Research report 55

DFM(A)- ASPECTS FOR A HORN ANTENNA DESIGN

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ISBN 951-764-955-X
ISBN 951-764-956-8 (PDF)
ISSN 1459-2932

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LTY digipaino 2004

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Keywords: Manufacturability analysis, design for manufacturing and assembly, microwave mechanics, horn antennas, antenna measurement, microwave mechanics

ABSTRACT

In this paper aspects of design for manufacturability and assembly (DFMA) are applied to the design of coaxially fed standard gain horn antenna for 1.70 - 2.60 GHz. Possibilities to utilize cross-technological approach method is examined. Methods of DFMA for laser processing are covered and practical design guides and methods are developed. Antenna construction for easy manufacturing and specialized performance is shown. Required dimensions and tolerances are discussed and suitable materials for laser processing are selected.

Acknowledgements

Research team is grateful to Antti Heikkinen, Esa Hiltunen and Juha Turku for their important support during the manufacturing process of the test antennas.

CONTENT LIST

1 INTRODUCTION

In this research manufacturability analysis will be made for a standard gain horn antenna. Possibilities to utilize cross-technological approach-method both for designing and making manufacturability analysis for MW-/RF-components will be discussed.

For helping to establish the necessary guidelines for easy manufacturing and assembly of the MW-/RF-component a specialized DFM(A)-questionnaire will be generated. The questionnaire gives also new information for collaborative designing approach in MW-/RF- engineering. Also the advantages and disadvantages of the selected design method are evaluated.

Practical guides and instructions for easy manufacturing are collected especially for sheet metal process. In this report we will focus in researching components, which are made of different aluminum alloys.

This research is part of the EU-project entitled “Collaboration for human resource development in mechanical and manufacturing engineering (Contract: ASIA-LINK -ASI/B7-301/98/679-023). Within the same series of publications belong seven reports, which are focused to following design methods:

- systematic design
- reverse engineering
- concurrent engineering
- cross-technological approach
- collaborative design
- use of integrated product teams
- virtual prototyping

All these seven reports will be published at Lappeenranta University of Technology during the year 2004 in the series of scientific reports of the Department of Mechanical Engineering.

2 TASK

In this research practical design guides and methods are developed to achieve better manufacturability of one specific microwave horn antenna. The antenna, which is designed in this research, is operating at frequency range from 1.7 to 2.6 GHz, but the same design ideas, manufacturing and assembly principles can be utilized within the designs of horn antennas, which are made for other operating frequencies as well.

3 COMPONENT

A standard gain horn antenna geometry is selected as the target of DFM(A) analysis. From the point of view of manufacturing accuracy a horn antenna is a quite challenging construction and its manufacturing methods are determined mostly by accuracy requirements.

3.1 Function

Standard gain antennas are utilized in antenna gain and phase pattern of far field measurements. Gain and phase of the examined antenna are measured in different directions by either rotating the antenna, which is tested or by transposing the standard gain antenna. A typical measurement setup is shown in Fig. 3.1.

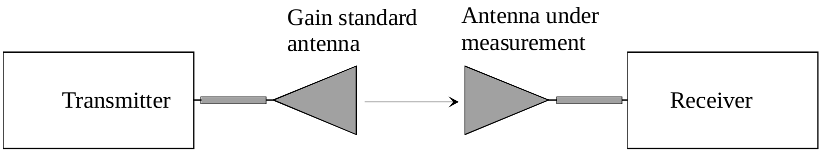


Fig. 3.1 A typical antenna pattern measurement setup.

3.2 Functional requirements

Functional requirements for gain standard antenna are low side- and back lobe levels, constant phase center and wide operating frequency band. Directive antenna is needed to minimize reflections from walls, which increase measurement accuracy. However, too narrow main lobe of a highly directive antenna causes error too.

Horn antenna satisfies these requirements and it is widely used for antenna measurements in microwave frequencies. In our case the selected operating frequency range is 1.7-2.6 GHz, which gives mid-band frequency $f_0 = 2.150\,\mathrm{GHz}$ and wavelength $\lambda_0 = 139.5\,\mathrm{mm}$.

3.3 Construction

In principal, a horn antenna is an opened waveguide. Horn can be linearly or exponentially tapered rectangular or circular, depending on type of feeding waveguide. Rectangular horn with flare in both planes is called a pyramidal horn. Dimensions of a linearly tapered pyramidal horn are easy to calculate and it has many desirable properties (see more in chapter 3.2, Functional requirements). In Fig 3.3 are shown the geometry and the critical inner dimensions of the designed pyramidal horn antenna and feeding waveguide.

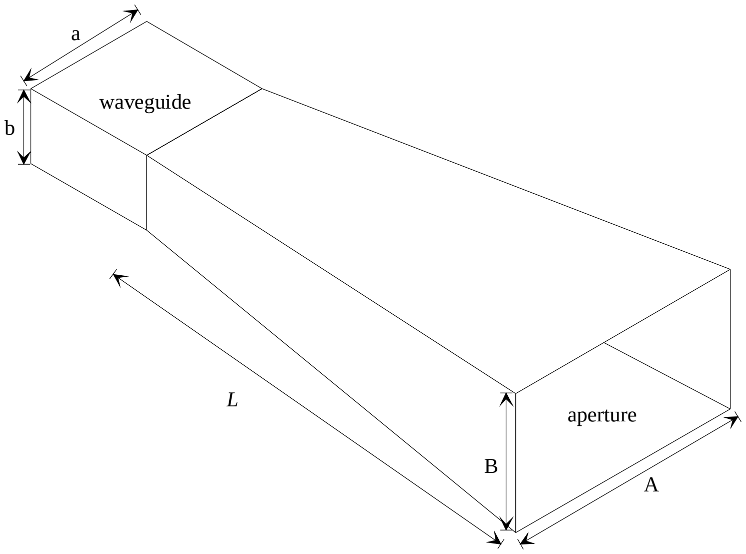


Fig 3.3 Pyramidal horn antenna and dimensions.

Horn antenna is fed from a waveguide, while interface of measuring system is coaxial. Transition from coaxial cable to waveguide is done with a waveguide to the coaxial transformer. This is simplified a monopole in a waveguide located ahead of a short-circuited plunger (= closed end of the waveguide). Waveguide to coaxial transformer is shown in Fig 3.4.

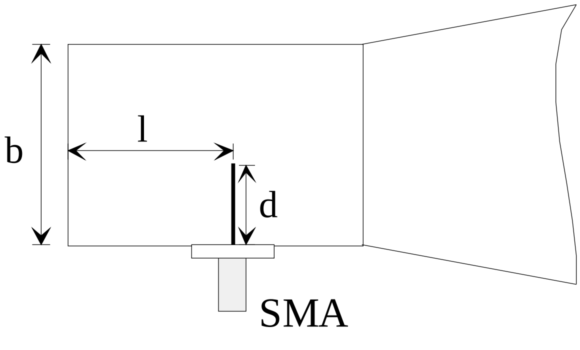


Fig 3.4 Waveguide to coaxial transformer with a SMA-connector. Symbols:
d = length of probe, l = distance of probe from the end of the waveguide,
b = height of the waveguide.

3.4 Dimensions

Dimensions of a standard WR 430 waveguide for selected 1.70-2.60 GHz frequency range are 109.2 x 54.6 mm^2 [3]. The cut-off frequency of this waveguide is 1.375 GHz. Coaxial to waveguide transformer can be matched by selecting the length and position of the feeding probe properly. Usually good matching is achieved by selecting

$$d = \lambda_0 / 4$$

and

$$l = \lambda_g / 4 ,$$

where λ_g is the wavelength in waveguide. By setting the total length of the waveguide part to $0.75 \cdot \lambda_g$ we can achieve VSWR minimum in waveguide. For selected mid-band frequency we have $d = 34.9\,\mathrm{mm}$ and $l = 45.3\,\mathrm{mm}$. In reference literature [4] it is given dimensions for 15 dB gain horn. For aperture dimensions we have $A = 368.5\,\mathrm{mm}$ and $B = 273\,\mathrm{mm}$ and for horn length $L = 265\,\mathrm{mm}$.

4 CROSS-TECHNOLOGICAL APPROACH

4.1 Introduction to the Cross-Technological Approach

The design engineer meets different areas of science, different human views, various industrial goals and many philosophical, psychological, social or socio-political opinions. This constantly changing environment can be seen as a disturbing factor against design work, but it should be preferably regarded as a source for new ideas and innovations. The environment must be turned from an annoying element to a supporting factor.

In microwave applications the tightest cross-technological connections should be between mechanical engineering (incl. design and manufacturing), microwave mechanics, electronics and computer aided means (see Figure 4.1).

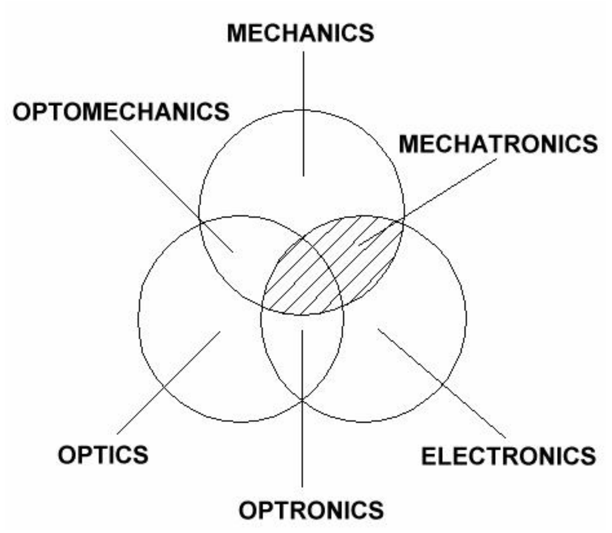


Fig. 4.1 The tightest cross-technological connections for the topic are shown as a hatched area. Note that the word "mechatronics" means the synergetic combination of mechanical engineering, electrical engineering and information technology for the integrated design of intelligent systems, in particular mechanisms and machines. The word "mechatronics" has been used to describe the rapidly increasing tendency to combine mechanical technology with electronics and computer control to enhance performance and flexibility of products and manufacturing equipment.

To maximize the possible advantages coming from this cross-technological approach, the following task-list for the designer has been produced:

- The most important cross-technological connections should be clarified in the beginning of a design project.
- The team members (experts) for the design work should be collected from the main cross-technological areas as demonstrated in Figure 4.1.
- The use of integrated computer-aided means can be a powerful tool to combine the cross-technological areas. The product data management systems (PDMS) are formulated to handle all the life cycle information in the same computer aided environment which is enlarged with the use of databases, by networking and with rapid prototyping.
- The product specifications must include also the aspects of ergonomic, recycling and environmental protection if applicable. These requirements must be established in the beginning of the design and not afterwards.
- Different fields and areas of science can be used as source for ideas and innovations. The individual designer must be supported to utilize these sources.

- The more complicated the product to be designed is the greater benefits are obtained by using a cross-technological approach
- Cross-technological approach is also needed "inside" each main area presented in Figure 4.1. E.g. experts on various manufacturing technologies might be needed for manufacturability analysis (inside the area of “mechanics”).

4.2 About the suitability of cross-technological approach for MW-design

Common requirements for an effective design method are as follows:
1. The method must be applicable to every type of design activity, no matter in which specialist field.
2. The method should facilitate the search for optimum solutions.
3. The method should be compatible with the concepts, methods and findings of other disciplines.
4. The method should not rely on finding solutions by chance.
5. The method should facilitate the application of known solutions to related tasks.
6. The method should be compatible with electronic data processing.
7. The method should be easily taught and learned.
8. The method should reduce workload, save time, prevent human errors, and help to maintain active interest.

A very simple way to estimate product’s manufacturability is to use the following four items:
1. Binary measures (whether or not a specific manufacturing method is suitable)
2. Qualitative measures (products can be classified according to their manufacturability e.g. into groups ”poor”, ”average”, ”good” or ”excellent”)
3. Abstract quantitative (some numerical index is counted to describe product’s manufacturability)
4. Time and cost comparison

If the design method does not include any of these check points in the early stages of the design process, obviously the method is not too effective for DFM(A)-analysis.

In many cases it is possible to divide the research area of design method into a function-oriented, a performance-oriented or a manufacturability-oriented product design. Alternatively various approaches can be developed for customer-oriented, quality-oriented, cost-oriented and organization-oriented design.

The real need for improvements is between these two extremes. This means that the effective method for the designers should not be too limited (like in the performance-oriented design) or too general (like in the organization-oriented design), but it should, however, include the context of design environment. That is why the traditional design methods are improved for specific design tasks, e.g. for MW- and RF-component or system design.

MW-mechanics design is one of those typical areas in which cross-technological approach could be most effective way to work. Usually the question is not about accepting this method's advantages, but some designers seem is impossible to admit that some information from other colleagues might be useful for their design process. The question is more about how to fit together different personal attitudes and characters.

5 DFM(A)-QUESTIONNAIRE FOR THE COMPONENT

5.1 General instructions to generate the questionnaire

To help to establish the special requirements of the MW- or RF-component it is possible to generate a questionnaire, which could be modified from the general presentation shown in table 5.1. The basic idea is to collect those design aspects which will later affect on mechanical design and from which the final requirements for design can be derived.

Table 5.1 A preliminary questionnaire for helping to form the requirement list of mechanical microwave subassemblies.

Question	Answer
1. What is the expected operating frequency?	_____ GHz
2. What is the required relative bandwidth?	_____ %
3.What is the maximum radio frequency power to be handled?	_____ dBm
4. Is the unit for a) receive (RX), b) transmit (TX) or c) both?	a) b) c)
5. What is the absolute maximum attenuation allowed?	_____ dB
6. Are semiconductor components involved in the design?	yes no
7. Is the preferred transmission line a) waveguide b) planar c) coaxial d) dielectric?	a) b) c) d)
8. Should the connection to adjacent modules go a) through coaxial connectors or b) waveguide flanges or c) none?	a) b) c)

9. Is the unit a) sealed for life or b) should there be a possibility for service & repair?	a) b)

One example to show how this table guides the design process: if the expected operating frequency of the device is lower than 1 GHz, generally any material could be used and dimensional tolerances can be even > 1 mm. If the operating frequency is <15 GHz, most metals are acceptable, including steel but oxidation is to be avoided, surface and alignment tolerances should generally be generally < 0.1 mm. And finally if operating frequency is over 15 GHz, only highly conductive metals (Cu, Au) can be used, most impurities are extremely harmful, and tolerances should be even better than 5 – 10 μm.

Typically the questionnaire presented in table 5.1 should be filled by a MW-/ RF- engineering expert. For specific designs some additional questions might also be useful.

Expert of manufacturing technologies is needed to generate the questionnaire for a specific manufacturing stages to ensure products DFM(A)-aspects. A lot of background information is needed to manage to present the right questions to the designer. However, the designer is the only expert who is able to explain the limits or restrictions due to product's functional aspect for different manufacturing operations. Example of a questionnaire, which is made especially for a laser processed product is presented in table 5.2. Depending on each possible manufacturing technology for the product's geometry, several questionnaires should be generated and filled in.

Table 5.2. Special DFM – questions for laser processing, illustrative examples

Question	Implementation
1. Are the possibilities to use the fixing systems for machining considered? (typically the requirements of accuracy of fixing in laser processing and machining are almost equal)	yes no
2. Could the carbon content of steel be kept under 0.2 % (or at least not higher than 0.3%)?	yes no
3.If highly reflective materials are welded (for example Cu- and Al-alloys), is the utilization of Nd:YAG recommended in design documents?	yes no
4. Are the joint preparations for laser welding documented including necessary tolerances and manufacturing methods? (laser cutting or machining are recommended, however Ra < 12,5μm is appropriate)	yes no

5. Are butt welds with raised edges or lap joints with seam welds used whenever it is possible due to constructional aspects?	yes no
6. Are more than two plates welded with the same (seam) weld whenever it is possible due to constructional aspects?	yes no
7. Is the construction possible to be laser processed from one direction or at least in one plane?	yes no
8. Are the values for air gap and allowed misalignment marked in the design documents (for example: butt joint/air gap 0.15 mm ,t<10 mm, misalignment<0.3 mm)	yes no
9. If the material’s hardenability properties must be taken into consideration, are the most appropriate joint geometry utilised? (for example the weld is placed mostly on the plates to be welded)	yes no
10. If wires or strings are welded, are the most appropriate joint types used? (power density should be dealt equally to the parts to be joined)	yes no
11. If jigs are needed, are the fixings of jigs designed and marked on the drawings? (in case when the workpiece is moving in front of the beam)	yes no
12. Is the need for grinding the reinforcement marked in the drawings if several sheet metal constructions are welded together?	yes no
13. When jigs are needed for welding partially closed structures, is the possibility of shrinking taken into account when removing the work piece?	yes no
14. Is the possibility to use various material combinations considered?	yes no
15. Are the possibilities to use different laser processing methods for the same construction or multi-processing methods considered?	yes no
16. Are the points were laser welding starts and ends designed to meet quality aspects?	yes no
17. Is the CAD-geometry of the workpiece saved in the DXF-format (or any other suitable) for CAD/CAM-integration?	yes no
18. Are the traditional instructions for designing sheet metal parts taken into account? (needed for example for cut-bend-weld multi-processing)	yes no

19. Are the adjusting holes or fits marked on the drawings? (or are other additional geometries necessary for adjusting the parts together)	Yes no

In general the list of actions to put DFM(A) in practice is relatively simple:

- minimize the number of parts in a construction
- design modular constructions
- try to find as many functions for a part as possible
- avoid additional components for joining other parts
- design the construction so that all the parts can be assembled from the same direction
- minimize the number of different manufacturing methods and stages to be used
- obey the rules of easy manufacturing for each manufacturing method (applied into your own production)
- check that there is enough space for necessary tools during assembly, fixing systems during manufacturing and a robotic gripper in automated systems
- use standardized geometry, tools and components
- check the machining allowances
- check the suitability of the material for the manufacturing methods
- use appropriate general tolerances for your own production
- check the summarized errors of the assembly and design a harmless place for manufacturing errors in the construction
- check that the values of surface roughness, tolerances for linear and angular dimensions and geometrical tolerances are adjusted together
- use parts which can be assembled from several directions and still function perfectly (avoid parts which easily assembled in wrong a position or which function only in one position)
- if there are several possible manufacturing methods choose the one, which needs least preparations
- try to repeat the same manufacturing stages, think that each manufacturing stage is also ”a module”
- use parametric design
- design the products directly for automated production (in most cases they will be extremely well suitable for manual production too)
- if manual production is used check the ergonomic aspects

During different design stages this list can be used as a check list to ensure that manufacturability aspect have been taken into account.

5.2 Special questionnaire for laser process of the horn antenna

Special questionnaire for the horn antenna design has been modified from the questionnaire shown in table 5.1 to help to establish general requirements. This modified questionnaire is shown in table 5.3.

Table 5.3 Modified questionnaire for the standard gain horn antenna

Question	Answer
1. What is the expected operating frequency range?	1.70-2.60 GHz
2. What is the maximum radio frequency power to be handled?	10 dBm
3. What is the desired gain in mid band frequency?	>10 dB
4. What is the minimum -3dB beam width?	20 °
5. What is the maximum VSWR allowed?	1.25
6. Are ferromagnetic components involved in the design?	yes no X
7. Is the preferred transmission line a) waveguide b) planar c) coaxial d) dielectric?	a)X b) c) d)
8. Should the connection to adjacent modules go a) through coaxial connectors or b) waveguide flanges or c) none?	a)X b) c)
9. Is the unit a) sealed for life or b) should there be a possibility for service & repair?	a)X b)

5.3 DFM(A) actions for the horn antenna

It is possible to put DFMA actions in practice within this horn antenna design by following the list shown in chapter 5.1.

Required number of parts in the horn antenna assembly depends on manufacturing technology. Machining from one piece is hardly possible even in theory and at least desired tolerances inside the horn will be hard to achieve. However, splitting construction into two pieces along a horizontal plane and machining the horn of two parts is possible and it is also a conventionally used method. Four pieces is needed in minimum if antenna is manufactured of bended sheets and if parts are joined by welding. Modularity of construction is achieved by dividing the horn and the waveguide into too parts, but this, however would increase the number of parts. The symmetric geometry of the antenna enables to use same parts at both sides and at the top and the floor of the horn. However, the mounting holes are needed for the connector. Additional parts in construction can be eliminated only on condition that material is thick enough so that threads for mounting screws of the connector are possible to manufacture and mounting brackets is possible to create as part of the basic construction. If sheet metal work is selected for the manufacturing technology and joints of the parts are welded, it is possible to design construction so that welding is done from three directions (top, bottom and back). During sheet metal work manufacturing stages contains shaping the sheet metal parts and welding. Mounting holes for the connector can be done during the bending phase and threads can be done before or after welding. Mounting brackets can be designed to be used as fixing points during assembly. Due the simple construction of the antenna there should not appear any problems with required space for fixing systems and tools during manufacturing and assembly. Material should be selected so that it is suitable for bending and welding. Also suitability for machining (threads) is important as well as rigidity (horn is pressed with the jigs during welding). Three different tolerance grades are utilized according to the components requirements to ensure antennas performance. First, the strictest, can be used for the pin length of the connector and its positioning (centricity and distance from the shorted end of the waveguide), another for inner dimensions of horn and waveguide and the third (general) tolerance for the fixing. Summarized error of the length should be left to the throat of the horn to get the length and the opening of the horn as desired. Surface roughness should be selected to match with tolerances and used frequency range. The horn antenna consists of five sheet metal parts, four of which are bended and one (back) is straight. If computer controlled sheet metal forming technology is available, design of these parts is easily done so that both automated and manual manufacturing is flexible. Notches can be designed to the joints of the horn and waveguide for easier fabrication and welding without a jig. Depending of the wall thickness these notches are not always required for exact positioning. Following this concept it is possible to design the horn antenna for easy manufacturing and assembly, so that functional and qualitative aspects are taken into account as well. DFM-questions for horn antenna, which is designed for laser processing, are shown in Table 5.4. Depending of the required tolerances of the antenna it might also be possible to apply TIG-welding for 3 mm aluminum parts made of alloy AlMg3.

Table 5.4 Specialized DFM-questions for the horn antenna, which is designed for laser processing

Question	Implementation
1. Are the possibilities to use the fixing systems for laser welding considered?	yes no X
2. If highly reflective materials are welded (for example Cu- and Al-alloys), is the utilization of Nd:YAG recommended in design documents?	yes X no
3. Are the joint preparations for laser welding	yes no X

documented including necessary tolerances and manufacturing methods? (laser cutting or machining are recommended, however Ra < 12,5µm is appropriate)	
4. Are butt welds with raised edges or lap joints with seam welds used whenever it is possible due to constructional aspects?	yes no X
5. Is it possible, due to constructional aspects, that more than two plates are welded with the same weld?	yes no X
6. Is the construction possible to be welded from two directions or at least in two planes?	yes no X
7. Are the values for air gap and allowed misalignment marked in the design documents (for example: butt joint/air gap 0.15 mm ,t<10 mm, misalignment<0.3 mm)	yes no X
8. If the material's hardenability properties must be taken into consideration, are the most appropriate joint geometry utilized?	yes X no
9. If jigs are needed, are the fixings of jigs designed and marked on the drawings?	yes no X
10. Is the possibility to use various material combinations considered?	yes X no
11. Are the possibilities to use different laser processing methods for the same construction or multi-processing methods considered?	yes X no
12. Are the points were laser welding starts and ends designed to meet quality aspects?	yes X no
13. Is the CAD-geometry of the workpiece saved in the DXF-format (or any other suitable) for CAD/CAM-integration?	yes X no
14. Are the traditional instructions for designing sheet metal parts taken into account?	yes X no

6 REQUIREMENT LIST FOR A PYRAMID HORN ANTENNA

This research is focused to the pyramid horn antenna design. Horn antenna assembly consists of pyramidal flange, waveguide, mounting bracket and SMA-type connector. Antenna body (flange and waveguide) is made of aluminum alloy. Dimensions of the antenna are selected from reference documents. Basic antenna geometry is presented in figure 6.1 without mounting brackets.

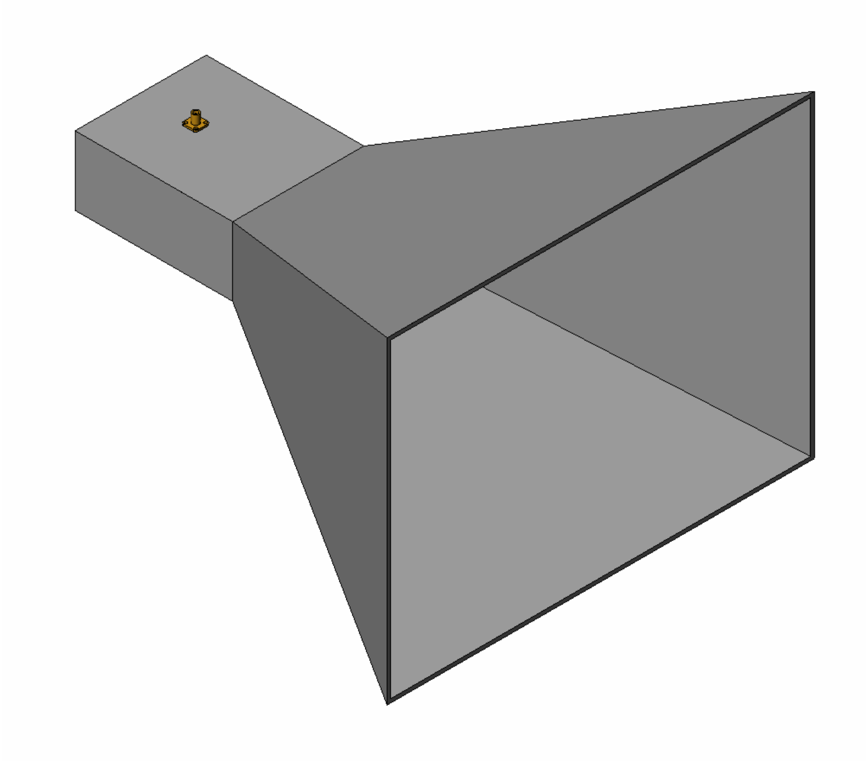


Fig. 6.1 Basic antenna geometry consists of an end-shorted waveguide (left), a SMA-connector (the feeding probe inside waveguide), a pyramidal horn flare and a horn aperture.

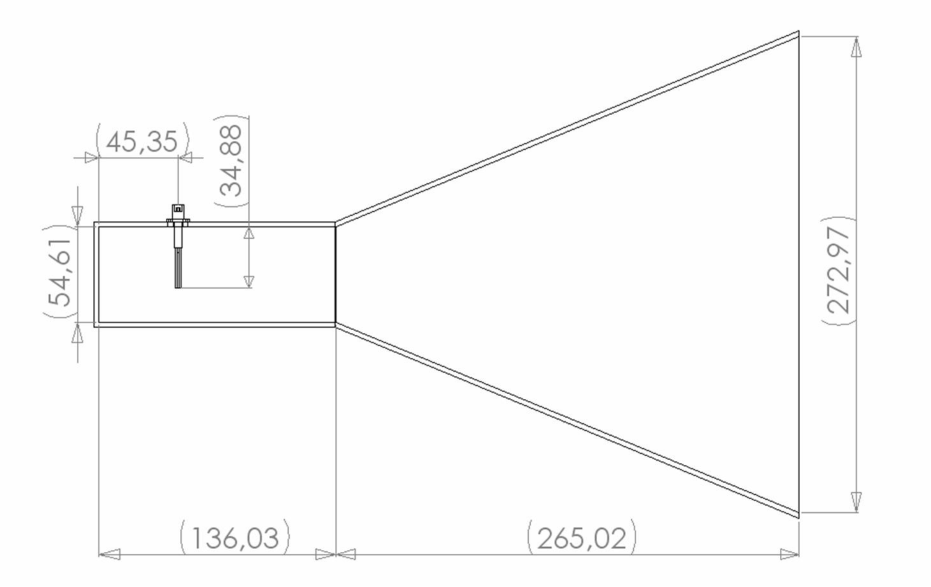
6.1 General requirements

Geometry

Waveguide geometry is standardized (width×height) and the size of the pyramid is selected from reference document [3] for this application. Also the SMA-connector is standardized and its joining data can be read from the standard. For connector's mounting the screw size M2.5 is recommended. Required dimensions of the antenna are presented in Figure 6.2

Forces

The antenna is operating in laboratory conditions, which means that no special requirements are set to its rigidity and strength. However, antenna’s geometry should be stabile and withstand normal handling during operation.



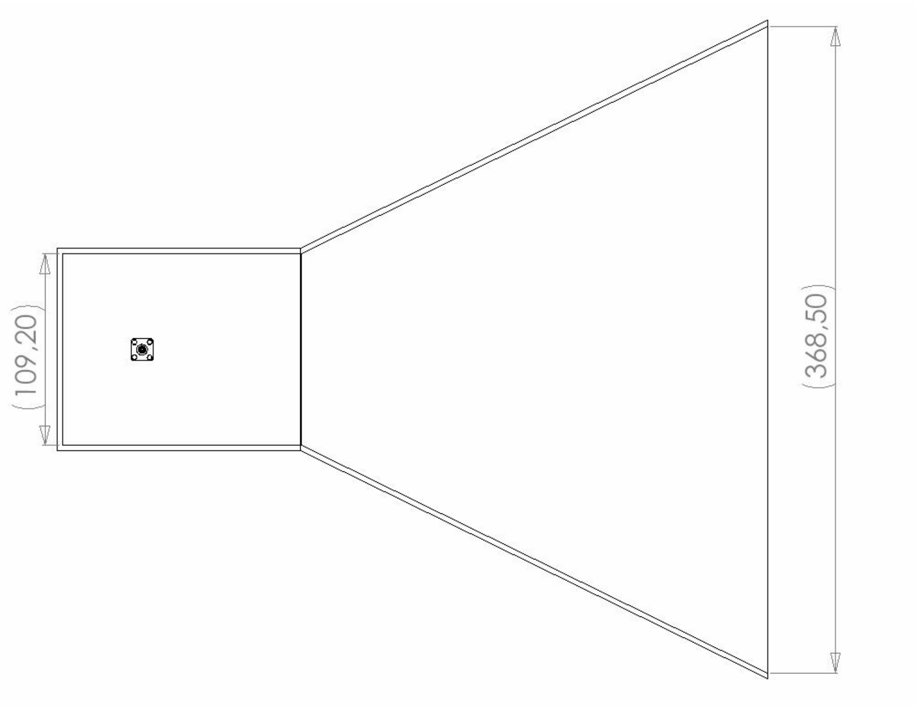


Fig. 6.2 Required inner dimensions of the horn antenna.

It is required that connector structure can withstand the maximum tensile load allowed for the coaxial cable joined with the connector and the maximum coupling torque of the connector. The same requirement goes for the mounting screws of its flange as well. The maximum allowed tensile load for the typical cable is around 500 N. Recommended coupling torque of the connector is between 0.8-1.1 Nm.

Also the forces during manufacturing (machining) might be critical due to relative small dimensions of the workpiece.

Material

Due to required electrical performance of the antenna the requirements for the material are shown in table 6.1. Other general mechanical requirements for material are good corrosion resistance and light weight.

Environment

This antenna should be used at room temperature, but the required environmental requirements at this research are as follows:

- Stability against chances of environmental circumstances and handling
- Lightweight construction is needed to ease operation and to decrease robustness requirements of the antenna supporting guides.

Safety and ergonomics

To ensure the easy manufacturing of antenna the required space for SMA-connector's mounting screws must be checked. There must also be enough room for using the special tool for tightening the threaded connection of the cable.

Production

During this research we will focus to different sheet metal technologies to be able to produce a small series of specialized horn antennas. Materials formability and joinability are therefore in key-role. On the other hand we must ensure that there will be enough space for bending and pressing tools. It should also be possible to use necessary fixing systems and jigs during various manufacturing stages. This aspect will be discussed in chapter 7 in details. Changes of the sharpness of the edge inside the waveguide and horn causes chances to velocity of the propagating wave in guide and affects to the shape of the radiation pattern of the antenna. Exact estimation of accepted roundness can’t be given, but edge sharpness requirement has to be noticed when selecting manufacturing method.

Quality control

The quality of the horn antenna could be measured by analyzing its performance by using gain pattern and VSWR-measurements. Also manual inspection of critical dimensions can be applied.

Assembly

The tightening moment for the M2.5 screws of the connector is 45 Nm.

Recycling
Antenna body is made of aluminum and it could be re-used.

Costs
During industrial manufacturing special automated machines are used for antenna production. When horn antennas are manufactured, main costs consists of three main aspects:

- writing the required DXF-files for sheet metal cutting and welding processes
- quality control of sheet metal parts
- assembly (welding) of sheet metal parts
- assembly of a connector and a horn body

6.2 Electrical requirements

Specialized electrical requirements are presented in table 6.1.

Table 6.1 Electrical requirements for material

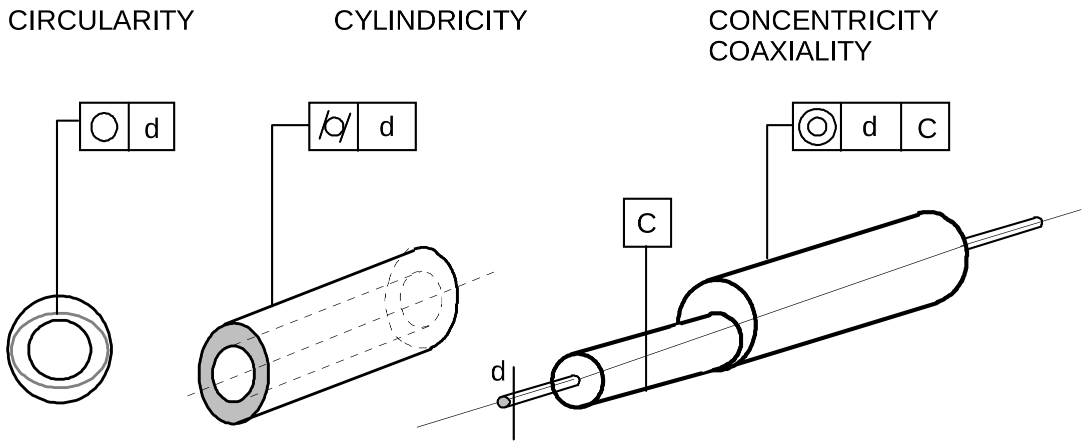
Influencing factor	Material characteristics	Required value
Penetration depth and Absorption loss	Relative conductivity	> 0.3
	Relative permeability	1

6.3 Requirements for geometric tolerances

Dimensional tolerances, which are given in the reference documentation for the standard WR 430 waveguide, are ±0.15 mm, which affect to the guided wavelength by 0.003 %. This is generally negligible chance for this application. Even 1 mm tolerance is acceptable tolerance for inner dimension, if smooth joint between the horn and the waveguide is ensured. This means IT-grade as high as 14. However, the positioning of the feeding pin (SMA-connector's center pin) inside the waveguide has the key-role to ensure antennas performance (see Fig. 6.6 top).

More important than dimensional tolerances are geometrical tolerances for the waveguide (see Fig 6.6). Walls that are joined together must be perpendicular and opposite walls must be parallel. Dimensional tolerances of the waveguide affect to center operation frequency and gain, which is not very critical, while geometrical tolerances affect to phase and gain pattern and VSWR of the antenna.

To ensure that the waveguide and the pyramid nozzle are assembled into same position the requirement for concentricity for the virtual center lines of those parts can be set (see figure 6.4). Of course the use of circularity and cylindricity would be impossible for square cross-sections. However, the use of concentricity requirement would not prevent the possibility that the assembled parts are in a twisted position related to each other (see figure 6.5). To avoid this assembly error, also perpendicularity should be required (both for the waveguide itself and for the nozzle positioning).


CIRCULARITY

CYLINDRICITY

CONCENTRICITY
COAXIALITY

Tolerance area
is inside two
"circles".The
distance between
the outlines is
"d". The true
surface should
lie between these
two circles.

Tolerance area
is defined with two
"tubes". The true
surface should lie
between them. The
distance between
the tubewalls is "d".

Tolerance area is
a fine tube (diameter
is "d") inside which
the theoretical
centerlines
of both cylinders
should lie. A datum
surface "C" is necessary.

Fig. 6.4 Explanation of circularity, cylindricity and concentricity. Only concentricity for virtual center lines could be useful for this antenna design.

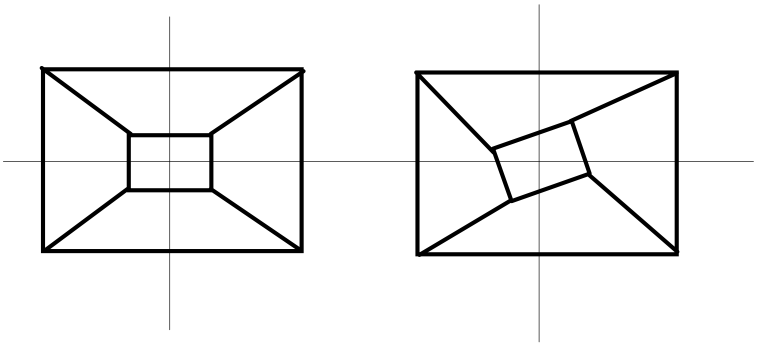


Fig. 5.5 Antenna's parts should not be assembled to a twisted position.

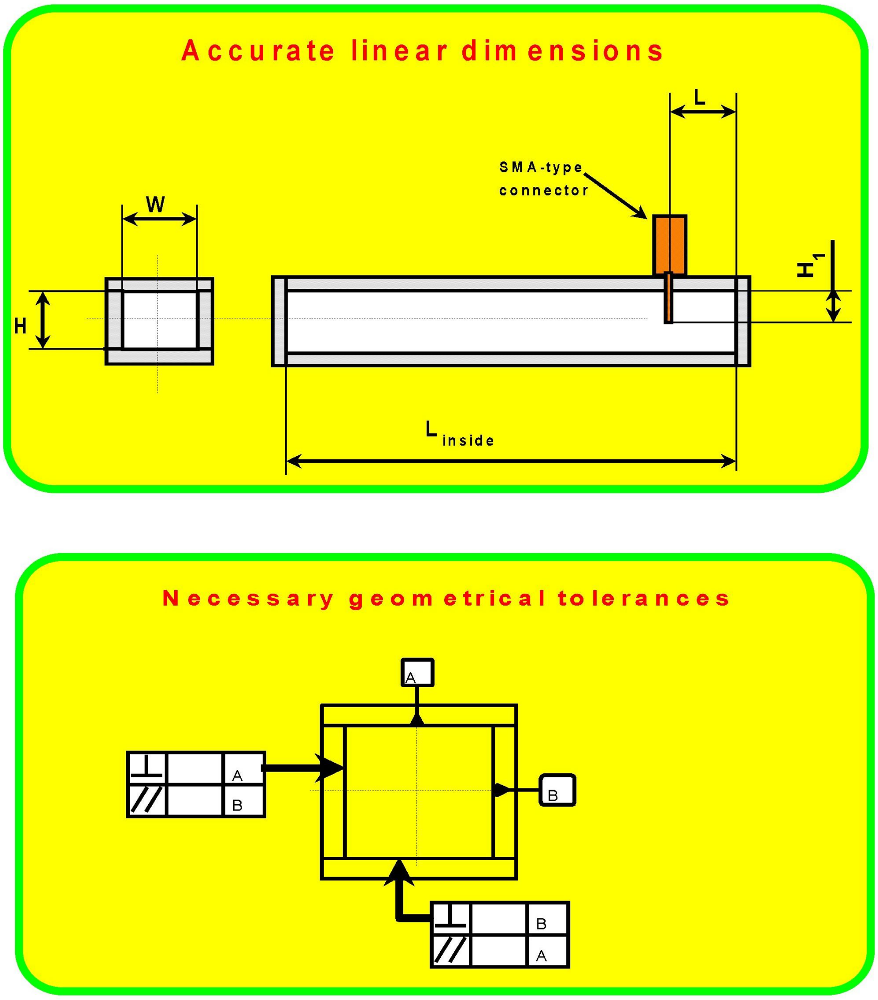


Fig. 6.6 Other geometrical and dimensional tolerances are needed e.g. to ensure the quality of the waveguide part. In addition to these angular tolerances are needed for the pyramid part of antenna.

Numerical estimation for the required dimensional and geometric tolerances could be estimated from table 6.2 according to the operating frequency range.

6.4 System requirements

Antenna stand has a 3x3 array of holes with M5 threads in 5 mm thick vertical plastic plate behind antennas intended position. Spacing between holes is 25 mm. Attachment of the antenna to the stand must be firm and accurate, and same kind of structure must be applicable with gain standards for other frequency ranges. Positioning of antenna in relation with plastic mounting plate is not so significant, which means that mounting brackets can be spread from two sides of antennas back plate (figure 6.7). Because the waveguide is wider than mounting plate in antenna stand, antennas mounting brackets must be placed to the sides of waveguide end next to each other. Clearance for mounting nuts must be taken into account.

Table 6.2 estimation of the required tolerance grade according to the operating frequency

Frequency (GHz)	**Surface roughness**	**Tolerance grade**
300-600	0.8 µm	IT5
150-300	1.6 µm	IT6
75-150	3.2 µm	IT7
35-75	6.4 µm	IT8
15-35	12.8 µm	IT9-10

It is important to note here, that to ensure a proper assembly of the standardized SMA-type connector, we should ensure that the dimensional deviations, which are presented in SMA-connectors standard sheets, are satisfied.

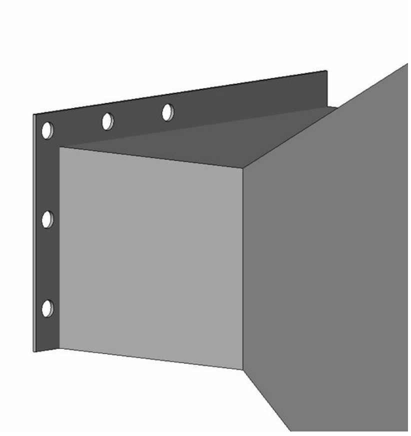


Fig 6.7 Antenna mounting brackets.

7 MANUFACTURING TECHNOLOGIES

Alternate technologies for manufacturing the horn antenna are sheet metal construction and machining. Also almost every imaginable manufacturing technology is applicable in some form, e.g. casting or deep drawing, but for a reasonable delimitation two first mentioned technologies are discussed here.

7.1 Sheet metal work

Sheet metal process contains three main stages: cutting, bending and joining.

Waveguide section of the horn antenna is a simple rectangular tube and the flange or horn section has otherwise the same geometry but it is tapered linearly. Both parts can be folded from one piece and joined together with transversal welds. Another possibility is to bend sides of the horn and waveguide and to weld them together with longitudinal welds. This method is better for maximizing the electrical performance of the antenna.

Cutting

Sheet metal is shaped by cutting. Main cutting technologies are CNC machining, pressing, nibbling, punching and flame, plasma, laser (CO_2 or Nd:YAG) and water jet cutting. Which technology is selected here, depends mostly on the surface roughness and accuracy requirements.

Machining

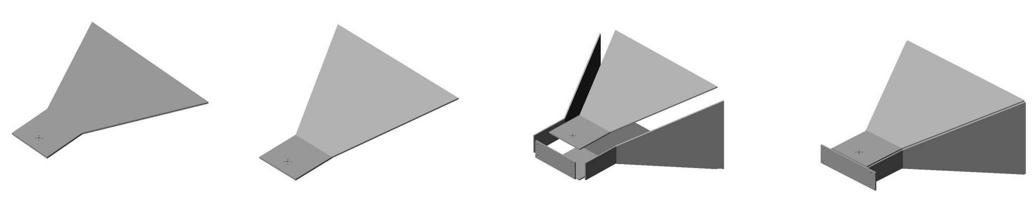
Holes, openings and threads are machined after cutting. There may be also need of machining slots for tight bends on thick material.

Bending

Sheet metal parts are bent to their geometry according to required angles and bending radius. Spring back effect and allowed minimum bending radius must be considered.

Joining

Bent sheets are joined together by welding. Either laser, TIG or even MIG welding could be used. However, due to accuracy requirements only laser and TIG-welding sound reasonable. Other usable joining technologies are soldering and gluing. Because of aluminum’s high reflectivity and high purity requirements during welding, extra attention has to be paid on acceptable welding process arrangements.



cutting and machining **bending** **assembly** **welding**

Fig. 7.1 Stages of sheet metal processing of horn antenna.

7.2 Machining

Machining of the antenna body contains milling of the horn and waveguide geometries. Geometry must be spliced in horizontal or vertical plane into two pieces for milling. Additional assembly stage is needed after milling to join machined halves together. Also additional machining of holes and threads is needed.

7.3 Plating

Plating is needed if material of antenna body is not corrosion resistant enough. By selecting material that has good corrosion resistance plating is not needed.

7.4 Assembly

Assembly stage depends on manufacturing technology. Two stages are included to this antenna design: setting SMA-connector to its accurate place and fixing four mounting screws. Screws must be tightened to the proper moment.

Additional assembly stage is needed if the antenna is manufactured by machining. In that case probably tens of screws might be needed for fixing the horn halves together.

8 APPLIED DFM(A)-ASPECTS

Applied DFM(A)-aspects can be classified to four groups: changes of the construction, changes of the geometry, choosing more acceptable material and detailed chances of dimensioning and tolerances. These changes should be made in early stage of design to avoid expensive redesign. Usually these changes are related to the manufacturing technology. In some cases to ensure easy assembly also changes of the construction are required. In laser processing weldability is most important DFM(A)-aspect. If material is suitable for laser welding, it is usually suitable also for laser cutting. The designed construction affects also to the practical arrangements of welding stages.

8.1 Changes of the construction

For better manufacturability few constructional changes have to be done. Figure 7.1 shows weldability of different joint geometries. Optimum between performance and weldability is achieved by using fillet-t weld joint.

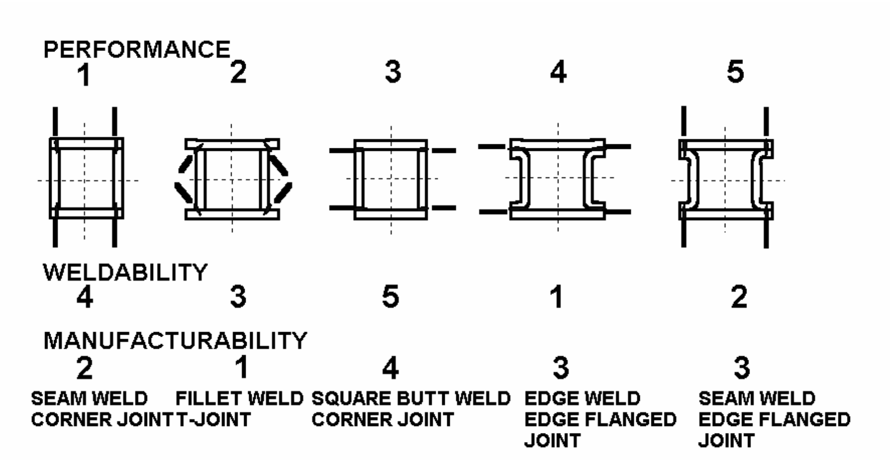


Fig 8.1 Weldability of different joint geometries. Number 1 means the best choice.

Manufacturability can even be improved by adding special teeth-hole pairs to the joint (Fig 8.2) for positioning parts better before welding. This kind of geometry ensures proper dimensions with unsophisticated jigs during welding.

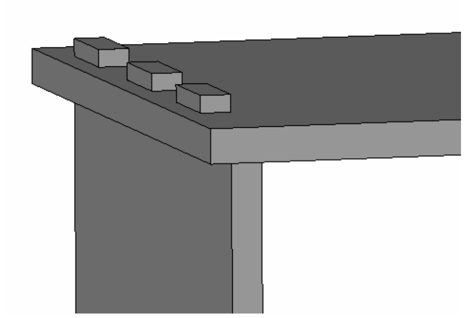


Fig 8.2 Applied joint geometry for better manufacturability, dimensioning and tolerances.

8.2 Changes of the geometry

Changes to basic geometry of the horn antenna are not needed due to manufacturability aspects. Constructional changes were discussed in chapter 7.1.

8.3 Choosing more acceptable material

While only one manufacturing technology (laser processing) is used, it is easy to select right material for easy manufacturing. Weldability of aluminum alloys are generally good, but surface reflectivity must be taken into account with laser processing. Energy absorption from laser beam to reflective surface is low. Power requirement for laser may raise unattainable high. Available power of laser beam depends on type of laser used. Needed rigidity is attained by choosing alloy with right hardening degree condition.

8.4 Detailed changes of dimensioning and tolerances

These changes are usually made directly to the technical drawings or other documents. Utilizing following rules manufacturing the component can be done more easily:

- indicate where is the allowed “open dimension” for manufacturing inaccuracy
- avoid so-called double tolerancing
- write allowed dimensional deviations directly after the dimensions
- show the required bulk size and geometry, from which the manufacturing should start from
- group dimensions according to sequential manufacturing stages
- use clear dimensioning, which does not lead to any further calculations during manufacturing or quality control to establish the required dimensions of the product

For this horn antenna construction dimensioning is easy due to the simple geometry of the antenna. Also the identifications and symbols for tolerance requirements are easy add to the documents. However, dimensions of the inside geometry of the horn must be expressed clearly for welding. Possible material removal during laser processing must be considered, though NC-program of laser processing calculates usually proper cutting lines.

9 DESIGN AND MANUFACTURING FLOWCHART

In figure 9.1 is shown a flowchart of the tuned design methodology for laser processing. Four main stages of design methodology can be found. At the begin product ideas are followed by search for specific manufacturing methods. After that the design is tuned by the manufacturability aspects. In third phase availability of standardization is checked and possibility the use of modular constructions. Finally value analysis and cost examination are carried out. Both the mechanical and functional advantages are derived from the common advantages of laser processing.

10 COST ASPECTS OF HORN ANTENNA DESIGN AND MANUFACTURING

Basically there are four main cost elements, which should be taken into account when evaluating the total costs of a MW- /RF-product. They are

- designing costs,
- material costs,
- manufacturing costs and
- costs spanning over the lifetime of the product.

Many MW- and RF- applications include difficult geometries or materials regarding traditional manufacturing processes (e.g. turning, milling or casting). This means that much time is needed to develop the first prototypes to be suitable for production. The design costs of a microwave component can be estimated to be at least double compared to any "non-high-tech" product.

MW- and RF-devices utilize several precious and expensive materials. E.g. gold or silver or some specially mixed powders are needed. It is also usual that the quality grade of alloyed metals used in microwave applications is extremely good and the price therefore higher too. If expensive materials are used their price is essential. In addition to this some of these materials are difficult for traditional manufacturing processes or at least some special arrangements are needed during production. These double the effects of material selection to the price. A direct comparison between a MW- and RF-application and "non-high-tech" product is hard to make, but typically material costs is at least ten times higher. In this horn antenna construction we do not need these types of expensive materials due to low operating frequency.

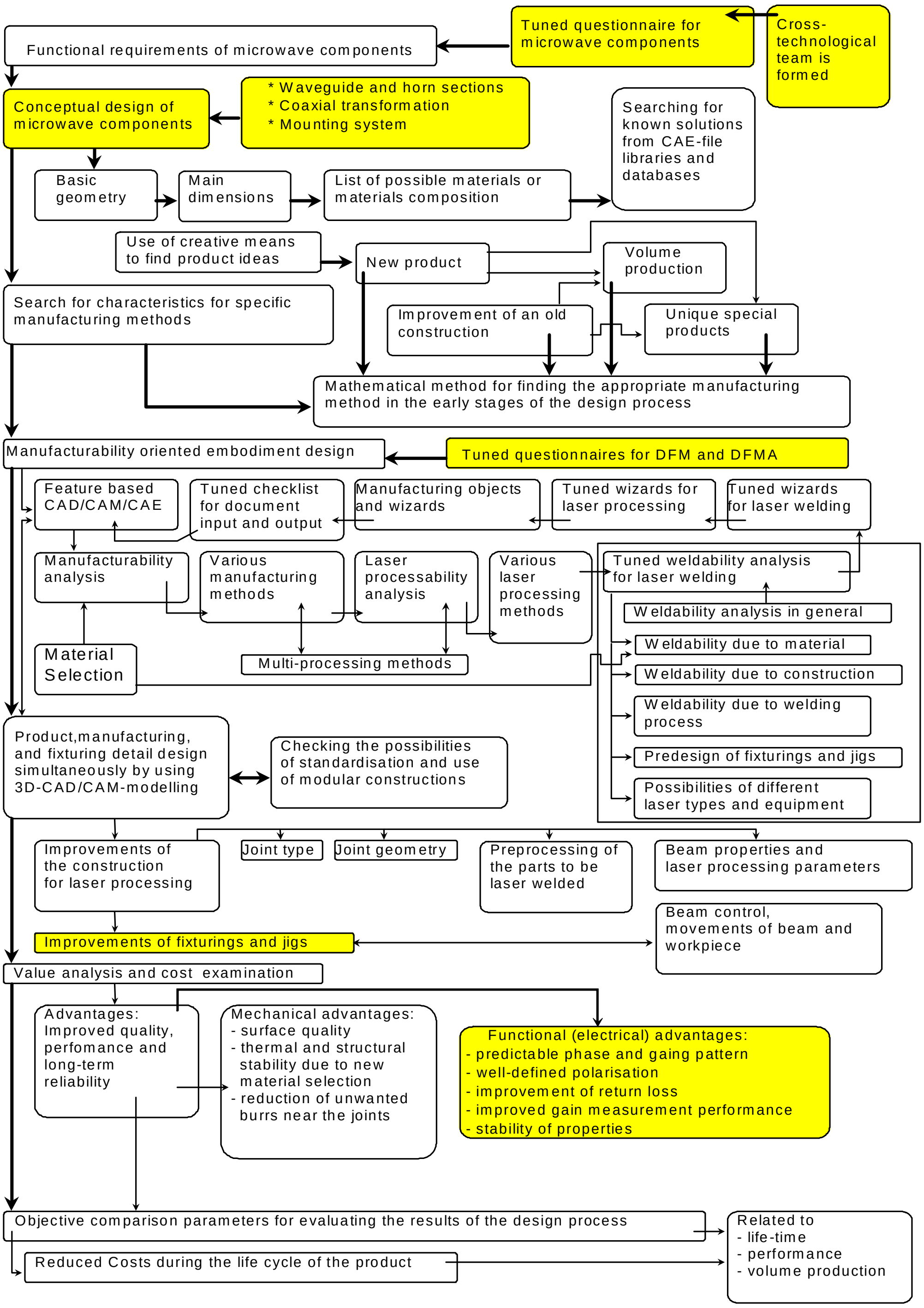


Fig 9.1 Flowchart of the tuned design methodology for laser processing of a horn antenna. Those process stages, which are of special interest in MW-/ RF-mechanics, are tinted.

In general MW- and RF-applications need specialized tooling and fixing systems and in some applications, depending mostly of the operating frequency, quite tight dimensional tolerances down to 1 µm. These call for some extra time to make a dedicated set-up into the production system. Although the manufacturing stages could be quite cost-effective, the long set-up times and specialized tools and fixings increase production costs by about 500 to 800 per cent in prototyping or small series production. In high volume production these cost elements are marginal. There is a tight relationship between manufacturing costs and surface roughness. After the specified surface roughness level the costs will increase exponentially. Nowadays in milling and tuning the limit is 0.8 µm and in grinding 0.4 µm. A better surface finish rapidly adds costs. Many MW- and RF-applications tend to lead to over-estimated dimensional accuracies. The surface requirements may be set too tight to ensure the products performance though an easier way might have been e.g. to change more reliable connectors to the device. The most important thing is to compose the requirements of dimensional accuracy and surface finish from the operating frequency of the device. In this construction the required IT-grade is 10, which means that the critical allowed dimensional deviations are 140 µm and corresponding required Ra is 3. The critical geometry is joining between waveguide and horn and corners of them.

There are several commercial semi-products or half-finished materials (like e.g. cold drawn waveguide profiles, flanges or coated raw materials), which could be reasonable alternatives to an in-house start from scratch. For this product there is no reason to use ready made waveguide profile or pre-coated material due to simplicity of construction.

In MW- and RF-device production the traditional principles to handle tooling costs, fixed costs, capital costs, labor costs, indirect labor costs etc. are as usual. The main acts should be focused in decreasing the lead-time - that is to minimize the time required to start production.

In many cases also MW- and RF-components should withstand environmental loads and there is a reason to compare different materials and their lifetimes. This comparison is typically made between two alternatives:

- common base materials with an appropriate coating, a relatively short lifetime, the product must be changed due to a break-through in the coated surface, relatively cheap,
- specialized base materials, a long lifetime, no changes needed during the lifetime, extremely expensive.

To make an objective comparison between various alternatives, a ratio, which shows the price in the form of a "unit" like [performance/ price/ lifetime], is needed.

This antenna construction does not have to withstand any specific environmental loading.

Regardless of technology - as long the dimensional accuracy is met with a standardized process - the costs depend only on the manufacturing time. Immediately if there is a need to change the process to ensure a better accuracy or dimensional tolerances the price rises essentially. To manufacture this horn antenna construction standardized processes could be used.

The development process of many high-tech products normally includes several prototype phases and tests before the final design. Unfortunately these prototypes can constitute the largest portion of the total developing costs. To minimize the costs of a prototype several manufacturing technologies could be applied:
- the prototype could be made of some soft materials like foam or plastic by using simple milling or tuning operations,
- the prototype could be manufactured by casting but the mould and the casting model are made of some cheap material,
- scale models could be utilized,
- rapid prototyping could be used (the geometry of the component is laser sintered according to the computer aided model).

One serious problem is that if the prototype is not manufactured with the final manufacturing technology, at least some of the geometrical limits are compromised. E.g. there are important rules for designing a product for casting or powder metallurgy, which are not necessary if the prototype is manufactured by milling or tuning. In practice this means re-design for final manufacturing, which increases cost. Additionally, the surface quality or dimensional tolerances may have a weak basis if the prototyping scheme relies on a different technology. Based on the results of this research a prototype of the horn antenna device will be manufactured using laser process technology. Table 10.1 presents the most important cost factors for various groups of manufacturing technologies.

There are some derived ratios to estimate MW- and RF-component's total costs. These characteristics are describing the effectiveness of production and the investment costs are taken into account as well. Typical ratios could be as follows:
- costs [€] [↓] / VSWR [dB] [↓]
- costs [€] [↓] / gain [dB] [↑]
- costs [€] [↓] / noise figure [dB] [usually ↓]
- costs [€] [↓] / phase error [rad] [↓]
- costs [€] [↓] / lifetime [h] [↑]
- accuracy [IT-grade] [↓] / attenuation [↓], gain [↑] or noise figure [↓] [dB]
- weight [kg] and dimensions [m^3] of the product [usually ↓]

Table 10.1 Cost factors for various manufacturing technologies

Manufacturing technology	Most important cost factors
Sheet metal work	- tool costs related to the geometry of the work piece - costs will decrease if several manufacturing stages can be done with a multi-processing machine - nesting makes it possible to use sheet metal material cost effectively
Machining	- set-up times - tooling and fixing systems - programming (tool control)
Joining	- set up times - pre- and post treatment after joining

When utilizing these types of ratios the designer calculates e.g. the costs due to changes, which should be made to the product to reduce the VSWR. After that the design procedure continues by calculating the cost ratios for attenuation, noise, phase error etc. The arrows [↑ or ↓] after each unit describe whether the aim is to maximize or minimize the corresponding property. E.g. the designer is searching the minimum manufacturing accuracy (IT-grade) which still satisfies the performance requirements of the desired standing wave ratio. After having collected all the ratios listed above the designer is able to make a numeric and objective comparison between various product alternatives.

11 SOME PRACTICAL RESULTS

During this research two test antennas have been manufactured. We used TIG-welding with the parameters of 120 A, 10 V, DC for the aluminum alloy AlMg3 (with welding consumable AlMg5). The basic geometry was modeled with Solid Works-software from which the cutting data of the sheet metal parts could be produced directly. Welded antenna body without the SMA-connector is presented in figure 11.1. According to the dimensional calculations the standardized SMA-connector's centre pin is too short and we had to manufacture a new pin of aluminum wire. The basic dimensions of the new pin design are presented in figure 11.2.

Fig 11.1 TIG-welded antenna body. The geometry of the open end of the conical horn antenna looks acceptable.

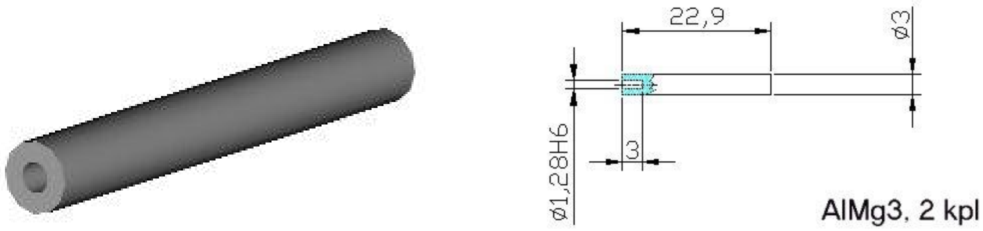


Figure 11.2 The basic dimensions of the new pin design

SUMMARY

In this research a coaxially fed standard gain horn antenna for the frequency range of 1.70 - 2.60 GHz has been designed and during the research also two practical test samples were manufactured. In this paper aspects of design for manufacturability and assembly have been applied to the design and also the possibilities to utilize cross-technological approach method have been examined with successful results. As a case example the DFMA-aspects for laser processing were developed. Methods for calculating the required antenna dimensions has been presented. Manufacturing documents, produced during this research, include also the results of tolerance analysis. Some aspects of selecting suitable aluminum alloy for laser processing have been discussed.

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