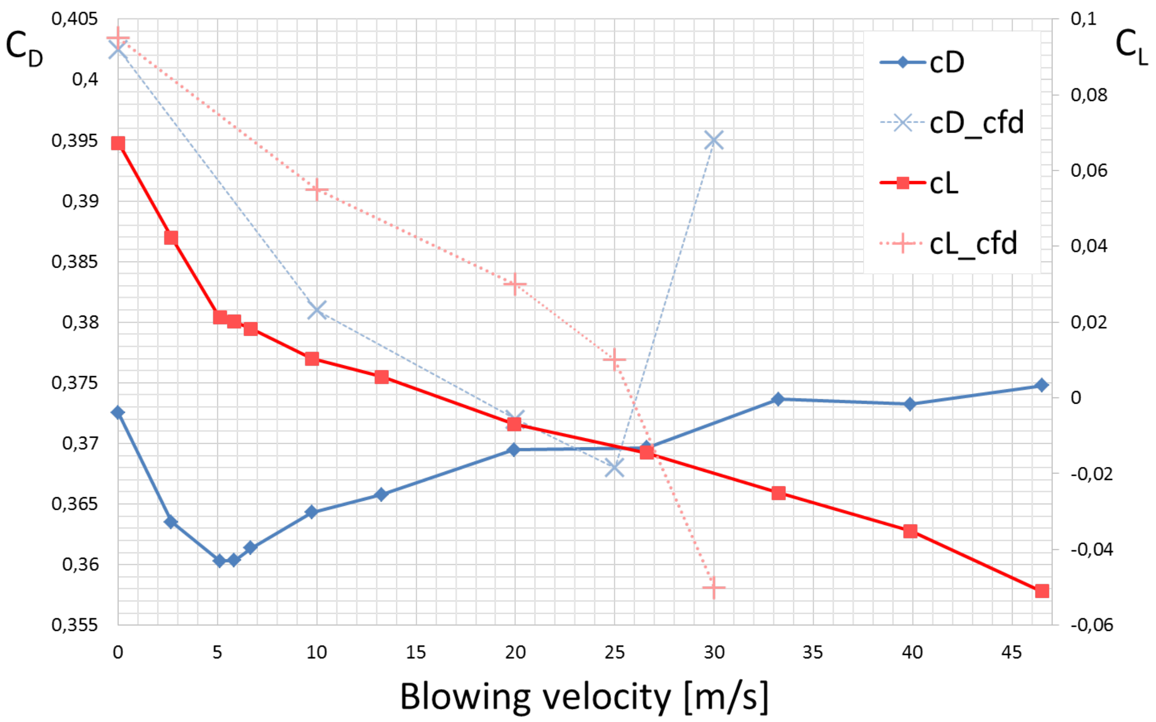


Figure 2.6: comparison of CFD prediction and wind tunnel testing results [1]

The drag dependence on blowing speed curve has similar behaviour compared to CFD; both have global minimum, however their values differ. The curves representing lift also follow the same pattern - the lift reduction increases with growing blowing velocity and the curves have no global nor local minimum.

After completing both CFD prediction and wind tunnel testing, the blowing velocity **5 [m/s]** was determined as relevant and thus it is used as a starting value for Škoda Roomster active spoiler design described in this thesis.

3 Spoiler design

3.1 Spoiler design requirements

3.1.1 Stiffness

The spoiler has to be stiff enough to withstand the effect of aerodynamic forces without major deformation. As the car velocity during testing is expected to be about **100 [km/h]** the forces are not expected to be high. However, as this particular spoiler does not work nor behave like a classic aircraft surface (wing, flap etc.), generally because there is no airstream similar to the upper side on the lower side, it would not be possible to use formulae used for calculating aerodynamic forces on aircraft surfaces. The calculation would therefore probably require CFD simulations which is too complicated and above all useless in the proof of concept design phase.

Provided load calculation will not be performed the eventuality of higher forces must be taken into account (although they are not expected) which means the spoiler's skin must be made relatively thick and therefore stiff enough to take most of the load both in torsion and bending.

3.1.2 Variable spoiler angle, locking system

The spoiler should allow changing its angle relative to the roof. Despite CFD and wind tunnel testing results it might appear the system performs better when the angle is slightly modified. To allow testing of more settings the spoiler must be adjustable up to approximately $\pm$**5 [deg]** and must be lockable in any position within described range.

3.2 Overall design

The spoiler basically is a system of parallel chambers divided by ribs and enclosed by spoiler's skin and spar parts as seen in the fig. 3.1. Each chamber is connected to a hose supplying compressed air. The ribs, despite dividing the chambers, allow pressure equalisation between particular chambers through openings in them. The spoiler has a trailing edge with **9 [mm]** radius and a slot parallel to trailing edge **8 [mm]** wide. These dimensions were derived from above mentioned previous research. On the side of the slot closer to car body there is a slat installed. The function of this slat is to break the airstream so that it does not reach the slot directly. In such case the airstream would affect the direction of blowing unfavourably as seen in fig. 3.2. Use of the blocking slat should improve this behaviour as seen in fig. 3.3.

The theoretical shape of spoiler upper side follows car roof trailing edge from the back view while it is tangent to the roof from the side view. The planes in which tangency

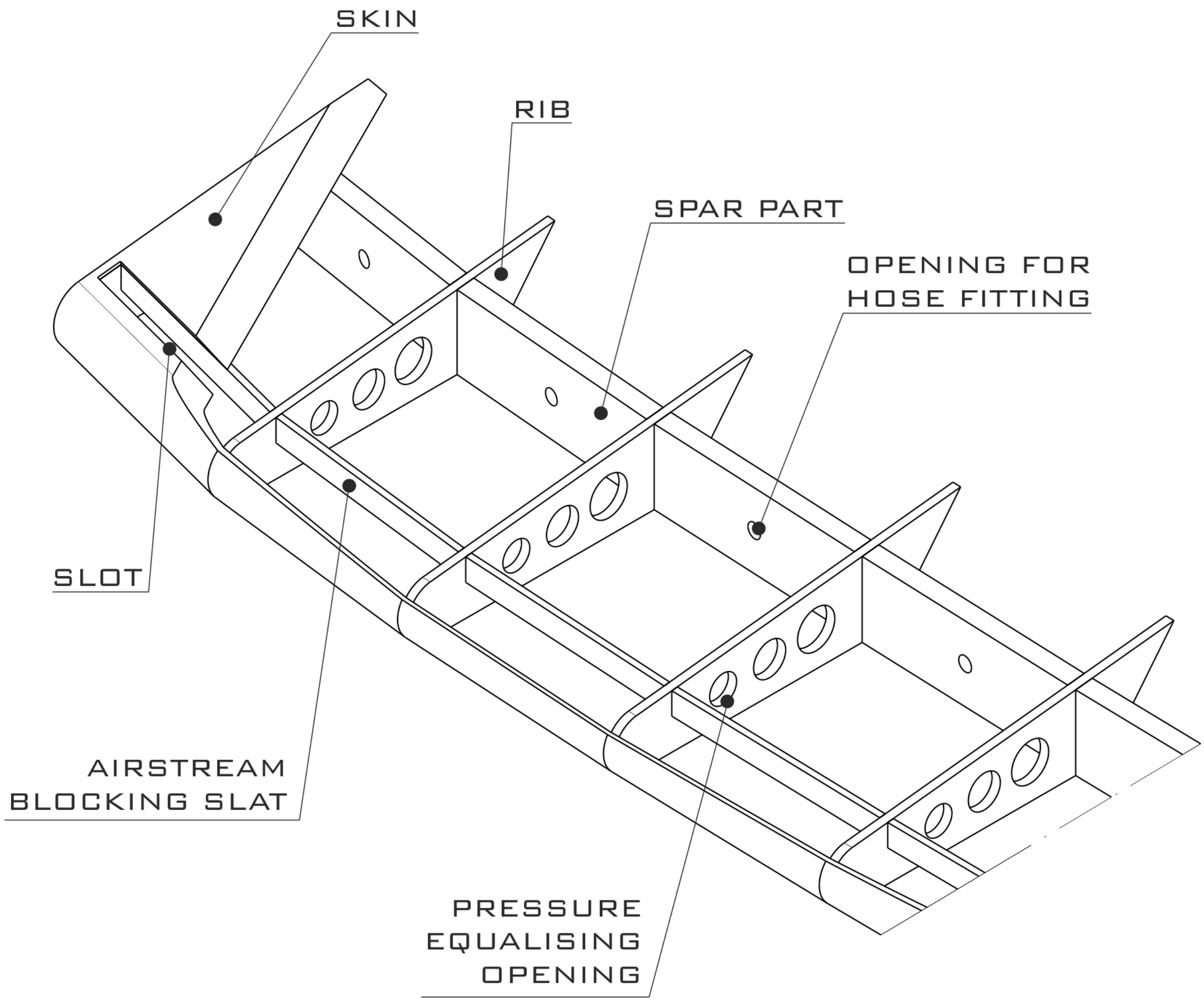


Figure 3.1: basic spoiler structure

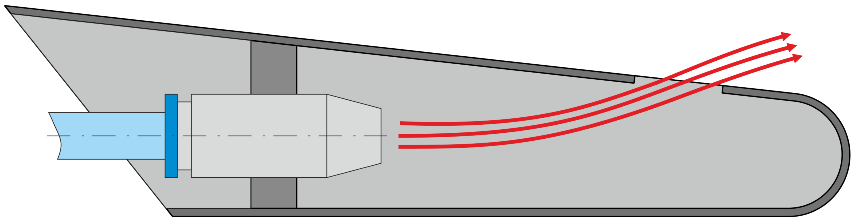


Figure 3.2: estimated airstream behaviour without blocking slat

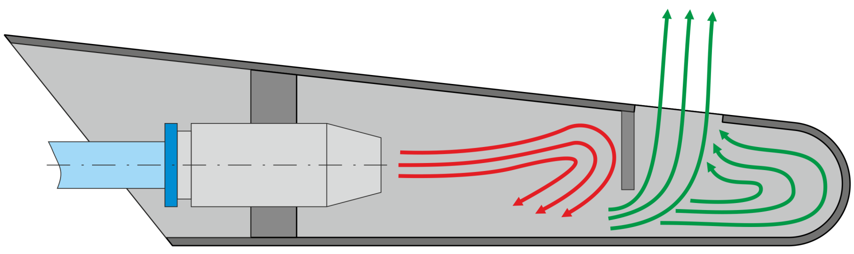


Figure 3.3: estimated airstream behaviour with blocking slat

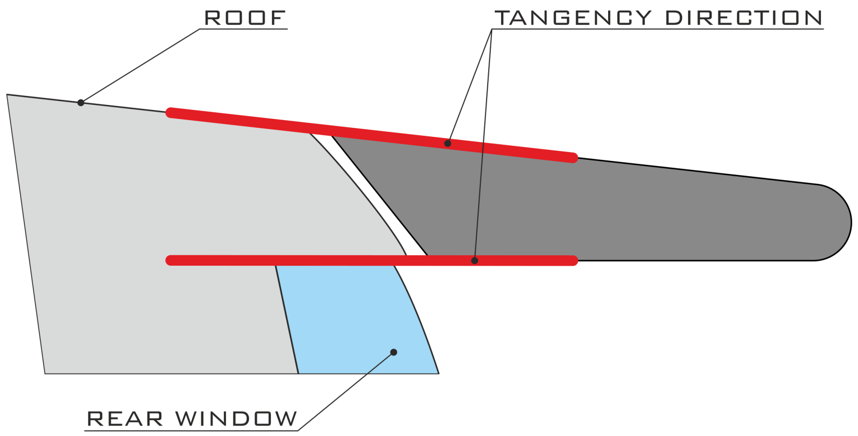


Figure 3.4: definition of tangency from side view

is defined are parallel to car symmetry plane. The lower side of spoiler follows the car body edge above the rear window from the back view and the x-axis from the side view. The described geometrical conditions are shown in fig. 3.4 and fig. 3.5. The upper and lower surface are then connected by a constant radius fillet. A 3D model of the spoiler was created taking these shape requirements into account.

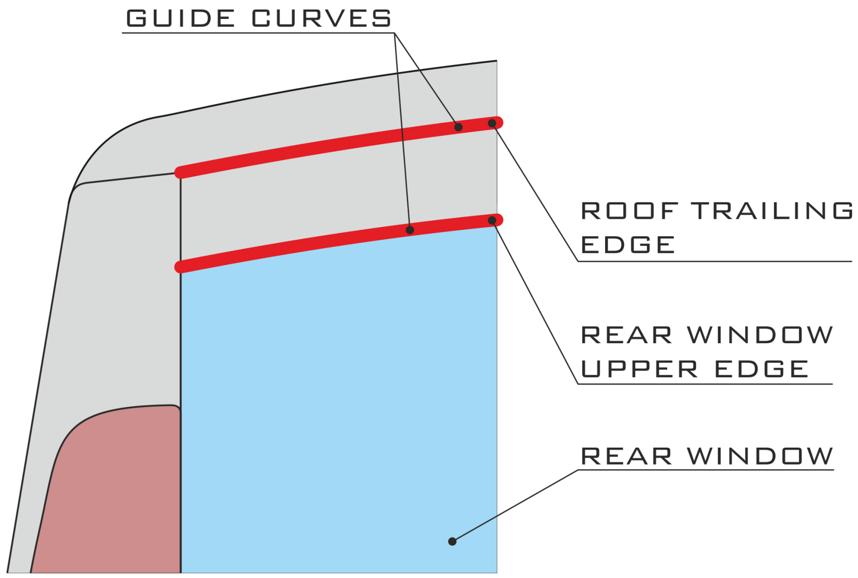


Figure 3.5: definition of guiding curves from back view

3.3 Possible manufacturing technologies

3.3.1 Sheet metal riveting

This proven technology used mostly on aircraft parts could be theoretically used to manufacture the spoiler. However, the spoiler shape is a shape with double curvature which requires expensive moulds and moulding machines. As every rib has different shape, each of them would need contour routing and a special mould. Riveting itself requires special positioning jigs to drill holes and consumes considerable amount of time and qualified human handwork. In other words, such technology is not suitable for proof of concept philosophy design because of its costs and complexity.

3.3.2 3D printing

3D printing has been a very progressive manufacturing technology during last years used mostly exactly in prototyping phase. For example, Evektor, a Czech aircraft manufacturer, uses 3D printed parts even on flying prototypes of their aircraft, such as aerodynamic covers, engine space air inlets or even wingtips [2]. Adopting this technology in prototyping phase may save costs compared to traditional manufacturing methods. However, this is true in industrial environments where future mass production is expected. In context of this thesis and means available 3D printing is still too expensive to be used for spoiler manufacturing.

3.3.3 Machined mould lamination

Composite materials represent an alternative to traditional all-metal design philosophy. In prototyping phase which is being dealt with hand lamination would be adopted. Laminating, however, requires a mould, which has to be machined using CNC milling machines. Manufacturing such a mould in order to laminate only one specimen is unacceptably expensive and therefore uneconomical.

3.3.4 Hand lamination using hand brushed polystyrene mould

This manufacturing technology is a result of simplification and cost-cutting effort. The basic idea is to manufacture spoiler ribs and spar parts from plywood and glue them together using dimensions which would define relative positions of these parts. Blocks of polystyrene are then glued between ribs and hand brushed to spoiler's final shape. Hereby a mould is created cheaply which is then used for lamination. After lamination the polystyrene is corroded out using acetone or toluene.

This manufacturing technology requires no machined moulds, specialised machines or fitting jigs which makes it the simplest and cheapest option of all above mentioned and therefore it was selected to manufacture the spoiler. However, it is not possible to maintain perfect theoretical shape of the spoiler by hand brushing, which means this technology lowers accuracy. As the design goal is to design a proof of concept spoiler, absolute accuracy is, however, not necessary. The principle of active flow control is expected to be working even with approximate shape.

3.4 Shape simplification

Adopting the above mentioned technology means slight shape differences compared to spoiler's theoretical shape are allowed. Under these circumstances the shape can be intentionally modified to make the manufacturing even simpler. The modified shape should not, however, differ too much from theoretical shape.

Taking manufacturing into account, the best option is to replace one curved surface with several planar surfaces. Such solution brings several manufacturing advantages such as:

- ribs have profiles with only linear sections and a circular fillet on the end
- spar parts have linear section profiles

- polystyrene blocks are brushed into planar shape, on upper convex side they can be cut with hot-wire using ribs as guides
- hose fitting installation to planar spar parts is simpler

To achieve described geometry the upper side of the spoiler cannot be exactly tangent to the roof throughout the whole spoiler span anymore because then the surfaces between ribs could not be planar but twisted. Unified upper surface direction from the side view was therefore used. This direction is defined by a line tangent to the roof in car symmetry plane.

A new 3D model based on this shape simplification was then created. Comparing this new shape with theoretical one shows only slight shape differences as seen in fig. 3.6 and fig. 3.7 where the original shape has white colour while the simplified shape is represented by green colour.

The most significant difference appeared on the side most chamber where from the top view the outer rib is shorter. The rest of the spoiler, however, does not differ significantly from the original shape. The simplified shape somewhere exceeds the original shape, somewhere it lays under the original shape, but the difference is neglectable and exchanged for considerable simplification and cost-saving is perfectly acceptable.

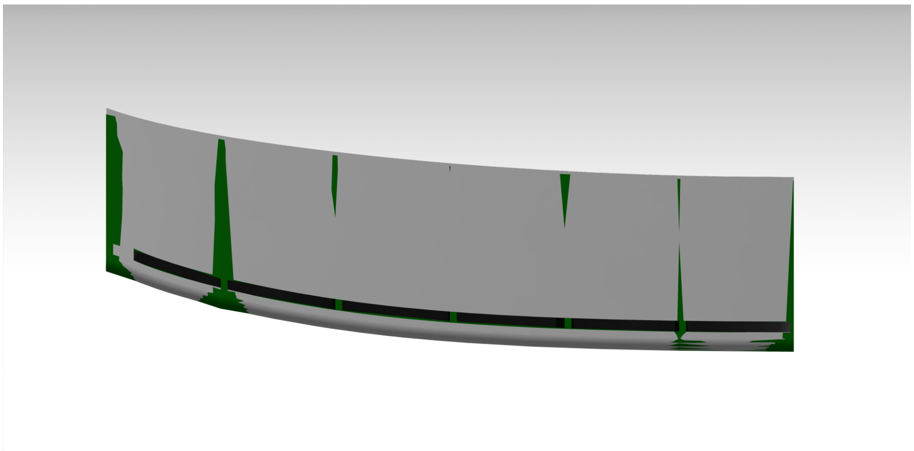


Figure 3.6: comparison of theoretical shape and simplified shape from the top view

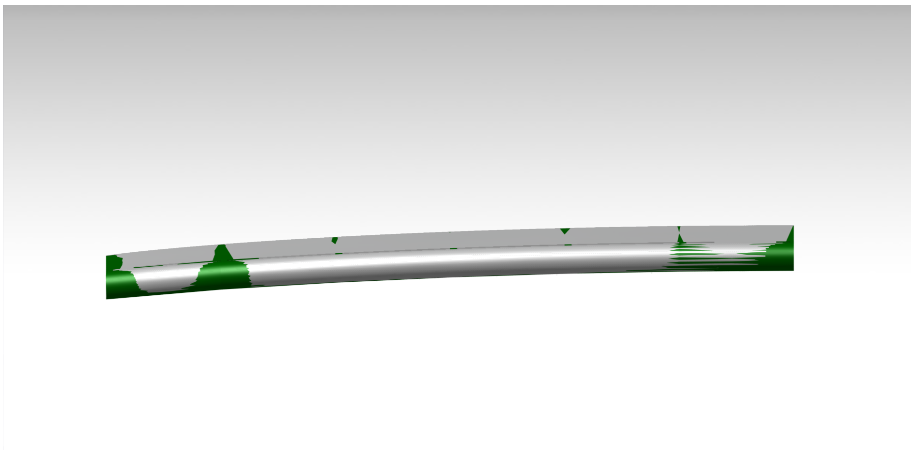


Figure 3.7: comparison of theoretical shape and simplified shape from the back view

3.5 Manufacturing process

The manufacturing process has several steps of which some will be discussed in more detail further on. These steps are:

1. semi-finished rib and spar part manufacturing
2. semi-finished slat part cutting
3. spar part holes re-drilling
4. slat and spar part chamfering
5. plywood framework assembly
6. polystyrene blocks cutting
7. polystyrene blocks gluing
8. brushing
9. lamination
10. machining of slot and other features
11. corroding the polystyrene out

3.6 System drawing and definition of parts

Before individual part design is presented the parts have to be defined first. The layout of the spoiler is obvious from fig. 3.8. The figure shows only left side of the spoiler from top view. The right side uses the same numbers as it is symmetrical. Ribs and spar parts are numbered here as well as blocking slat parts. There are also numbers of separate polystyrene blocks used for lamination defined in blue colour. The part numbers defined here will be referred to further in this thesis. These numbers will also be engraved on ribs and spar parts by manufacturer.

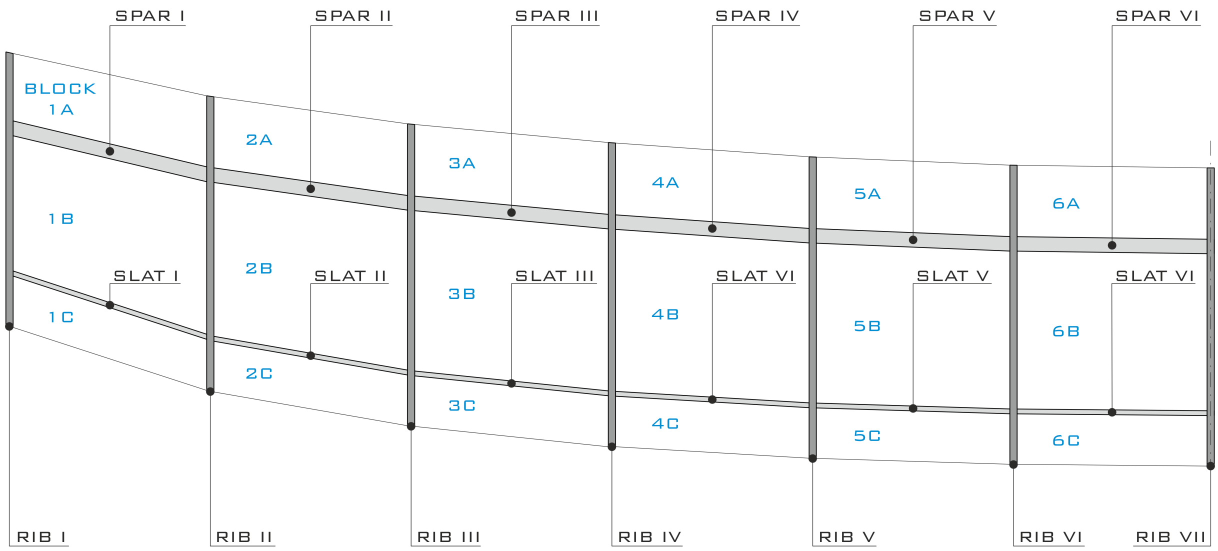


Figure 3.8: definition of part numbers (black colour) and numbers of polystyrene blocks (blue colour)

3.7 Ribs

3.7.1 Shape

As there is no high load expected the primary function of ribs is to maintain desired spoiler's shape. The material which was therefore selected is **3 [mm]** plywood. The thickness is sufficient with respect to described primary function.

Thanks to adopted shape simplification the rib shape consists of linear sections with circular fillet on the end. There are holes in each rib as seen in fig. 3.9 which are meant to connect chambers and therefore balance eventual pressure differences in separate chambers as described before. The only exception are the outer ribs. These ribs have no openings in them except for a hole close to the fillet. This hole is meant for a rivet nut which will be a part of spoiler angle locking system which will be described later.

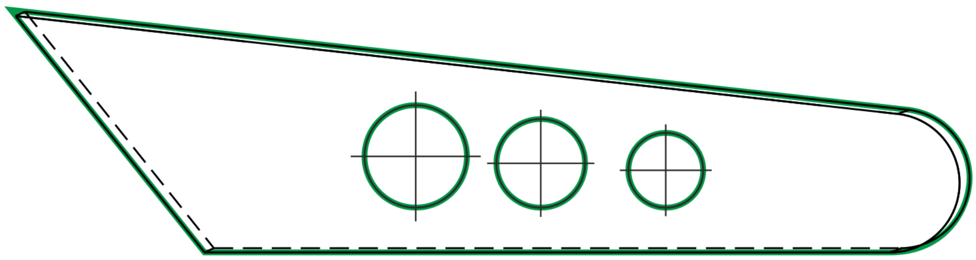


Figure 3.9: a rib example with outer shape curve for laser cutting definition

3.7.2 Manufacturing

For manufacturing, laser shape cutting was selected. This technology is optimal for cutting 2D shapes from constant thickness sheets combining cutting with engraving, which is in this case very advantageous as each rib should be marked to make final assembly easier.

In 3D model each rib has angled edges following spoiler's outer shape. In order to be able to cut it as constant thickness part using 2D curve the shape to be cut is the rib's projection taking only outer lines into account as seen in fig. 3.9 where the shape to be cut is marked with green colour. The chamfers will be hand brushed after the ribs are assembled together with spar parts. This allows the ribs to be cut from plywood using only 2D curves.

Again, certain inaccuracy is inherent in such solution. On the other hand it simplifies manufacturing and lowers costs considerably and therefore it is acceptable for a prof of concept design philosophy.

As mentioned above, each rib is to be laser engraved. A rib number according to fig. 3.8 will be engraved and the outer rib will have rotation axis position marked as well, which will help to mount hinges on spoiler later. The 2D curves were derived from previously created 3D model and handed over to the manufacturer in electronic form. The result of the manufacturing process are semi-finished ribs ready for further processing.

3.8 Spar parts

3.8.1 Similarity and difference to ribs

The spar design philosophy is similar to ribs. Individual spar parts will be manufactured from plywood using laser cutting technology. Each part will be laser marked with its number. Again, the shape to be cut is the spar part's projection when only outer lines are taken into account as seen in fig. 3.10 where the shape to be cut is marked with green colour. The chamfers will be hand brushed after assembly. The only exception are chamfers on shorter sides where the spar parts are in contact with ribs. These chamfers have to be machined before the assembly and therefore they have to be defined.

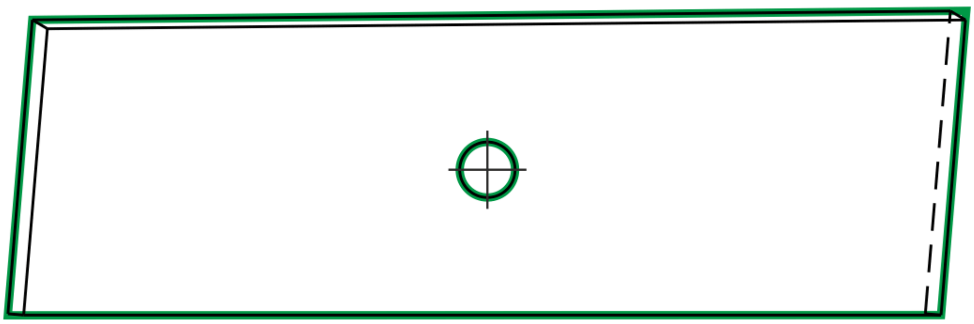


Figure 3.10: a spar part example with outer shape curve for laser cutting definition

The difference lies in plywood thickness. While on ribs **3 [mm]** plywood is used, on spar parts the thickness was increased to **6 [mm]**. The reason for this decision is the fitting installation in spar parts. They must be solid enough to withstand possible side loads applied on those fittings, for example as a result of hose deformation. If only **3 [mm]** plywood was used these loads, although not very high, could lead to spar part cracking or breaking the fitting out. Therefore the thickness was increased so that these dangers are prevented.

The hole cut in each spar part is meant for above mentioned fitting installation. As the particular fitting to be installed into the spar parts had not been selected yet when laser cutting was ordered, the holes are only **5 [mm]** in diameter serving primarily to mark the hole position. When the fitting is selected the diameter of these holes will be modified. Again, the 2D curves handed over to the manufacturer in electronic form were derived from 3D model of the spoiler. The result of the manufacturing process are semi-finished spar parts ready for further processing.

3.9 Slat parts

The slat parts, in contrast to other parts, are not laser-cut. As their cross section is constant it was decided to manufacture the slat parts simply by cutting pieces of wooden slat used for model-making. An **8x2 [mm]** slat will be purchased and pieces will be cut of it according to fig. 3.11 and tab. 3.1.

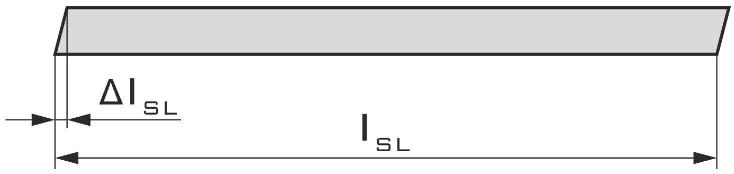


Figure 3.11: slat part dimensions

Slat part number	l_{SL}	Δl_{SL}
[-]	[mm]	[mm]
I	85.4	0.7
II	82	0.5
III	81	0.4
IV	80.6	0.3
V	80.5	0.2
VI	79	0.1

Table 3.1: slat part dimensions

It is obvious the values of Δl_{SL} are very small and the probability of keeping them perfectly is low when it comes to hand cutting. The same goes for the length and the digits after the decimal mark. Generally the effort should be made to manufacture the part rather a little longer than shorter as the length can always be reduced during edge chamfering which will be described later but if the part was too short it would be a mistake not correctable. The result of the manufacturing process are semi-finished slat parts ready for further processing.

3.10 Spar part hole re-drilling

The pneumatic connectors used will be Festo® QS-3/8-12-I. These fitting have the outer diameter **20.8 [mm]**. As discussed later, the fittings will be glued in into the holes in spar parts. Therefore some clearance has to be ensured. The required hole diameter is then **21 [mm]**. The holes will be re-drilled before assembly.

3.11 Chamfer definition

Every spar and slat part will have its shorter sides chamfered as shown in the fig. 3.12. From the figure it is obvious which edge of the part is meant to be kept and which should be machined. The angle defined in this figure is individual for each spar and slat part and the values of these angles are presented in tab. 3.2.

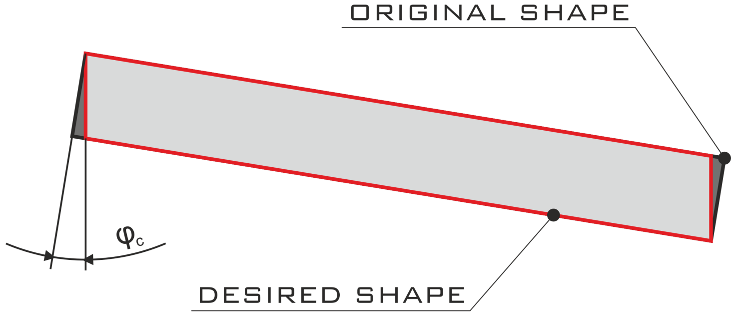


Figure 3.12: definition of chamfer angle on spar and slat parts (top view)

Spar or slat part number	φ_c for spar parts	φ_c for slat parts
[-]	[deg]	[deg]
I	13	18
II	8	10
III	5	6
IV	4	3
V	2	2
VI	1	1

Table 3.2: values of spar and slat chamfer angle

3.12 Framework assembly

For purposes of the assembly part numbers defined in fig. 3.8 are used. The most important problem is relative positioning of the parts. It is even more difficult as some part edges are to be chamfered while some should stay unaltered. Because the chamfers will be hand-brushed only after assembly, during assembly it is not obvious yet which edges will stay and which will be brushed. Without this information, however, the assembly cannot be done correctly and therefore these edges will have to be defined.

It is also important to mention that the assembly procedure including dimensions and angles comes from theoretical 3D model and describes the ideal state. It is almost impossible to keep all the dimensions and surfaces as described by hand brushing. Therefore these instructions should be considered a guide and the manufacturer should try to get as close as possible to this ideal state, but certain slight differences, inaccuracies or modifications are allowed.

The selected manufacturing technology takes these eventualities into account and allows acceptable level of shape simplification. As the shape was simplified from its theoretical shape to planar surfaces already, local inaccuracies are not expected to cause a major change of functionality. Again, the spoiler should serve as proof of concept which is a fact that defines the whole design and manufacturing approach.

3.12.1 Edge definition

Ribs

The fig. 3.13 clearly shows which edges will stay (green colour) and which will be chamfered (red colour). The circular part of each rib must be brushed as a transition as the edge layout is opposite on the upper and lower side of the rib.

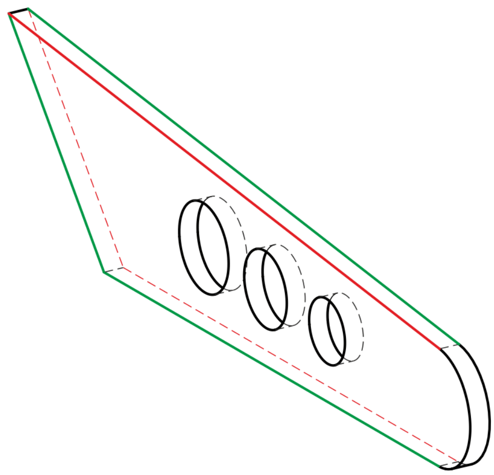


Figure 3.13: definition of edges on a rib (left-back view)

Spar parts

The edges are defined in fig. 3.14. Edges to be machined are marked with red colour, edges to be kept with green colour. The shorter edges will be already machined during assembly as described above, but for assembly purposes it is better to remind the way the machining was carried out.

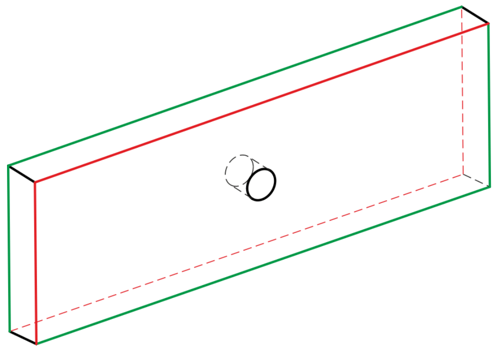


Figure 3.14: definition of edges on a spar part (left-back view)

Slat parts

The edge definition can be seen in fig. 3.15. Again, the red colour means machining while green marks an edge to be kept. The shorter edges of each slat part will be machined already during assembly, but again they are marked with corresponding colour to remind the prior machining process. This is very useful for assembly purposes.

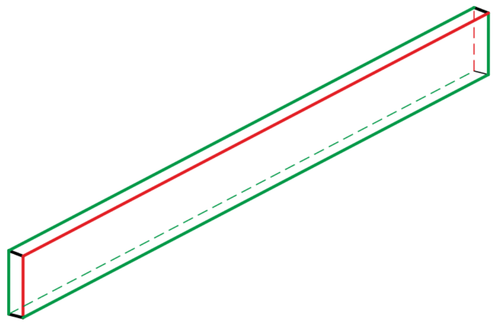


Figure 3.15: definition of edges on a slat part (left-back view)

3.12.2 Part positioning

The positioning uses above defined edges. The parts will be positioned using only edges which will be kept (marked with green colour). The assembly philosophy is obvious from fig. 3.16.

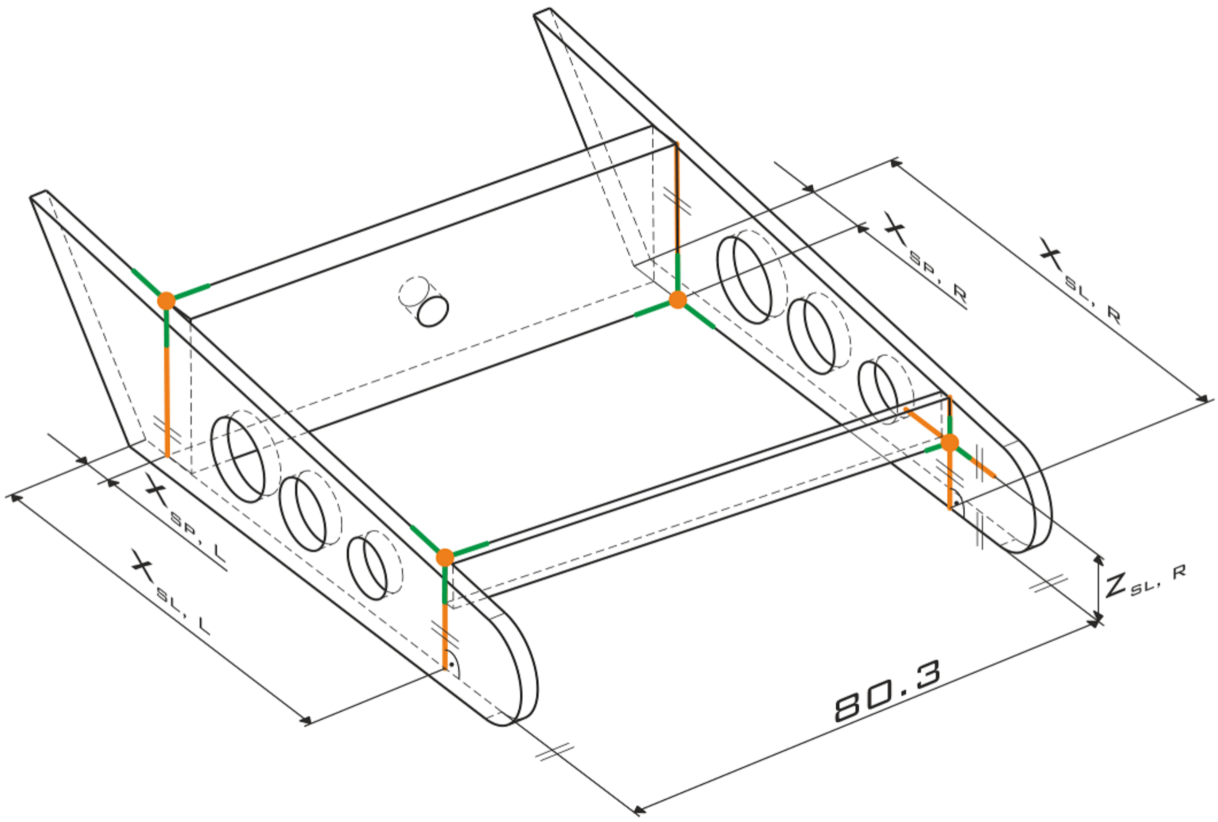


Figure 3.16: framework assembly scheme (left-back view)

Assembly process has several steps.

1. Lines are drawn on a rib. This is done according to fig. 3.16, where these lines are marked with orange colour. They are perpendicular to rib's lower edge and their distances measured from the starting point of rib's lower edge are defined in tab. 3.3. There is one more line which is parallel to rib's lower edge and its distance from it is defined it tab. 3.3 too.

2. Corresponding spar part is glued to the left rib first. The positioning is obvious from fig. 3.16. The green marked edges meet in orange marked point which defines the desired position. These edges will not be machined later.

3. The right rib is glued to created subassembly, too. Again, the positioning is done using previously drawn line and the final position is defined by orange point.

4. The slat part is positioned and glued. This is, however, done by gluing the slat between two corresponding ribs as the contact area between a rib and a slat part is too small to ensure right part direction if glued gradually as in case of spar parts so that the slat part could not meet the desired position on the other rib. The positioning is done according to fig. 3.16 again. The positioning method is the same as in case of spar parts.

Rib number	$x_{SP,L}$	$x_{SP,R}$	$x_{SL,L}$	$x_{SL,R}$	$z_{SL,R}$
[-]	[mm]	[mm]	[mm]	[mm]	[mm]
I	5.7	—	67.9	—	—
II	5.4	11.2	75.3	76.5	11.7
III	5.3	11.1	77.8	79.4	11.6
IV	5.2	11	78.4	80.2	11.6
V	5.1	11	77.4	79.3	11.6
VI	5	11	76.5	78.5	11.6
VII	—	11	—	78.1	11.6

Table 3.3: part positioning values

During gluing it is vitally important to constantly check parallelism of ribs as well as their relative distance which should be approximately **80.3 [mm]** as seen in fig. 3.16. There is, however, a different distance between ribs VI and VII. The distance between them is approximately **78.8 [mm]**.

3.13 Polystyrene blocks

3.13.1 Shape

As seen in fig. 3.8 there are three blocks per chamber marked

- A for the space between the spar and car body
- B for the space between the spar and the slat
- C for the space between the slat and trailing edge

Every block itself is a constant thickness part where the vertical edges are perpendicular to the base surface. The base surface is defined by a polygonal curve that can be seen in fig. 3.17. The values of dimensions defined in the figure are presented in tab. 3.4

It is important to note that the dimensions are approximate only as the accuracy of hand cutting the polystyrene is limited. In case a block manufactured using these dimensions

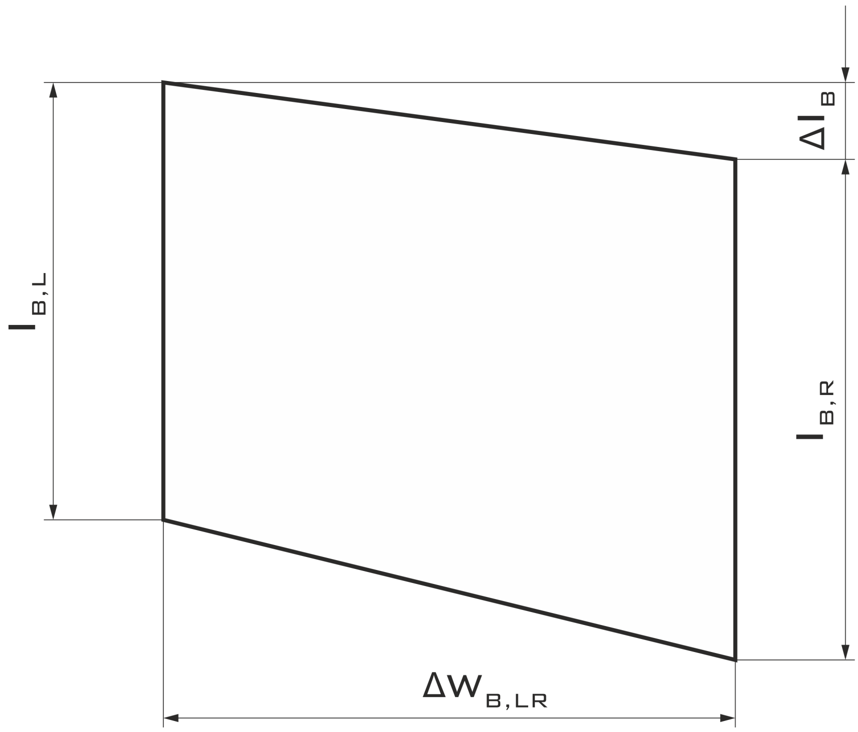


Figure 3.17: definition of polystyrene block dimensions (top view)

Block type	A					B					C				
Block number	$l_{B,L}$	$l_{B,R}$	Δl_B	$\Delta w_{B,LR}$	t_B	$l_{B,L}$	$l_{B,R}$	Δl_B	$\Delta w_{B,LR}$	t_B	$l_{B,L}$	$l_{B,R}$	Δl_B	$\Delta w_{B,LR}$	t_B
1	30	30	18	80.3	40	56	63	19	80.3	40	22	22	26	80.3	30
2	30	30	12	80.3	40	63	66	11	80.3	40	22	22	14	80.3	30
3	30	30	8	80.3	40	66	67	8	80.3	40	22	22	8	80.3	30
4	30	30	6	80.3	40	67	66	6	80.3	40	22	22	5	80.3	30
5	30	30	3	80.3	40	66	65	3	80.3	40	22	22	2	80.3	30
6	30	30	1	78.8	40	65	65	1	78.8	40	22	22	1	78.8	30

Table 3.4: block dimension values (dimensions in [mm])

does not fit between plywood parts it has to be adjusted, for example brushed. The dimensions derived from 3D model were rounded or modified in such a way the block always exceeds the plywood edges so that there is never a gap between two plywood parts but extra material that is to be brushed into final shape. The B type block, however, has its base curve dimensions rounded downwards so that the block for sure fits into its place.

3.13.2 Gluing

The polystyrene blocks are then glued into the plywood framework as shown in the fig. 3.8. They should be glued in such a manner that the polystyrene always exceeds the edges of framework. It is not necessary to apply the glue on whole surface. The glue is only meant to fix the polystyrene to the framework so it cannot move but as the block is to be corroded out later there is no need for fixing it too firmly.

This should be taken into account especially for A type blocks which will be accessible from outside after lamination. Provided the block is fixed to the framework only locally it is not necessary to corrode it out chemically as it can be broken out mechanically. Any polystyrene that would stay fixed on glue after breaking the block out can be cut or corroded.

Potential small slits between a polystyrene block and an adjacent plywood part which may appear because of polystyrene block cutting and/or plywood framework assembly inaccuracy are not a problem. During lamination such small gap is not expected to deform the skin shape as there is enough material around to support the skin. On the lower side of the spoiler there will be **2 [mm]** gap between B and C type blocks caused by s slat part. This gap could potentially influence the skin shape, but on the lower side the accuracy requirements are much lower than on the upper side and this shape deformation is not expected to affect the functionality.

3.14 Brushing

Polystyrene blocks are then brushed into planar surfaces between ribs. Whenever possible, they may be cut with hot wire using ribs as guides. The hot wire cutting should be, however, used only to get close to the final shape as the rib edges are not brushed in this phase yet and using their edges as guides does therefore not give the desired shape. When the polystyrene is brushed close to plywood parts it is necessary to brush their edges as described before. The newly created chamfers should follow the planar surface of polystyrene block as shown in fig. 3.18. The only exception is rib VII which is located in the symmetry plane of the spoiler. On this rib no edge is brushed so that this rib creates a horizontal transition between the right and left part of the spoiler.

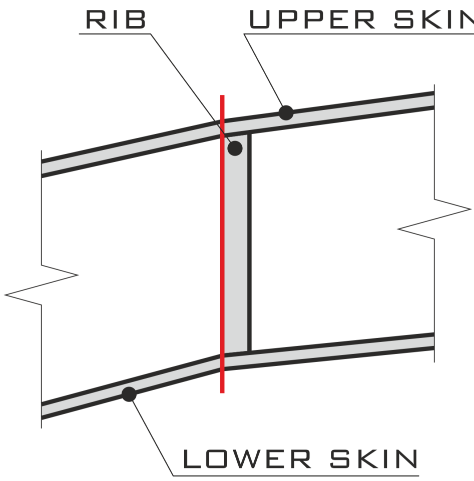


Figure 3.18: sesired shape after lamination, shape breaking on rib edge marked with red line (back view)

The brushing should start on block 6 and after this block and adjacent framework parts are brushed the manufacturer should move on to block 5 and then carry on up to block 1. Starting at block 6 simplifies following the desired shape. The procedure shown in the fig. 3.19 is the same for every block. On rib VII the edges are not brushed so they define the planar surface on the right side. On the left side the edges to be kept correspond with fig. 3.13.

After this block is brushed block V is brushed in accordance with fig. 3.19 again. On the right side no edge is brushed (these edges were brushed in the previous step) while on the left side the brushing corresponds with fig. 3.13. This method is then repeated until all the blocks are brushed.

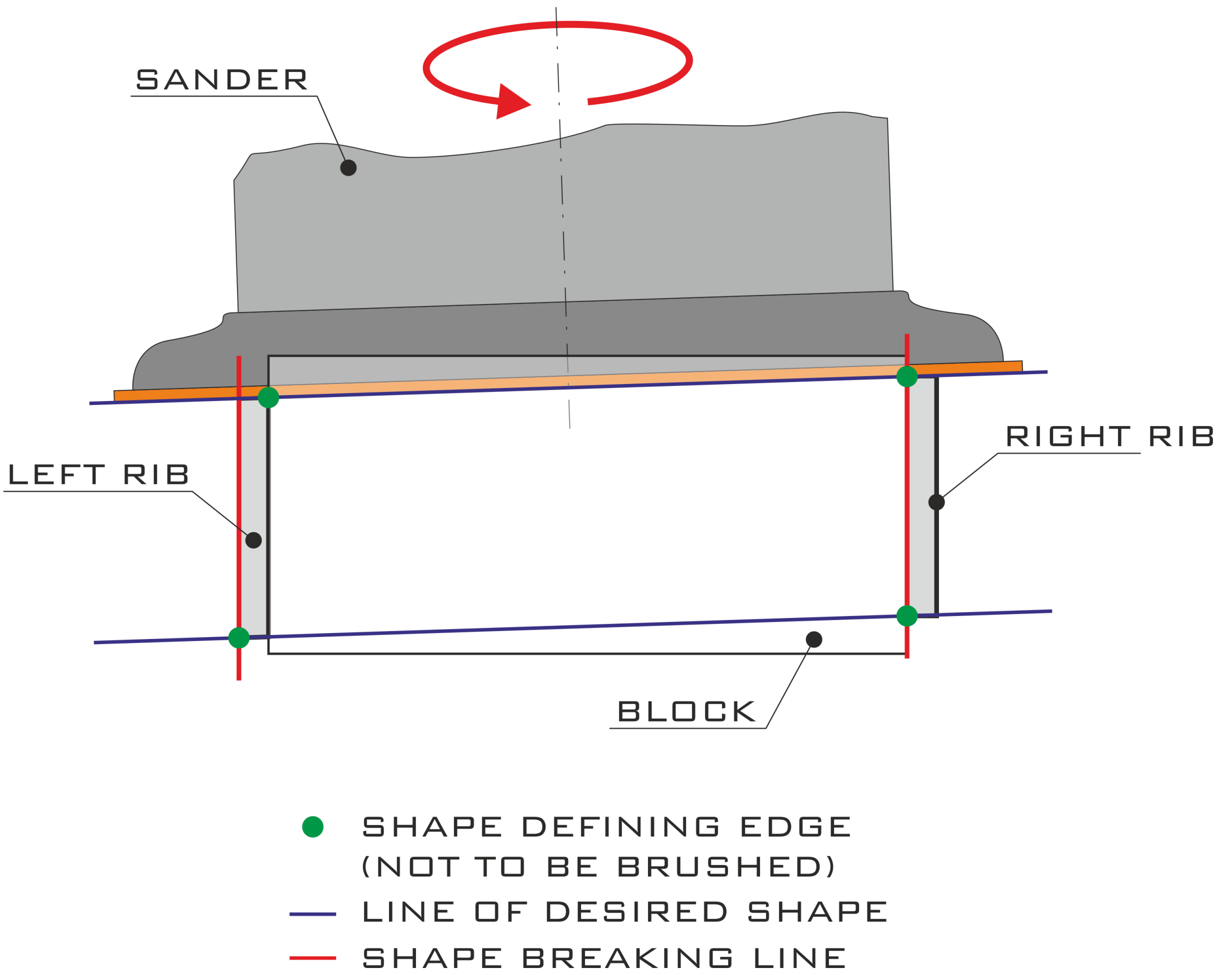


Figure 3.19: surface brushing (left side of spoiler, back view)

The described method is used to create the upper and lower surface of the spoiler. The rounded trailing edge and the oblique short edges of ribs together with corresponding polystyrene must be brushed in a different manner. The short oblique edges of ribs can be brushed freely according to fig. 3.8. Here the shape accuracy is not important.

The fillet on the trailing edge, however, requires careful model-making handwork as on the upper surface the edge to be brushed is on the opposite side of the rib than on the lower surface. The fillet is therefore made as an transition and the shape cannot be simply defined by dimensions. The accuracy therefore depends on manufacturer's carefulness and skill.

3.15 Lamination

The lamination itself is a procedure which has to be performed by qualified personnel with experience. Detailed description of lamination process is therefore not necessary. This paragraph contains basic requirements only.

For lamination glass fibre should be used as it is cheaper than carbon fibre and its higher weight does not matter in automotive application. The fibres should be laminated into the most common epoxy resin as there is no high load expected.

The orientation of fibres should cover all typical directions - **0 [deg]**, $\pm$**45 [deg]** and

90 [deg] - symmetrically if possible. The overall skin thickness is designed to be **1 [mm]** which is expected to ensure required stiffness both in torsion and bending safely. The ribs and spar parts have also been designed for this skin thickness so that the upper spoiler surface should smoothly follow the car roof after lamination.

The particular way the skin will be laminated is, however, up to the manufacturer whose experience is the most important factor. Should any of these recommendations complicate the manufacturing the manufacturer is free to decide otherwise and to adjust the lamination process to his/her needs and means available. The only reqirement which should be kept is the desired skin thickness.

3.16 Machining

After the lamination some of the features must be created, namely the slot and openings in the lower skin shown in fig. 3.20 which will allow corroding the polystyrene out. Also the skin edges on the side of car body must be machined so that they are clean and straight.

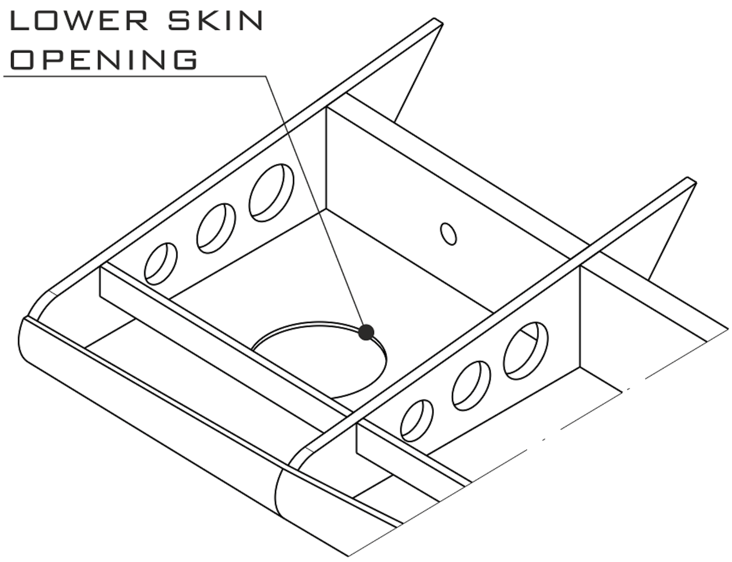


Figure 3.20: opening in the lower skin

The opening positioning does not need to be defined exactly. They should be placed approximately in the middle of each chamber and they must not interfere with the spar. The spar position, if undetectable because of skin, can be determined by corroding or breaking out the A type polystyrene blocks. The diameter of openings is **30 [mm]**.

The skin edges have to be machined using straight lines connecting rib endpoints on the upper and lower side of the spoiler.

The slot is a little more complicated as it is not possible to locate the slat under the skin. Its position has already been defined is the Framework assembly section, however, it was defined using lower rib edge which is useless in current situation when the upper skin is to be machined and the ribs are hidden under the skin. It is therefore necessary to define the slat position using the upper skin above rib edge. The skin edges have to be machined already.

The dimension is defined in fig. 3.21 while from fig. 3.22 it is obvious which rib edge is used for measuring. The values are summed up in tab. 3.5 The procedure will then have these steps which can also be seen in fig. 3.22

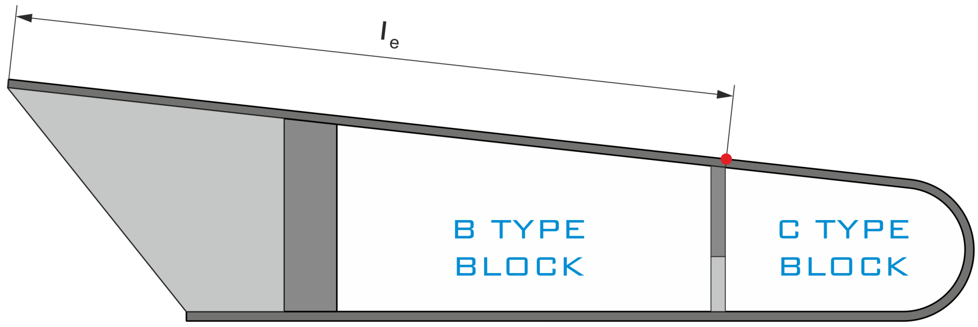


Figure 3.21: definition of slot positioning dimension (left side of spoiler, left view)

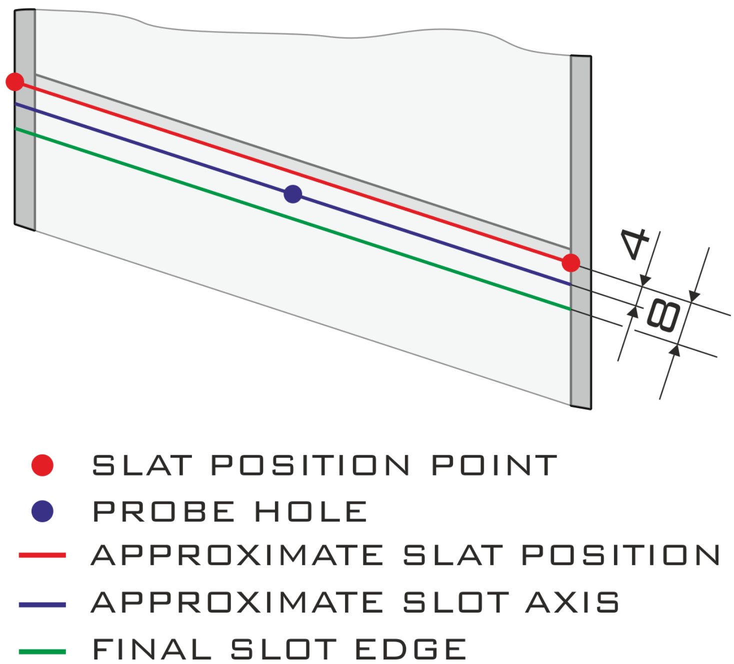


Figure 3.22: slot machining geometry (left side of spoiler, top view)

1. a point marking the position of slat edge is marked on skin on both sides of the chamber
2. a line is drawn using these two points
3. a **4 [mm]** towards the trailing edge offset line is drawn
4. on the offset line a probe hole is drilled
5. from this hole machining starts towards the slat, it must be done carefully so that the slat is not damaged
6. when the slat is all uncovered a line parallel with the slat is drawn on the skin in **8 [mm]** distance
7. the skin between ribs, the slat and the newly drawn line is cut out

Rib number	l_e
[-]	[mm]
I	93
II	102
III	105
IV	106
V	105
VI	104
VII	104

Table 3.5: approximate slat position

3.17 Corroding the polystyrene out

After machining the polystyrene must be corroded out of the spoiler. For this purpose, toluene or acetone will be used. Primarily it will be applied on the polystyrene through the machined openings on the lower side of the spoiler, but the holes in spar parts and the slot can be used as well.

Toluene is poured into the opening and when it transforms the polystyrene into pulpy matter the spoiler is turned upside down so that this matter can flow out. Also the liquid polystyrene can be taken out using a spoon-like tool. The process has to be repeated several times until the spoiler's inside is as empty as possible.

Finally the spoiler's skin is cleaned and the spoiler is ready for final assembly.

4 Hinge design

4.1 Hinge design requirements

The hinges must enable installation of the spoiler on car body. The spoiler must be attachable and detachable from the car body while the car mounted hinge parts are still attached to car body. The hinges must enable free rotation of the spoiler around rotation axis within desired range. Also the hinges must enable locking the spoiler in any position within desired range.

4.2 Overall design

The hinge consists of two major parts - the car mounted hinge part 1 and the spoiler mounted hinge part 2 - which can be seen in fig. 4.1. Both of these parts consist of two pieces which are welded together. As there are no high force expected, the material used is standard weldable steel **S235JR**.

These two major parts are joined together using special insert 3 and an M6 screw 4. This solution allows installing and removing the spoiler when the car mounted hinge parts 1 are already fastened to car body. The fastening is ensured by M5 screws which are screwed into rivet nuts installed in the car body. The spoiler mounted hinge part 2 is fastened to the outer rib using two blind EN 14588 **3.2 [mm]** rivets.

The locking system uses a cutout in the car mounted hinge part 1 and a threaded rod 5 passing through it. Using nuts 7 and 8 and washers 9 put on the threaded rod 5 the spoiler can be locked in any position within desired range.

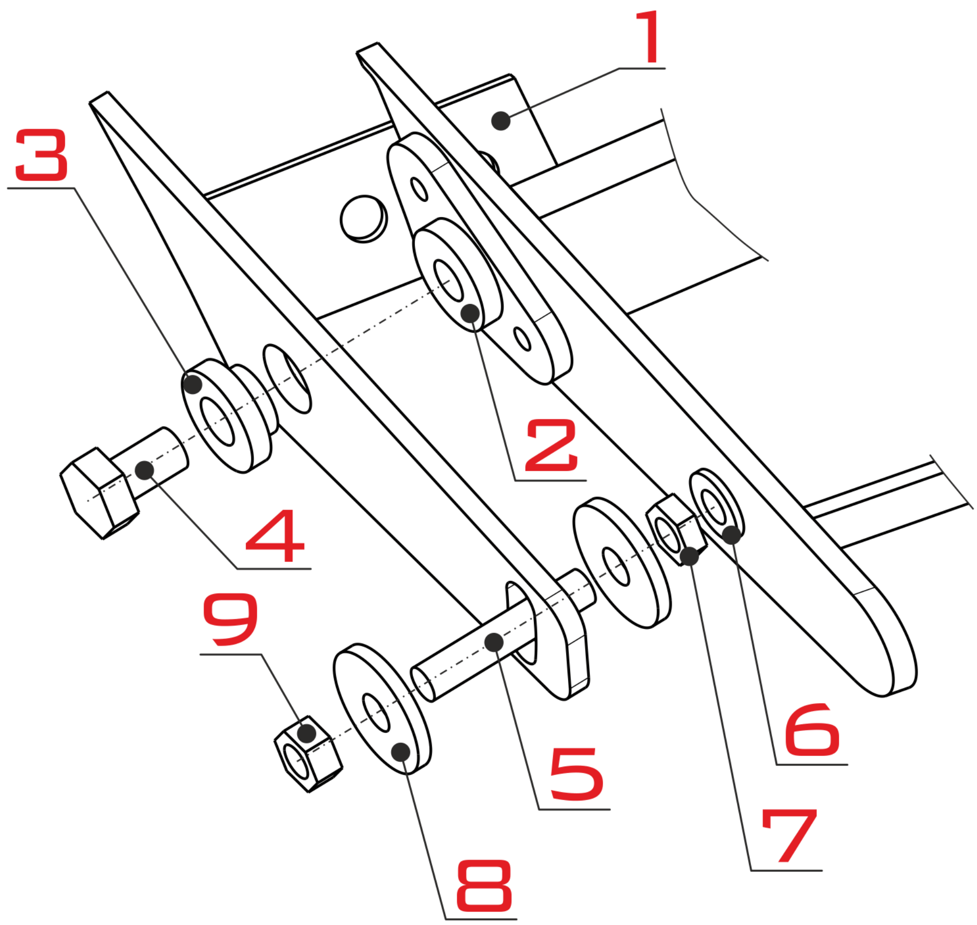


Figure 4.1: hinge assembly and part definition

4.3 Car mounted hinge part

This part is welded from two individual parts defined in fig. 4.2 by red numbers. Both of them are planar and are made of **3 [mm]** thick metal sheet. The shapes of these parts as well as the final welded product are defined in drawings which can be found as appendices of this thesis.

The shapes of these parts were derived from created 3D model and they were designed taking the proof of concept design philosophy into account. The curved shape of car body was therefore neglected on the short distance between both screws fixing the part to car body. Part 2 in which screws are installed is then designed as tangent to car body in a point which is a centre of a line connecting the centres of holes for M5 screws marked with green colour in fig. 4.3. The part's dimensions are then chosen with respect to the spoiler and its angular movement within desired range.

Part 1 touches the car body by one edge only as seen in fig. 4.3 where the edge is marked with red colour. The edge itself is not defined by intersection with car body, but consists of three linear sections. Each of them is tangent to car body so that three contact points marked with green colour in fig. 4.3 are ensured. This solution was again selected in order to simplify manufacturing.

The whole product is then in contact with car body in four points in total - three on the part 1 and one on part 2. As there are generally three points necessary to fix a body in space the position of the whole part should be ensured sufficiently. The contact is then

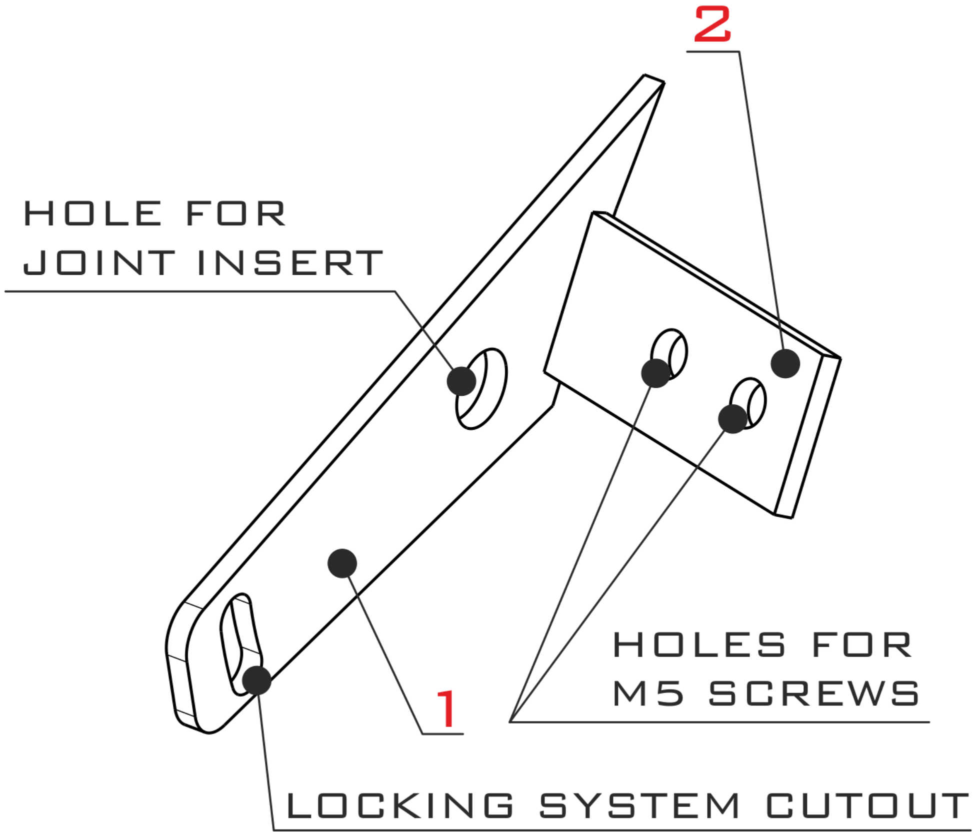


Figure 4.2: car mounted hinge part

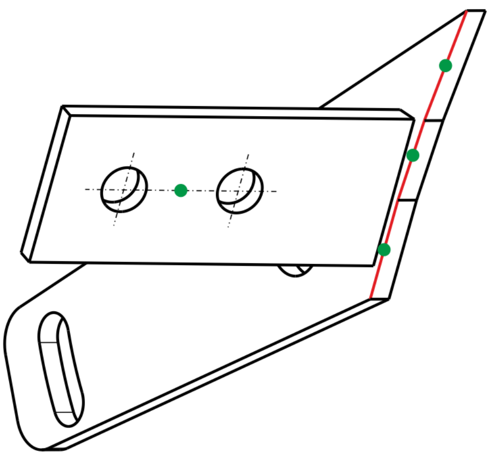


Figure 4.3: definition of contact points with car body

secured by tightening the screws.

4.4 Spoiler mounted hinge part

This part is again welded together from two individual parts as seen in fig. 4.4. Part 1 is again made of **3 [mm]** thick metal sheet, the other is, however, made by turning. An M6 inner thread is then cut inside it.

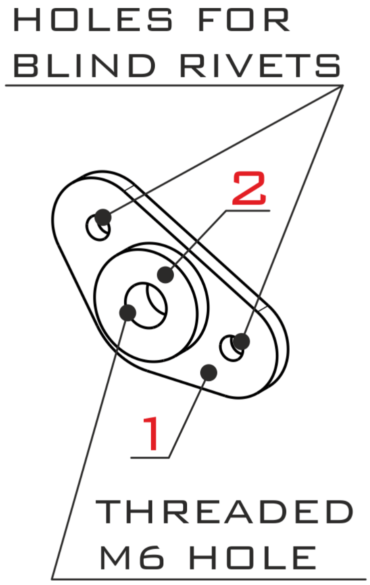


Figure 4.4: spoiler mounted part

The turned part creates a nut for a screw which holds both parts of the hinge together. It also keeps distance between car mounted hinge part and the outer spoiler rib and creates a basis on which the car mounted hinge part lays and turns. Both parts are also defined in drawings which are found in appendices.

4.5 Insert

This insert seen in fig. 4.5 is used to join the car part and the spoiler part together. This solution was selected in order to allow installing and removing the spoiler without a need to remove the car parts. The function of the insert is creating the rotation pin for the spoiler as well as disabling the axial movement of the spoiler.

The rotation pin length is **0.1 [mm]** longer that the car mounted hinge part thickness which means there is always **0.1 [mm]** clearance even when the screw is tightened so that the spoiler can rotate freely. The hole through which a screw passes has larger diameter than the screw so that there is some clearance ensured. This clearance enables moving the spoiler in all directions slightly before tightening the screw which means the compensation of eventual manufacturing or installation inaccuracies is possible. The part is defined in a drawing which can be found in appendices.

Figure 4.5: hinge insert

5 Blowing system design

5.1 Blowing system requirements

The blowing system must ensure compressed air supply at sufficient flow rate for time necessary for completing the test. This time was estimated to approximately **5 [min]**. The air supply must be continuous and smooth and must be ensured in all spoiler positions within available range. The air must not freeze in the system. The system must contain a safety valve in case a hose gets blocked. Blowing system calculation itself will be discussed later.

5.2 Overall design

The system should consist of compressed air supply, a pressure regulator to adjust pressure in the system, and air distribution system which delivers compressed air to particular chambers of the spoiler. The outlet pressure of the regulator is unknown and has to be determined. There are possibly several ways to determine the pressure.

It could be calculated using known kinetic energy factors of every component used so that minor losses could be calculated together with friction losses in piping. Using known system output pressure and the calculated pressure losses the necessary inlet pressure could be determined. The problem lays in the fact that some of the specialised components used in the design, for example multiple outlet distributors, are non-standard parts such as various elbows and therefore their kinetic energy factors are unknown.

To determine pressure losses the airstream velocity has to be known also. It is, however, dependent on the pressure regulator outlet pressure which is being sought. Also the compressibility of air complicates the calculation even further as with decreasing pressure the volume increases and velocity grows. In other words, there are too many unknown values in this phase and described method is therefore not suitable.

Another option could be CFD simulation. However, as discussed above in case of aerodynamic forces, CFD simulation is not suitable for the proof of concept phase due to its complexity and time necessary.

The simplest option is taking advantage of previous research, using its results as primary estimation and determining the desired value experimentally. Generally speaking the system will be designed to withstand the pressure based on results of previous research and after assembly the desired pressure will be tuned. This will be done using Pitot-static probe installed into airstream flowing out of spoiler's slot measuring the blowing velocity. As the desired velocity is known the outlet pressure will be adjusted using pressure regulator until the velocity is reached.

The previous research apart from others dealt with the matter of so called self-blowing. The concept used the aerodynamic compression in stagnation point on the front part of car body as compressed air supply. There was a tapered intake placed in the stagnation point connected to a pipe. The pipe transported the air into a chamber from which it was delivered into particular spoiler parts. The system together with absolute pressure in different parts of the system is shown in fig. 5.1.

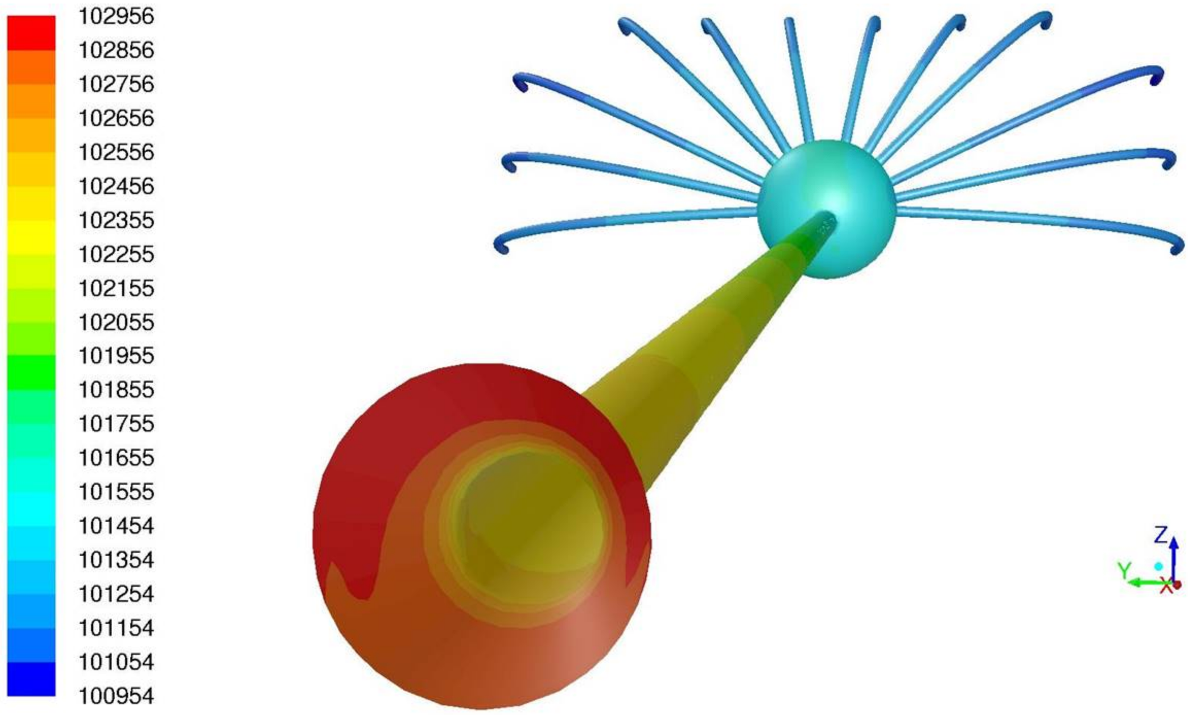


Figure 5.1: self-blowing system and absolute pressures reached in particular parts of the system [Pa] [1]

The highest pressure in the system is **102956 [Pa]** which is approximately **1.03 [bar]**. There are of course some differences, for example the blowing and freestream velocities are different as well as the system structure, but as the device has the same purpose and basically works the same way, this value can be used to estimate the initial estimation for the design. In order to compensate possible differences the value was increased to

$$\mathbf{p_b = 2 \quad [bar]}$$

This value will be used as initial for pneumatic system component selection, however, an effort will be made to select components able to withstand significantly higher pressures so that there is reserve available as the system may require higher pressure than estimated.

5.2.1 Air supply

As the system will be carried on board of a car, the compressed air supply must be transportable. If the concept proved its functionality and such a spoiler became a part of mass-production based car, the air supply would probably be a compressor powered by car engine.

Such solution, however, cannot be used in proof of concept phase. Powering a compressor using car engine would require major construction intervention into engine which is complicated, expensive and therefore unsuitable. A cheaper and simpler solution must be adopted.

Another option is to store necessary amount of air on board using pressure cylinders. This would not require any major intervention into car's systems or body and it would be also cheaper compared to purchasing a compressor. This option was therefore selected as most suitable for proof of concept phase.

5.2.2 Air distribution

The air must be split equally and delivered to each chamber. This will be ensured by a system of hoses and fittings connecting the air supply and the spoiler. Any pressure or volume flow rate differences between particular air paths which might appear due to imperfect flow splitting in junction points should be eliminated thanks to holes in ribs dividing chambers.

Generally an effort should be made to use as high hose diameter as possible so that with same volume flow rate the flow speed is as low as possible. This precaution will lower the risk of freezing and also pressure losses in the system.

In order to reduce costs and increase simplicity of assembly or later modification it was decided to use push-in type fittings. A system based on classic threaded fittings requires threaded counterparts in both ends of every hose used - that means two new parts per hose and more complicated assembly. In contrast the push-in system only requires the hose to be cut precisely perpendicularly. The hose end is then pushed into the fitting which locks it effectively.

5.2.3 Pneumatic fittings system supplier

There are several manufacturers in the market who produce push-in pneumatic fittings such as Parker [8], Festo [9] or Schwer [10]. As all of these suppliers offer similar and comparable solutions the selection of particular supplier should not affect the system functionality and any of above listed suppliers can therefore be selected.

For positive experience from previous cooperation with IAE Festo was chosen as supplier and all pneumatic elements have been selected from their supply.

5.3 Calculation

In order to design the blowing system its parameters have to be determined. The most important parameter is desired volume flow rate. It will be determined using slot area and desired blowing velocity, however, the velocity itself will have to be calculated. The above mentioned value **5 [m/s]** determined during previous research cannot be used as it is related to 1:4 scale model.

5.3.1 Blowing velocity

To determine the blowing velocity for Škoda Roomster a similarity calculation has to be performed using a formula which was obtained from previous research done by BUT:

$$c_b = \frac{A_S \cdot {v_b}^2}{A_F \cdot {v_f}^2}$$

It calculates so called blowing coefficient, which is calculated for the scale model. To ensure same conditions the blowing coefficient must be the same for the real car. Using calculated value desired blowing velocity is calculated. Necessary parameters for both the model and Škoda Roomster are summed up in tab. 5.1.

Parameter	Unit	1:4 Volkswagen UP! model	Škoda Roomster
A_F	m^2	0.129	2.28
A_S	m^2	$4.97 \cdot 10^{-4}$	$7.79 \cdot 10^{-3}$
v_f	[m/s]	50	27.78
v_b	[m/s]	5	to be calculated

Table 5.1: 1:4 scale model and Škoda Roomster parameters [1]

Using the calculated blowing coefficient value and the values from tab. 5.1 the blowing velocity for Škoda Roomster can be isolated from the formula and reckoned:

$$\mathbf{v_b \doteq 4,17 \quad [m/s]}$$

5.3.2 Volume flow rate

The volume flow rate through the slot (where atmospheric pressure is expected) will be calculated using basic formula

$$Q = \frac{V}{t} \quad [m^3/s]$$

Provided

$$V = A \cdot l$$

the formula can be transcribed into form

$$Q = \frac{A \cdot l}{t}$$

If

$$v = \frac{l}{t} \quad [m/s]$$

then

$$Q = A \cdot v$$

In this case $v \equiv v_b$ and $A \equiv A_S$. Then

$$Q = A_S \cdot v_b \quad [m^3/s]$$

Using values for Škoda Roomster taken from tab. 5.1 and the above calculated blowing speed the volume flow rate is

$$\mathbf{Q \doteq 0.0325 \quad [m^3/s] \doteq 32.5 \quad [l/s]}$$

5.3.3 Compressed air total volume

Knowing the volume flow rate and required blowing time total compressed air volume can be calculated. The blowing time is the time necessary for one test ride which was estimated to be

$$\mathbf{t_b \doteq 5 \quad [min]}$$

Total air volume is generally calculated using formula

$$V = Q \cdot t \quad [m^3]$$

In this case

$$V_t = Q \cdot t_b \quad [m^3]$$

Using known and calculated values a result is obtained

$$\mathbf{V_t \doteq 9.752 \quad [m^3] = 9752 \quad [l]}$$

It is obvious this enormous amount of air cannot be stored unless compressed. The generally available cylinders designated for compressed air are typically pressurised to pressure [3], [4], [5], [6]

$$p_c = 200 \quad [bar]$$

With this pressure the desired volume of cylinder is

$$V_c = \frac{V_t}{p_c} = 48,76 \quad [l]$$

As there are **50 [l]** cylinders for compressed air generally available [3], [4], [5], [6] the suggested solution should be feasible.

5.4 Component selection

5.4.1 Fittings

There are several ways of organising the air supply system. After analysing Festo catalogue four possible variants were put together. The variants are compared mutually from various points of view. On of the most important is the price. As the component prices are not publicly available information they are considered a business secret and cannot be presented here. Therefore the most expensive variant has been selected as a reference value and all other prices are expressed in per cents of this value.

As mentioned above, the effort was made to keep the inner diameter of hoses and fittings as high as possible. The limiting element is the pressure regulator output thread. Pressure regulators usable for compressed air use G1/4" outer thread [7] (as GCE is a dominant supplier on the market and their pressure regulators are manufactured in accordance with EN ISO 2503 one citation in this case is considered to be sufficient). Therefore the air supply system connected to the regulator must start with a fitting with corresponding thread.

All variants start with an adaptor with G1/4" internal thread on one side which is mounted on the pressure regulator, and G3/8" inner thread on the other side. This solution allows use of higher diameter fittings than those with 1/4" thread which would be mounted straight on the regulator. All variants also use Y-shaped fitting after the adaptor which splits the airstream to halves.

Variant 1A

This variant seen in the fig. 5.2 aims to build the system using simple components such as Y a T shaped fittings. The advantage lies in smooth airstream splitting thanks to use of Y shaped fittings. The disadvantage, on the other hand, is higher number of components used which implicates higher number of joints to be sealed where there is a danger of leakage and the fittings in series also require more space. The parameters of particular components can be seen in tab. 5.2.

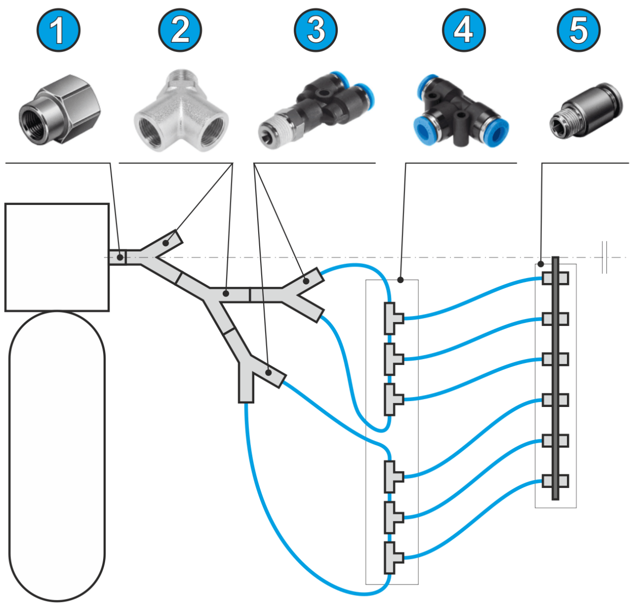


Figure 5.2: variant 1A (component pictures taken from Festo catalogue [11])

Position	Component	Component number	Price per unit [%]	Number [-]	Price [%]	Input	Output
1	Adaptor	QMR-3/8-1/4-B	1.74	1	1.74	G1/4" inner thread	G3/8" inner thread
2	Y fitting	NPFC-Y-R38-2G38-MFF	1.74	3	5.22	R3/8" outer thread	2 x G3/8" inner thread
3	Y fitting	QSY-3/8-12	5.49	4	21.96	R3/8" outer thread	push-in 12 mm
4	T fitting	QST-12	3.90	12	46.80	push-in 12 mm	push-in 12 mm
5	straight fitting	QS-3/8-12-I	2.04	12	24.48	push-in 12 mm	R3/8" outer thread
				Σ	100		

Table 5.2: parameters and price estimation of variant 1A (prices in % of variant 1A total price) [11]

Variant 1B

This variant seen in the fig. 5.3 is almost identical with variant 1A. The difference lies in replacing two Y-shaped fittings with one 4 outlet distributor. This solution lowers complexity, space demands, number of sealed joints and number of parts. The price is also lower which can be seen in tab. 5.2. On the other hand the airstream splitting may not be that smooth compared to variant 1A because of the fact the distributor is L-shaped.

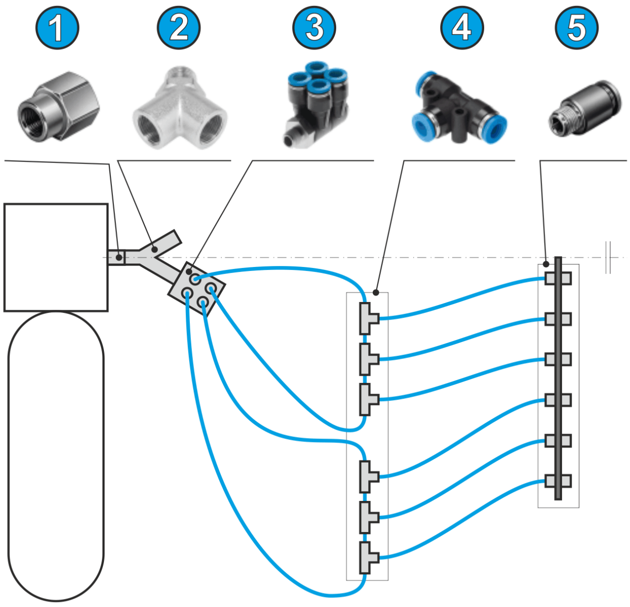


Figure 5.3: variant 1B (component pictures taken from Festo catalogue [11])

Position	Component	Component number	Price per unit [%]	Number [-]	Price %]	Input	Output
1	Adaptor	QMR-3/8-1/4-B	1.74	1	1.74	G1/4" inner thread	G3/8" inner thread
2	Y fitting	NPFC-Y-R38-2G38-MFF	1.74	1	1.74	R3/8" outer thread	2 x G3/8" inner thread
3	4 outlet distributor	QSLV4-3/8-12	8.02	2	16.04	R3/8" outer thread	push-in 12 mm
4	T fitting	QST-12	3.9	12	46.8	push-in 12 mm	push-in 12 mm
5	straight fitting	QS-3/8-12-I	2.04	12	24.48	push-in 12 mm	R3/8" outer thread
				Σ	90.8		

Table 5.3: parameters and price estimation of variant 1B (prices in % of variant 1A total price) [11]

Variant 2A

This variant seen in the fig. 5.4 follows the same philosophy as variant 1A but replaces three T-shaped fittings with one 2 inlet and 3 outlet distributor. Again, it lowers cots, complexity, number of parts and sealed joints. There is, however, one disadvantage. The highest input diameter this distributor is available with is **10 [mm]** and the output diameter related to this input is **8 [mm]** [11]. This means the diameter of hoses is limited from Y-fittings further on which increases airstream velocity. The parameters and price estimation of this variant can be seen in tab. 5.4.

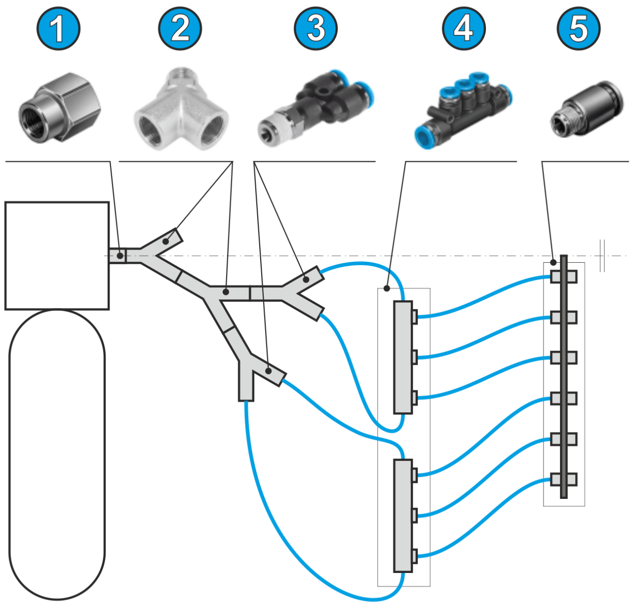


Figure 5.4: variant 2A (component pictures taken from Festo catalogue [11])

Position	Component	Component number	Price per unit [%]	Number [-]	Price [%]	Input	Output
1	Adaptor	QMR-3/8-1/4-B	1.74	1	1.74	G1/4" inner thread	G3/8" inner thread
2	Y fitting	NPFC-Y-R38-2G38-MFF	1.74	3	5.22	R3/8" outer thread	2 x G3/8" inner thread
3	Y fitting	QSY-3/8-10	5.26	4	21.04	R3/8" outer thread	push-in 10 mm
4	3 outlet distributor	QST3-10-8	5.48	4	21.92	push-in 10 mm	push-in 8 mm
5	straight fitting	QS-1/4-8-I	1.20	12	14.4	push-in 8 mm	R1/4" outer thread
				Σ	64.32		

Table 5.4: parameters and price estimation of variant 2A (prices in % of variant 1A total price) [11]

Variant 2B

The difference between this variant and the variant 2A is the same as between 1A and 1B. Two Y-shaped fittings were replaced by one 4 outlet distributor. The advantages and disadvantages of such arrangement are obvious from above described variants and therefore are not described here. The variant can be seen in fig. 5.5 while its parameters and price in tab. 5.5.

Position	Component	Component number	Price per unit [%]	Number [-]	Price [%]	Input	Output
1	Adaptor	QMR-3/8-1/4-B	1.74	1	1.74	G1/4" inner thread	G3/8" inner thread
2	Y fitting	NPFC-Y-R38-2G38-MFF	1.74	1	1.74	R3/8" outer thread	2 x G3/8" inner thread
3	4 outlet distributor	QSLV4-3/8-10	7.77	2	15.54	R3/8" outer thread	push-in 10 mm
4	3 outlet distributor	QST3-10-8	5.48	4	21.92	push-in 10 mm	push-in 8 mm
5	straight fitting	QS-1/4-8-I	1.20	12	14.4	push-in 8 mm	R1/4" outer thread
				Σ	55.34		

Table 5.5: parameters and price estimation of variant 2B (prices in % of variant 1A total price) [11]

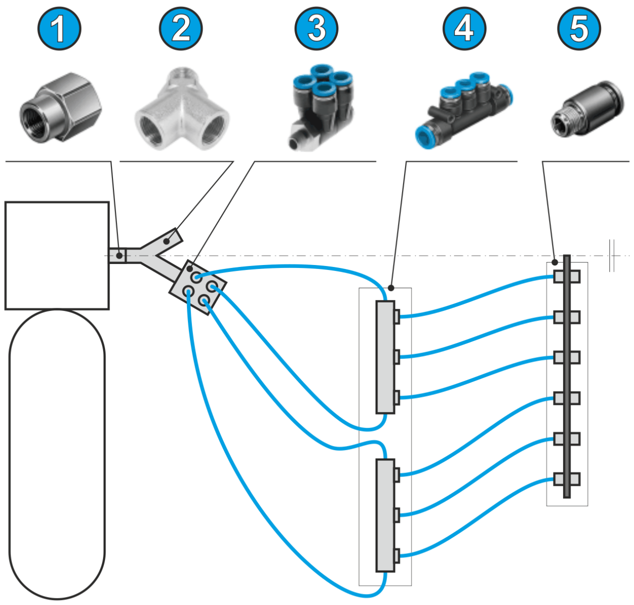


Figure 5.5: variant 2B (component pictures taken from Festo catalogue [11])

Variant 3

This variant shown in fig. 5.6 abandons the idea of feeding a group of chambers from two sides. The air is split in a 3 outlet distributor close to air supply and each chamber is then connected to this fitting by a hose. This solution brings lower number of components and is generally simpler compared to variants 1 and 2. There is, however, a risk the air will not be distributed equally which is something the previous variants tried to solve by feeding a group of three chambers from two sides. The parameters and price estimation of this variant are presented in tab. 5.6.

Position	Component	Component number	Price per unit [%]	Number [-]	Price [%]	Input	Output
1	Adaptor	QMR-3/8-1/4-B	1.74	1	1.74	G1/4" inner thread	G3/8" inner thread
2	Y fitting	NPFC-Y-R38-2G38-MFF	1.74	3	5.22	R3/8" outer thread	2 x G3/8" inner thread
3	3 outlet distributor	QSLV3-3/8-12	9.77	4	39.08	R3/8" outer thread	push-in 12 mm
5	straight fitting	QS-3/8-12-I	2.04	12	24.48	push-in 12 mm	R3/8" outer thread
				Σ	70.52		

Table 5.6: parameters and price estimation of variant 3 (prices in % of variant 1A total price) [11]

Variant 4

This variant shown in the fig. 5.7 represents the simplest solution from number of parts, sealed joints and space demands point of view. The air is split by an Y-shaped fitting just after the supply and then straight in a 6 outlet distributor. The distributor is expected to behave more like a pressure chamber than piping and the problem with high airstream velocity before splitting should be then eliminated. The disadvantage may be the L-shape of the distributor meaning higher minor losses as well as possible unequal air splitting in the distributor. On the other hand, the later should be overcome by allowing pressure equalisation between particular spoiler chambers. The parameters and price estimation are shown in tab. 5.7.

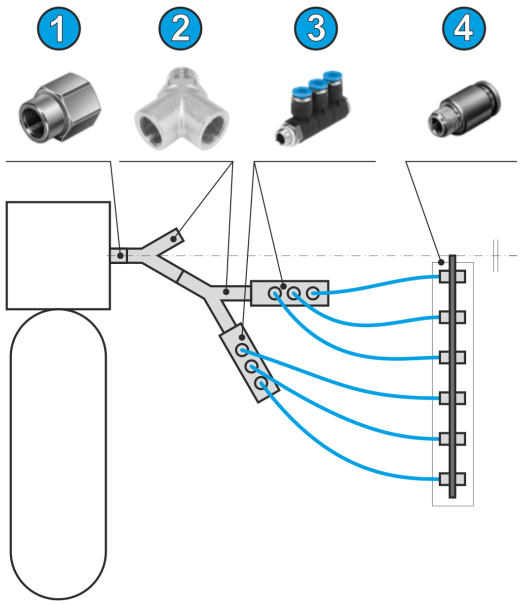


Figure 5.6: variant 3 (component pictures taken from Festo catalogue [11])

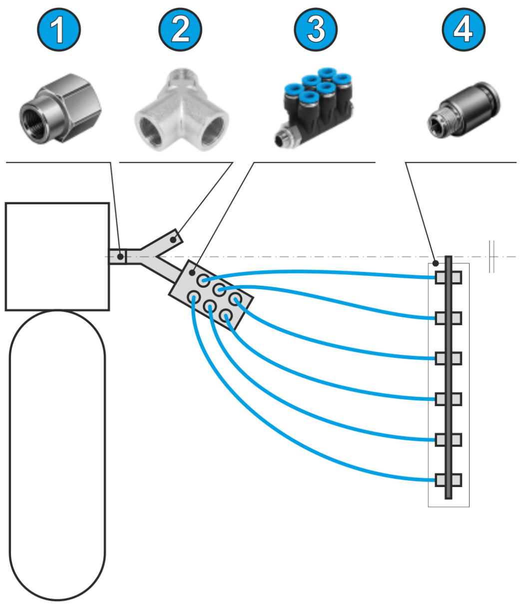


Figure 5.7: variant 4 (component pictures taken from Festo catalogue [11]

Position	Component	Component number	Price per unit [%]	Number [-]	Price [%]	Input	Output
1	Adaptor	QMR-3/8-1/4-B	1.74	1	1.74	G1/4" inner thread	G3/8" inner thread
2	Y fitting	NPFC-Y-R38-2G38-MFF	1.74	1	1.74	R3/8" outer thread	2 x G3/8" inner thread
3	6 outlet distributor	QSLV6-3/8-12	12.47	2	24.94	R3/8" outer thread	push-in 12 mm
5	straight fitting	QS-3/8-12-I	2.04	12	24.48	push-in 12 mm	R3/8" outer thread
				Σ	52.9		

Table 5.7: parameters and price estimation of variant 4 (prices in % of variant 1A total price) [11]

5.4.2 Hoses

Thanks to selected variant **12 [mm]** hoses can be used for this purpose Festo PUN hose was selected. It is the most common Festo hose which can be used up to **10 [bar]** [12] which is sufficient for intended purpose as the pressure in hoses is expected to be much lower than before the distributors due to major pressure loss on distributors. **16 [m]** of the hose were ordered together with fittings.

5.4.3 Pressure cylinders and pressure regulators

As stated above, at least **50 [l]** of **200 [bar]** compressed air are required. Under these circumstances one pressure cylinder should be sufficient. There is, however, another requirement represented by necessary volume flow rate. As stated above, approximately **32.5 [l/s]** must be delivered. So the suitability of air supply is not only a matter of sufficient cylinder volume but also a matter of pressure regulator's ability to deliver such amount of air per second.

The desired volume flow rate has, however, been calculated for the spoiler output slot where almost atmospheric pressure is expected. As gases are compressible the higher the pressure the lower the volume is provided the temperature stays the same. Therefore the volume flow rate from the pressure regulator is expected to be lower as the output pressure is higher than atmospheric. However, the regulator outlet pressure is still unknown as it will be determined experimentally which means the pressure regulator cannot be selected using exact volume flow rate value.

To make sure the selected pressure regulator reliably meets the requirements it must be oversized. There are generally three types of **200 [bar]** cylinder pressure regulators for compressed air presented in tab. 5.8.

Type [-]	Outlet pressure [bar]	Volume flow rate [m^3/h]
1	10	30
2	20	60
3	30	100

Table 5.8: parameters of 200 [bar] compressed air pressure regulators [13]

As the outlet pressure is unknown and can be determined only after the components are purchased it must be assumed to be as high as possible. The last one is not likely to be used. The fittings right behind the pressure regulator are all metal design suitable for pressures up to **50 [bar]** [11] which would be sufficient, however, the 6 outlet distributors are designed for maximum pressure **14 [bar]** only [11]. There will probably be some pressure loss between the regulator and the 6 outlet distributor, however, its value is also unknown. Therefore the pressure between the regulator and the 6 outlet distributor is considered to be approximately the same. If the regulator type 3 was used it would have to be set to **14 [bar]** only with lower flow rate which makes it uselessly powerful as only about a third of its capacity would be used. It could be then replaced by type 2 which can be set to **14 [bar]** also while using its capacity more effectively. Type 1 is not suitable either as it offers the maximum outlet pressure **10 [bar]**. It means it would not allow increasing the outlet pressure up to the value set by fittings in case the outlet pressure up to **10 [bar]** proved insufficient for achieving the desired blowing velocity.

On basis of above mentioned reasons pressure regulator type 2 was selected. A pressure regulator meeting these requirements is manufactured for instance by GCE company. The regulator is seen in fig. 5.8 while its parameters are presented in tab. 5.9.

Figure 5.8: GCE pressure regulator [©GCE Group. Available at: http://czech.gcegroup.com/products/dincontrol-vzduch]

Type	[-]	GCE 0780629
Fluid	[-]	air
Inlet pressure	[bar]	200
Outlet pressure	[bar]	20
Volume flow rate	[m^3/h]	60
Inlet connection	[-]	G5/8" outer thread
Outlet connection	[-]	G1/4" inner thread

Table 5.9: parameters of selected pressure regulator [13]

5.5 System testing

After selecting the components the system had to be tested in order to validate the basic concept or propose modifications in case its performance does not meet the requirements. As the spoiler has not been manufactured yet in the moment of testing the previously proposed test could not have been performed. Therefore an alternative solution had to be found.

5.5.1 Test layout

The major output of testing is the information whether the system is able to deliver the air at desired volume flow rate. An alternative to actual spoiler is piping with the same cross sectional area as the slot area.

For this purpose classic KG sewerage pipe was used. The pipe will have one end free while there will be a normalised stopper installed in the other end. The stopper will hold all the hoses meant to be installed in the spar parts on the final spoiler. The hoses will be distributed in the stopper regularly so that the airstream field inside the pipe is as homogenous as possible. It is expected the individual airstreams coming from individual fittings will mix together into one continuous airstream coming out of the pipe reliably if the pipe length is **1 [m]**. The expected velocity profile is a typical profile of turbulent flow.

Parallel to pipe's axis at the pipe's open end a pitot-static probe will be installed. This probe will be mounted on traversing device able to move the probe in two perpendicular directions in a plane perpendicular to pipe's axis. This probe will be used to measure the velocity across the pipe's cross section. The test layout is obvious from fig. 5.9.

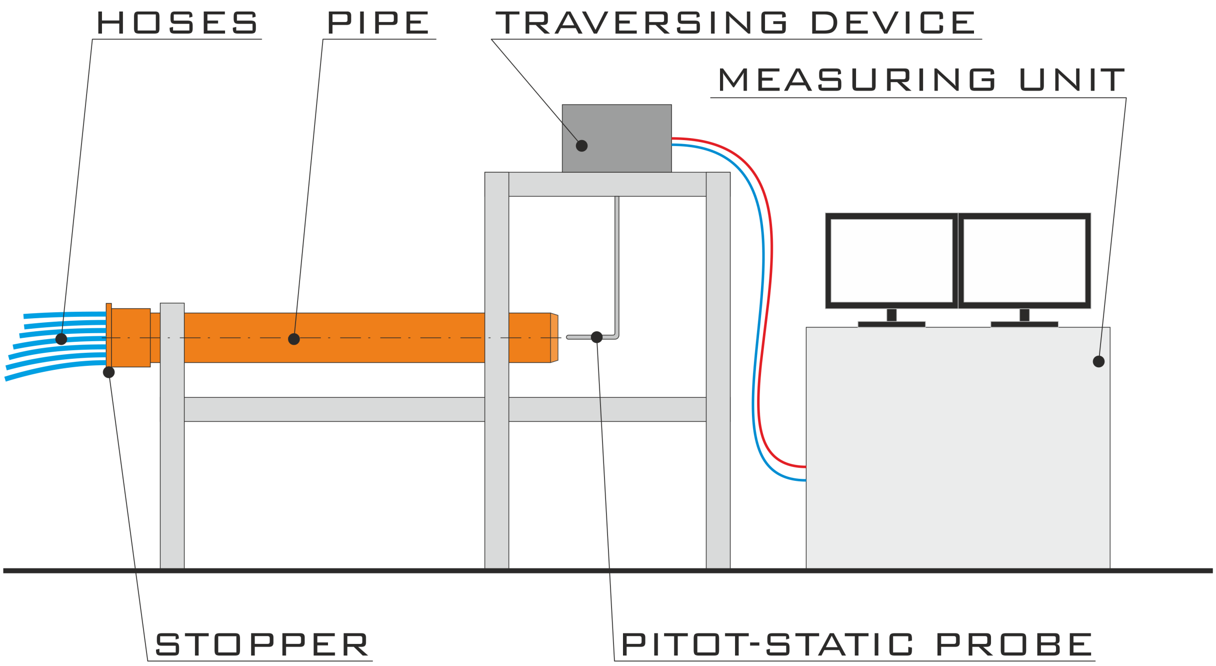


Figure 5.9: test layout

5.5.2 Pipe diameter

The diameter of pipe used will be calculated easily from the slot area. If generally the area of circle is calculated as

$$A = \frac{\pi d^2}{4}$$

then

$$d = \sqrt{\frac{4A}{\pi}}$$

Using the slot area value taken from tab. 5.1 a result is obtained:

$$\mathbf{d_p \doteq 99.61 \quad [mm]}$$

This value fits almost exactly the DN100 normalised pipe which was therefore selected.

5.5.3 Test preparation

First the delivered hose was cut to **1 [m]** long pieces which is the length estimated for the real system. Then 12 **12 [mm]** holes were drilled through the stopper in accordance with fig. 5.10.

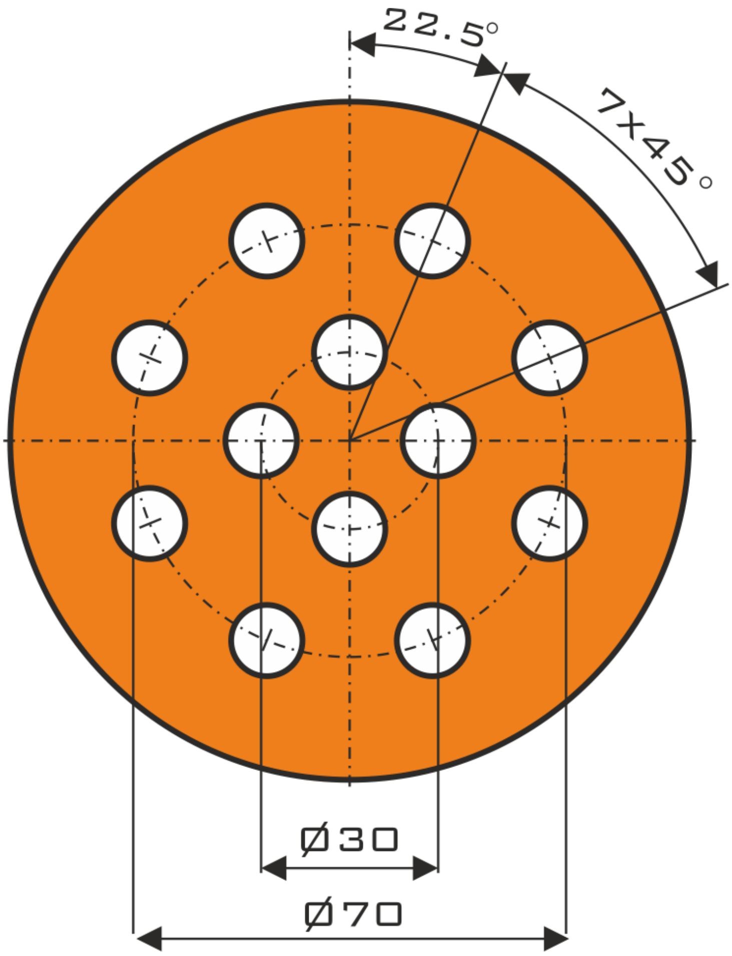


Figure 5.10: the hole distribution in stopper

After drilling the blowing system presented in fig. 5.7 was assembled. The parallel threaded connection between the pressure regulator and the adaptor fitting was sealed by a thicker layer of PTFE tape. The rest of the fittings use the combination of tapered and parallel thread which ensures the joint sealing.

The pipe was then fixed relative to the pitot-static probe as required using a spirit level and a laser levelling device as sen in appendix.

5.5.4 Testing

Two major test were carried out. As the time for testing using pressure cylinders is short it was decided to measure the velocity profile from the pipe axis to its edge only and determine the volume flow rate using numerical integration. This can, however, be done only provided the flow is rotationally symmetrical. A test proving or disproving this condition had to be performed first.

Test 1

During this test a complete grid was measured. The pitot-static probe measured points in a range from **-50 [mm]** to **50 [mm]** in both directions with **10 [mm]** step. After moving to a new position and stabilisation the measuring lasted **3 [s]**. The grid can be seen in fig. 5.11. In the figure the dark blue line indicates the movement of the pitot-static probe through the grid while the green line shows the pipe diameter.

As this test requires longer blowing time than can be assured by pressure cylinder, different solution had to be chosen. The IAE testing facility is equipped with central compressed air distribution system which does not limit the experiment time. This system can, however, deliver the air at constant pressure about **7 [bar]** only.

The impossibility of pressure regulation implicates the impossibility of using this compressed air supply for searching the optimal pressure, but it can be used to verify the velocity profile in piping so that the measuring with the cylinder would not require measuring the full grid but profile from pipe axis to its edge only.

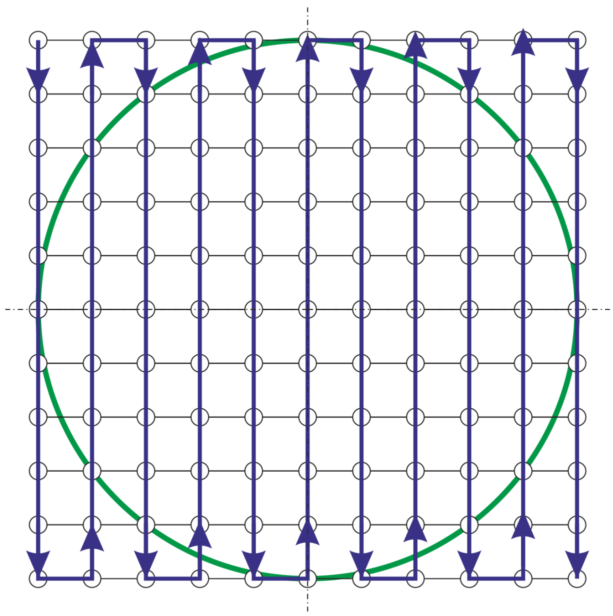


Figure 5.11: the grid for velocity profile validation test

The system presented in fig. 5.7 was removed from the pressure regulator and connected to the compressed air distribution system hose as seen in appendix. The above described measuring was then carried out. The log from measuring can be found in appendix. The data were analysed and figures were generated using MatLab software. The results are presented in fig. 5.12 and fig. 5.13.

From fig. 5.12 it is obvious the velocity is almost constant across the pipe diameter and descends close to pipe walls. The velocity profile is not perfectly rotationally symmetrical

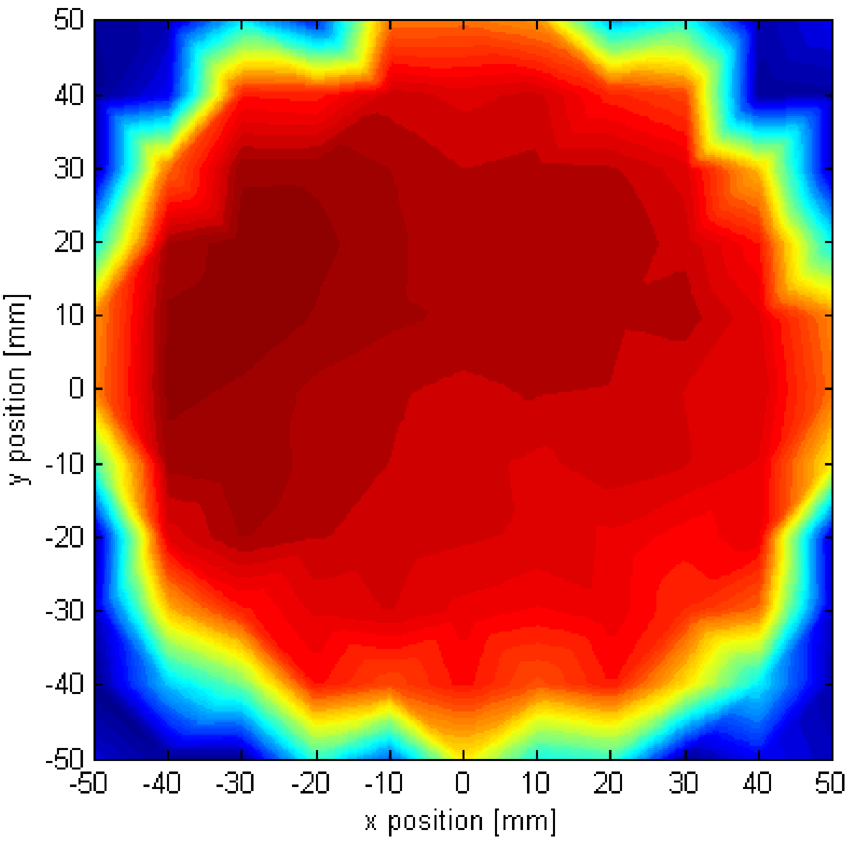


Figure 5.12: 2D velocity profile visualisation

which is probably caused by imperfect hose positioning in the stopper but the difference is rather minor and for purposes of this test is not significant.

Almost constant velocity is typical for turbulent flow [14]. The velocity profile is more obvious when shown in 3D in fig. 5.13. The profile follows the typical turbulent flow profile presented in [14]. Therefore it is possible to state the flow in pipe is turbulent and homogenous. The test therefore proved the prerequisite for the main test.

Test 2

Because the previous test was done using central compressed air delivery system which can deliver constant pressure air only the blowing velocity was also constant and it was lower than required - less than **4 [m/s]**. Therefore during testing with pressure cylinder higher pressure had to be set.

As the turbulent flow velocity is almost constant across the diameter and the constant value equals the maximum velocity the pressure was tuned measuring the velocity in the pipe axis only. It was found out the desired velocity **4.2 [m/s]** was reached with pressure regulator outlet pressure between **8** and **9 [bar]**.

To make sure the system performance is sufficient it was decided to test the device even with higher pressure setting to prove the system is capable of higher performance. If the system can deliver higher volume flow rate than required it means it meets the requirements reliably. The pressure for the main test was therefore set to **10 [bar]**.

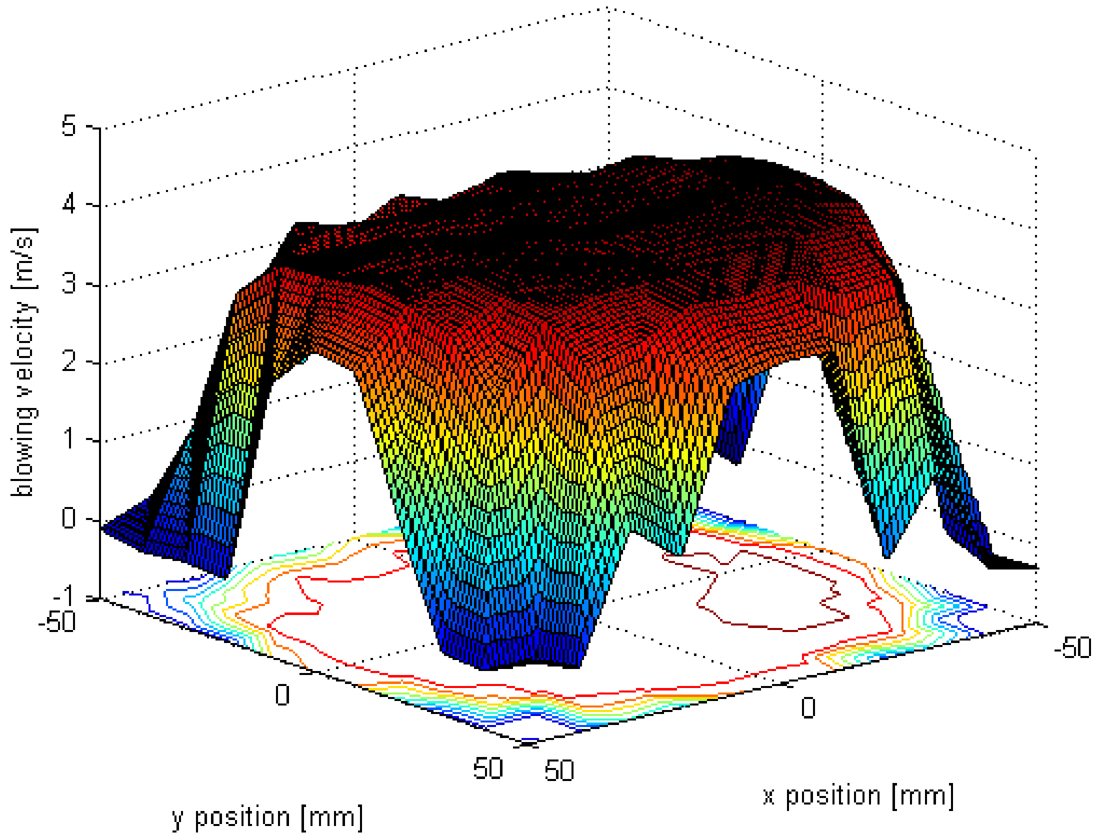


Figure 5.13: 3D velocity profile visualisation

The pitot-static probe movement was programmed in the vertical plane starting at the pipe edge and ending in the axis with **5 [mm]** step. The measuring time was set to **1 [s]**. The log from the test is found in appendix. The data were then used to generate fig. 5.14.

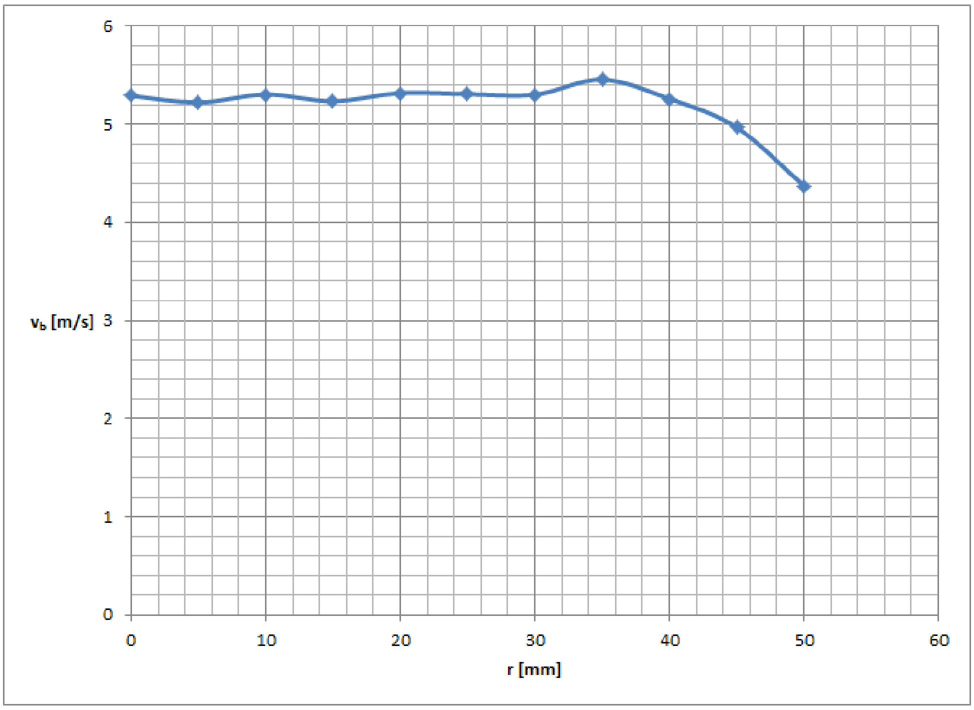


Figure 5.14: velocity profile obtained by test 2

5.6 Test evaluation

The main purpose of testing was proving the system's ability to deliver desired volume flow rate. Using the measured velocity profile from test 2 which can be seen in fig. 5.14 the volume flow rate was calculated. Generally

$$dQ = v\,dS \quad [m^3/s]$$

When calculating a rotationally symmetrical cross section an area element definition shown in fig. 5.15 can be used

$$dS = dr\,r\,d\varphi$$

which changes the equation into form

$$dQ = v\,dr\,r\,d\varphi$$

transcribeable as

$$dQ = v\,r\,dr\,d\varphi$$

The volume flow rate is then calculated using integration

$$Q = \int_0^{2\pi}\int_0^R v\,r\,dr\,d\varphi$$

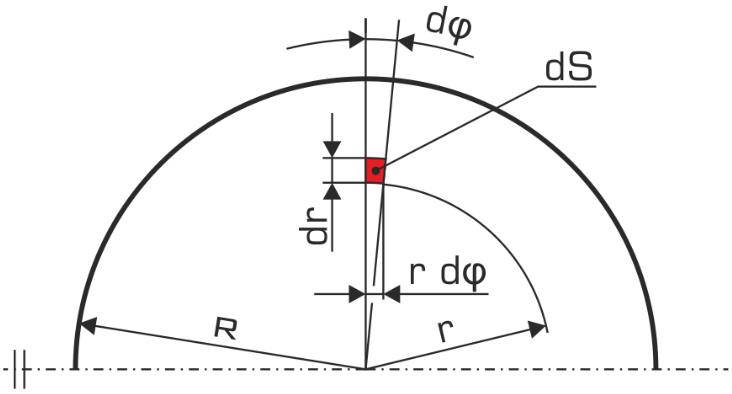


Figure 5.15: definition of area element used for integration

As the data obtained by the test are discrete the analytic integration cannot be used and was therefore replaced by numerical integration. As only rough estimation is required the rectangle method [15] was used. The volume flow rate is then calculated as

$$Q = 2\pi \sum(r_{i+1} - r_i)\left(\frac{r_{i+1}\, v(r_{i+1}) + r_i\, v(r_i)}{2}\right)$$

After evaluating the measured data a result is obtained

$$\mathbf{Q} \doteq \mathbf{40.57} \quad [\mathbf{m^3/s}]$$

As the desired volume flow rate was **32.5** [**m³/s**] the system proved its ability to deliver the desired amount of air more than reliably. The amount of air delivered could be even higher as the maximum outlet pressure reached during pressure tuning was **18 [bar]**. This would, however, reduce the blowing time significantly.

5.6.1 Test results conclusion and proposed design modification

Although the testing proved the system's ability to deliver desired amount of air it also showed a major shortening of blowing time. It was generally expected the time would be shorter than desired **5 [min]** as the pressure cylinder can hold the outlet pressure constant only as long as the pressure in cylinder is higher or equal than the outlet pressure. Also potential air bleed caused by imperfect sealing was expected.

A little shorter time than required was considered acceptable exchanged for carrying only one pressure cylinder on board and for reducing the cost by purchasing only one pressure regulator. During testing, however, the time of blowing at **10 [bar]** of outlet pressure was about **2 [min]** only.

This time drop was definitely caused by considerable volume flow rate required. The previous calculation took only slow air flow from the cylinder into account. In this case, however, the air flow must be very high in order to maintain the outlet pressure as there is huge air consumption by the system. To reach such airflow the pressure drop between the cylinder and the pressure regulator output must be equal or higher than certain value. Under this value the airflow starts to decrease and the pressure regulator cannot maintain the desired outlet pressure even if fully opened.

This could be solved by measuring the outlet pressure and increase the desired outlet pressure on the regulator when the real outlet pressure drops so that the real outlet pressure would remain the same. This would, however, require complicated and expensive electronic equipment controlling the regulator which would increase cost significantly. Simpler and more viable solution is the use of higher number of pressure cylinders.

There is one more aspect which supports the described solution. During testing because of high volume flow rate from the cylinder rime started to appear on Y shaped fitting straight behind the pressure regulator and started to grow towards and eventually on the pressure regulator. As the air used in pressure cylinders is not dried but contains moisture there is a danger of rime inside the fittings which could affect the system performance unfavourably.

Use of higher number of cylinders means the desired volume flow rate from one cylinder is as many times lower than from one only as many cylinders are used. Therefore the risk of rime should be lowered. Also, with lower volume flow rate from the cylinder required lower pressure drop between the cylinder and the pressure regulator output is necessary to maintain it which means more capacity of pressure cylinder can be used and therefore the blowing time prolongs.

Using several pressure cylinders brings the necessity of pressure equalisation between them. As each of them has its own pressure regulator the correct system operation should be ensured by setting the same outlet pressure on all of them. In practice, however, such perfect behaviour cannot be expected and pressure equalisation is then necessary.

The equalisation can easily be solved by use of equalisation chamber which has inputs from cylinder pressure regulators one side and two outputs with a 6 way distributor in each of them on the other side. There can be a closing valve before each distributor allowing pressure setting before the system is activated and above all to turn the system on and off immediately. The proposed solution is presented in fig. 5.16.

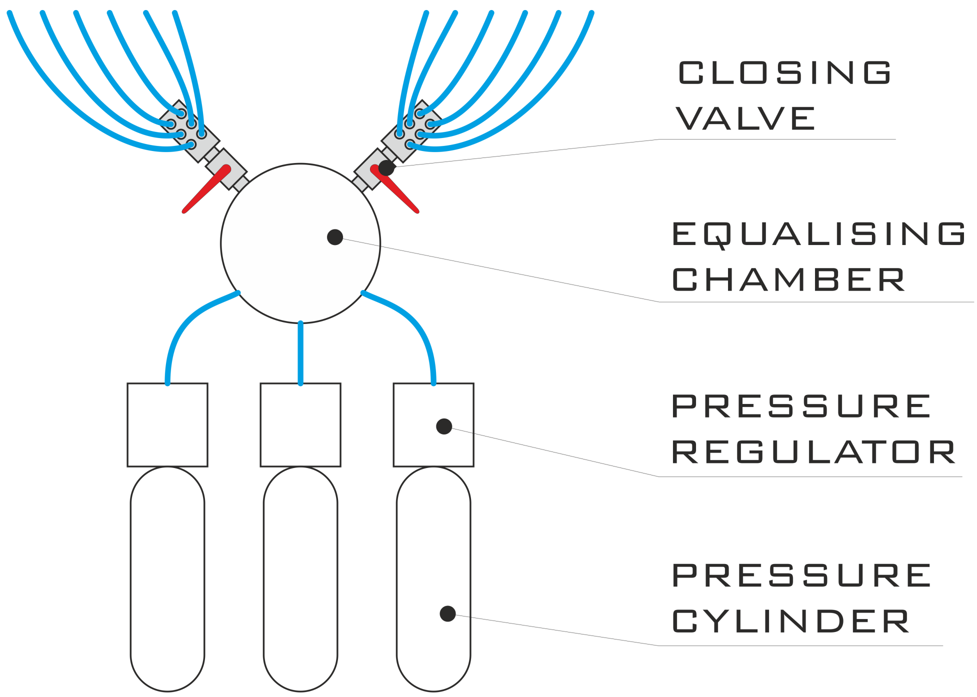


Figure 5.16: solution using pressure equalisation

6 Final assembly and installation

This part of the thesis describes the final assembly of spoiler, pneumatic system and hinges and the installation on Škoda Roomster passenger car. All the subassemblies described in previous chapters (pneumatic system, spoiler, car mounted hinge part, spoiler mounted hinge part, hinge insert) are considered to be ready.

6.1 Final spoiler assembly

The spoiler should in the moment of final assembly be laminated and the polystyrene corroded out. There are four major steps which have to be done:

1. fitting gluing
2. rivet nut installation
3. spoiler mounted hinge part installation
4. outer rib edge machining

For purposes of this assembly various fasteners is used. All fasteners necessary is summed up in tab. 6.1.

Fasteners	Standard	Number
Screw M6x10	ISO 4017	2
Screw M5x12	ISO 4017	4
Nut M5	ISO 4032	2
Nut M5 long	DIN 6334	1
Washer 5.5x18x2	DIN 440 R	4
Threaded rod M5x26	DIN 975	2
Rivet nut M5 open	[22]	6
Blind rivets 3.2x10	EN 14588	4

Table 6.1: assembly fasteners list

6.1.1 Fitting gluing

To make the spoiler ready for connecting to the blowing system push-in fittings have to be installed in it. These fittings will be glued into holes which were re-drilled to diameter **21 [mm]** during spoiler manufacturing. In this step right position of fitting presented in

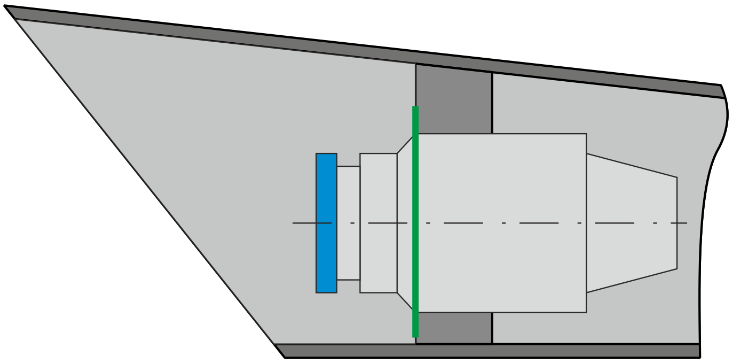


Figure 6.1: correct fitting positioning in spar part

fig. 6.1 is essential as spoiler's movement or the hose releasing could be disabled in case of wrong positioning.

In fig. 6.1 the green line shows the correct alignment. The fitting should be pushed into the hole up to its tapered transition and glued in this position.

The middle cylindrical part of the fitting should be roughened with sandpaper for better adhesion before gluing. The glue should first be applied on the hole surface. Then the fitting will be pushed into right position and the glue will be applied on the edge between spar part and the tapered part of the fitting from the outside of the spoiler. If possible, the same should be done from the inside using the holes in lower skin. It is important to make sure the glue does not leak inside the fitting or does not disable the hose locking/unlocking mechanism.

The glue used must be able to glue metal (fitting) and wood (spar) and in the best case be able to seal the joint. Several construction glue manufacturers can be found in the market such as Pattex, Henkel or Den Braven. A polymer based glue can be used such as Den Braven's Mamut Glue [16], MS Unifix [17] or Pattex 100% [18]. A very important group of polymer glues are polyurethane glues like Den Braven's Bond Flex PU 40 FC [19] or Pattex Chemoprén Extrém [20]. Henkel's acrylate glue Loctite AA 330 [21] is also suitable for desired purpose.

The selection of particular glue depends on manufacturer's experience and preference. As all of these glues should ensure the same result the choice is up to manufacturer to make. These glues are only meant as recommendation; provided the joint is firm and tight enough any glue of manufacturer's choice can be used no matter if it is on this list or not. The manufacturer should follow instructions valid for particular glue used.

6.1.2 Rivet nut installation

On both outer ribs a rivet nut according to tab. 6.1 is installed into the hole close to the spoiler's trailing edge as seen in fig. 6.2. The rivet nut used is a stainless steel open-type grooved rivet nut with circular head according to [22]. The hole dimensions were deigned according to [22] also. Glue may be applied on the hole before riveting the nut to prevent slipping.

6.1.3 Spoiler mounted hinge part installation

The side most ribs have a circle with centre mark engraved on them. This engraved symbol marks the position of rotation axis. The spoiler mounted hinge part should be placed on the rib and the threaded hole aligned with the centre mark engraved on rib. The part should be positioned in accordance with fig. 6.2. The positions of little holes on hinge part are then marked on the rib and holes with same diameter **3.3 [mm]** are drilled through. The hinge part is then attached to the rib using two EN 14588 **3.2x10 [mm]** blind rivets according to [23]. The holes are designed with respect to [23] also.

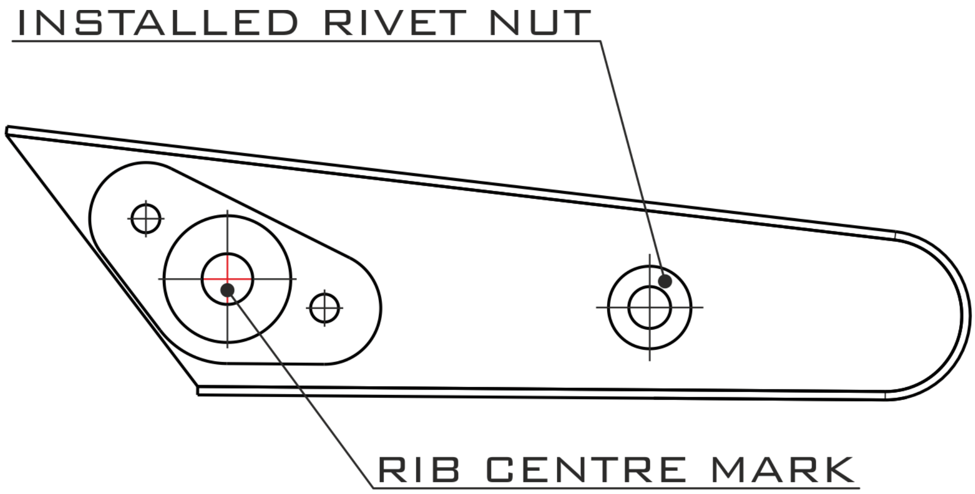


Figure 6.2: hinge part positioning with rivet nut installed

6.1.4 Outer rib edge machining

In order to ensure free spoiler rotation within desired range the outer rib edge must be modified so that it does not interfere with car mounted hinge part. The geometry of cut is presented in fig. 6.3. This cutout is made on the rib using hand rotary milling tool. The machined surface should not be perpendicular to rib face but should follow the car body. The described geometry is indicative only. After installing the spoiler it might appear necessary to remove a little material more to ensure free rotation of the spoiler.

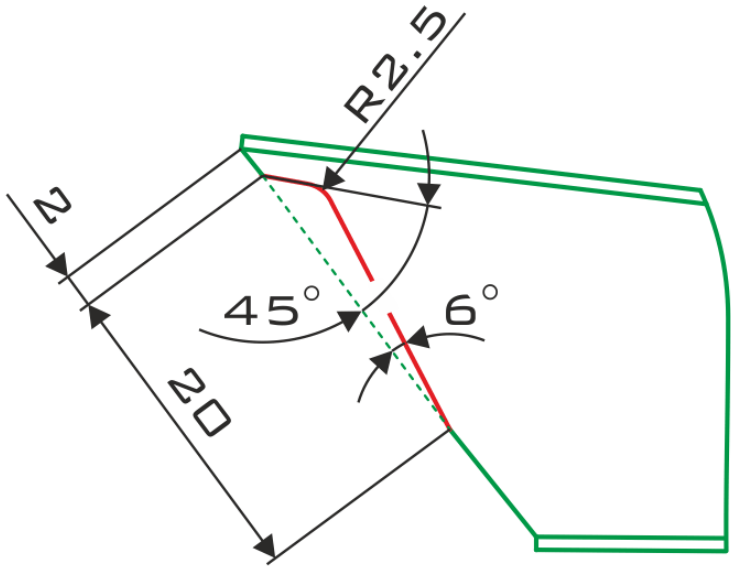


Figure 6.3: rib cutout geometry (green colour marks the original shape while the red colour the machined shape)

6.2 Blowing system installation

The most important task is securing she pressure cylinder in the car interior. Again an effort was made to solve the problem as simply as possible. Therefore it was decided to take advantage of the front passenger seat which will support the cylinder after head support is removed.

The advantage of the seat is its adjustability allowing the cushion to move forwards and backwards and the backrest to tilt in both directions. Therefore after placing in the car the cylinder position can be set as desired. The bottom of the cylinder is based on the floor. In case it is in contact with the floor by its edge only polystyrene or polyurethane foam can be used to soften the contact and to fill the space between the cylinder bottom and the floor.

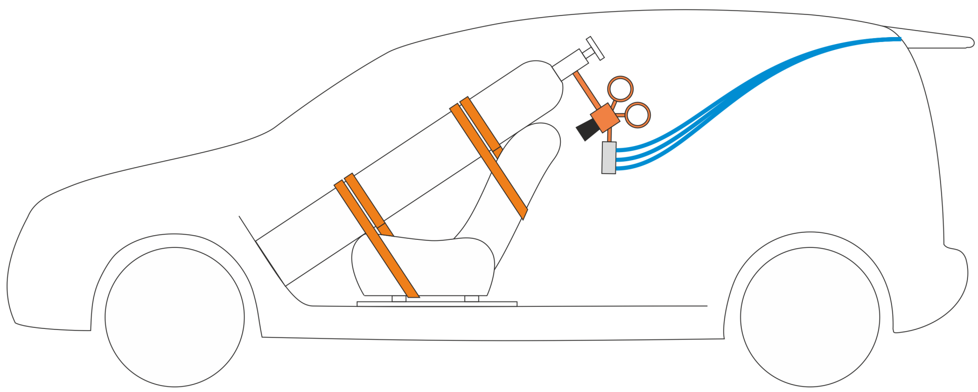


Figure 6.4: cylinder positioning inside the car (the cylinder and car are scaled equally)

The solution is presented in fig. 6.4. The cylinder is secured by two load binding belts (equipped with tightening clamps). To prevent the cylinder from movement special way of wrapping the cylinder is adopted. The method is shown in fig. 6.5.

The wrapping starts at the tightening clamp and follows the black arrows. Here the belt is marked with orange colour. When the cylinder is wrapped from the right side the belt

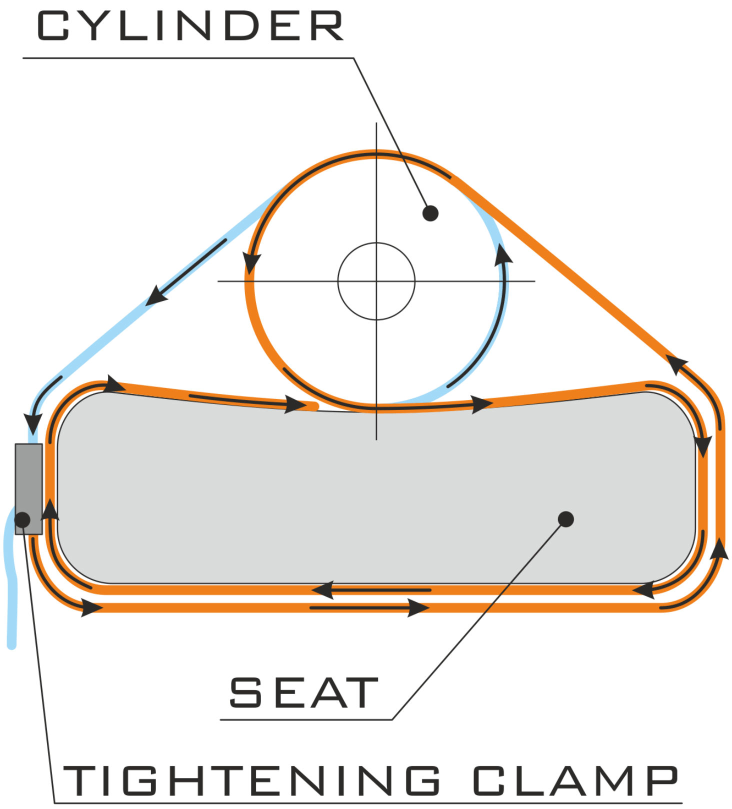


Figure 6.5: the cylinder wrapping scheme

goes behind the seat again and then back to the cylinder from the left side. Here the colour changes to light blue which indicates the fact the loop wrapping the cylinder from the left side is placed behind the orange one. Then the belt reaches the clamp and can be tightened. There are two belts in total as seen in fig. 6.4, one binding the cylinder to the backrest and the other to the seat.

6.3 Spoiler installation

The installation consists of two major tasks - attaching the car mounted hinge parts to the car body and then the spoiler to these parts. As positioning of isolated car hinge parts would be complicated the spoiler shall be put together with hinges first, positioning will be done using the whole assembly and then the car hinge parts will be removed from the spoiler and fixed to car body. The spoiler will then be installed.

6.3.1 Spoiler and hinge assembly

The assembly philosophy is obvious from fig. 4.1 where parts are defined by their numbers. These numbers will be used further on in order to simplify the description.

First a part of the locking system has to be installed. The M5 threaded rod 5 is screwed into the rivet nut 6 previously installed in the outer rib close to spoiler's trailing edge. On the threaded rod a nut 7 is screwed and tightened against the rivet nut head. Then a large diameter washer 8 is put on the threaded rod. The nut 7 is made from a classic long nut by turning. Its length depends on real washer and rivet nut head thickness which may vary piece by piece. The nut is then shortened on lathe to desired length which is calculated easily as the distance between rib face and the car mounted hinge part 1 must be **6 [mm]**.

Now the part 1 is placed from each side of the spoiler. The threaded rods 5 are put into corresponding cutouts in part 1 as seen in fig. 4.1. Then the insert 3 is put into corresponding hole in the part 1 and a screw 4 is put into it and screwed into the spoiler mounted hinge part 2. Hereby the spoiler is joined with parts 1 rotationally. Now it is necessary to fix the spoiler in **0 [deg]** position. This is done by placing the assembly on a planar pad. If the part 2 was placed correctly and the outer edge on the lower side of side most rib was not damaged during machining it should align the lower edges of ribs and parts 1. When the edges are aligned another large diameter washer 8 is put on the threaded bar 5, this time from the outside, and the position is then fixed by screwing and tightening a nut 9 on the threaded rod 5. All fasteners used is defined in tab. 6.1.

6.3.2 Car mounted hinge part installation

Now the whole assembly is placed on car body above the rear window and positioned. For better orientation it is recommended to draw a vertical centre line of the car on the car body using a marker. Horizontally the middle rib should be aligned with this line. Vertically the spoiler upper surface must tangentially follow the roof shape seen both from right and left view.

When the position is set and the spoiler held in its place by two assistants the hinge parts 1 have to be temporarily fixed. This is done using hot glue applied into a wedge-shaped gap between the part 1 and the car body. Both surfaces must be degreased first. The glue is not meant to hold the spoiler on the car body; it must still be held by assistants, but it should prevent it from moving from its position.

After the glue is cooled down the manufacturer must loosen the locking mechanism nuts 9 and by deflecting the spoiler upwards and downwards the sheet of the part 1 with holes for screws becomes accessible. The manufacturer then marks its edges and also approximate positions of hose fittings on the car body with marker and the assembly can be removed from the car body.

Using drawn lines the car mounted hinge part can be placed on the car isolated which allows marking the hole positions with marker. Then **7 [mm]** holes according to [22] can be drilled through the car body and M5 rivet nuts defined in tab. 6.1 installed. After installing the nuts the car mounted hinge parts can be fixed using M5 screws according to tab. 6.1. The right position is controlled by previously drawn lines.

In this phase cutouts for hoses must be cut in the car body. The manufacturer uses positions of fittings marked in previous step to cut these oval shaped cutouts. The ovals should be oriented vertically where the width is determined by outer hose diameter **12 [mm]** by adding few millimetres on each side. The exact number cannot be specified here as due to imprecise fitting position marking the cutouts may require further widening after the hoses are connected so that each cutout may be unique. The height should allow the spoiler's angular movement around the rotation axis. Generally to make sure the operation is secured within desired range the height should be as high as the corresponding car body surface allows. Again, after the hoses are connected the cutout height may require further modifications.

Next step is attaching the spoiler. This is done similarly to previously described assembly.

First the spoiler is placed between the hinge parts 1 and using inserts 3 and M6 screws 4 rotationally joined to the hinges. Thanks to clearance between the screw and the insert hole certain position correction of spoiler is allowed in case of inaccuracies during hinge installation. During the installation of locking system the threaded rod 5 must be put through the cutout in the car mounted hinge part 1 first and then through the washer 8 and the nut 7 before it is screwed into the rivet nut 6 in spoiler's rib.

The last step is connecting the blowing system, which should be placed inside the car already, to the spoiler. The hoses are simply put through cutouts in car body and pushed into the fittings. Although the fittings should be secured by glue in their positions it is recommended to install the hoses with a help of an assistant who supports the fitting by fingers or by a tool from inside the spoiler using the cutouts in the lower skin.

By finishing this last step the manufacturing and installation is finished and after covering the cutouts in lower skin and the gap between the spoiler and car body with tape the car is ready for intended testing.

7 Conclusion

This master's thesis contains a complex design of active flow control system mounted on Škoda Roomster passenger car meant for testing of the influence of active flow control on aerodynamic properties of the car in real conditions. The thesis follows previous research in this field done by BUT and TUB on Volkswagen UP! car which included CFD simulations and scaled model wind tunnel testing. That research determined input values for this thesis such as required blowing velocity.

The system consists of a spoiler with slot close to its trailing edge from which the air will be blown perpendicularly to the freestream, hinges which allow angular setting of the spoiler and locking it in desired position and the blowing system. The whole design is adjusted to proof of concept design philosophy which determines materials, manufacturing technology and methods used.

The spoiler itself is a hollow part containing 12 chambers with plywood framework and glass fibre composite skin. The plywood structure consists of ribs, spar parts and a stream blocking slat which is meant to improve blown stream behaviour. The theoretical shape of the spoiler was simplified so that the spoiler surface consists of planar sections instead of one curved surface. The ribs and spar parts are laser cut parts manufactured using 2D curves derived from a 3D model while the blocking slat is made from generally available rectangular slat.

The spoiler is manufactured by gluing the plywood framework together followed by gluing polystyrene blocks between the framework parts. The polystyrene blocks together with framework edges are then brushed into desired shape ad the result is used as o mould for lamination. After lamination the polystyrene is chemically corroded out.

The hinges are made of common steel S235JR by welding. The hinge has two major parts - the car mounted and the spoiler mounted hinge part. Drawings defining these parts are found in appendices of this thesis. An effort has been made to use as many standardised fasteners parts as possible.

The blowing system consists of a pressure cylinder placed inside the car and secured by load binding belts, a pressure regulator installed straight on the pressure cylinder valve and the system of pneumatic push-in type fittings which divides the airstream flowing from the cylinder into 12 hoses. These hoses then go through cutouts in the car body and each of them is connected to corresponding chamber of the spoiler.

The system was tested using a pipe with same cross sectional area as the spoiler slot. The test reliably proved the system's ability to deliver desired volume flow rate **32.5 [l/s]** (which correponds to desired blowing velocity **4.2 [m/s]**) of air to the output. The test, however, revealed several problems which have to be solved. Namely the blowing time is significantly shorter than intended and also rime appears on fittings during operation. The thesis therefore offers a recommendation to use several pressure cylinders with pressure equalising chamber to prolong blowing time and lower volume flow rate from one cylinder which should lower the risk of freezing also.

The last part of this thesis describes the final installation of the system on the car so that it is ready for intended testing.

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List of symbols

Symbol	Unit	Meaning
A	$[m^2]$	area
A_F	$[m^2]$	car's frontal area
A_i	$[m^2]$	internal cross section area of piping
A_S	$[m^2]$	slot area
c_b	$[-]$	blowing coefficient
d_i	$[m]$	inner diameter of pipe used for system testing
l	$[m]$	length
p_b	$[bar]$	blowing system designing pressure
p_c	$[bar]$	cylinder filling pressure
Q	$[m^3/s]$	volume flow rate
t	$[s]$	time
t_b	$[s]$	blowing time
v	$[m/s]$	velocity
V	$[m^3]$	Volume
v_b	$[m/s]$	blowing velocity
v_i	$[m/s]$	internal airstream velocity in piping
v_f	$[m/s]$	freestream velocity
V_c	$[m^3]$	cylinder volume
V_t	$[m^3]$	total air volume

List of acronyms

Acronym	Meaning
BUT	Brno University of Technology
CFD	computational fluid dynamics
CNC	Computer numerical control
IAE	Institute of Aerospace Engineering
PTFE	polytetrafluoroethylene
TUB	Technische Universität Braunschweig (University of Brunswick - Institute of Technology)

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C3: CAR MOUNTED HINGE PART

C4: SPOILER MOUNTED HINGE PART 1

C5: SPOILER MOUNTED HINGE PART 2

C6: SPOILER MOUNTED HINGE PART

C7: INSERT

A Testing photographs

A.1 Pressure regulator mounted on cylinder valve

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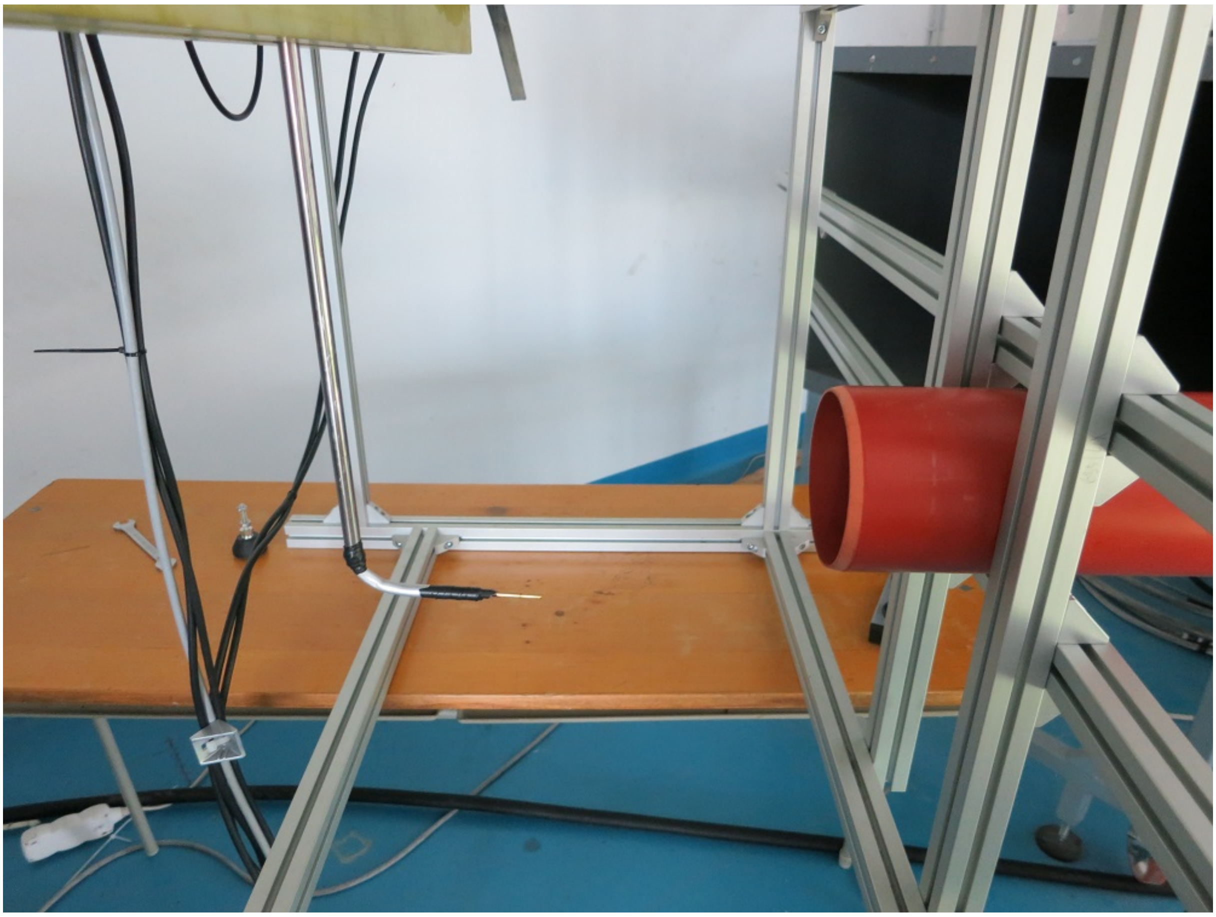
A.3 Central compressed air distribution supply

A.4 Pitot-static probe detail



A.5 Test layout

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