International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 10, October-2016

Development of Microwave Ridged Horn Antenna using DFMA Approach

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***Abstract*— Design for manufacture and assembly (DFMA) is aimed at improving the product quality at the mean while reducing the cost and time to manufacture using some laid down structured approach. Antenna is a device which converts electronic signals into electromagnetic waves or vice versa. Microwave antennas used in Electronic Warfare (EW) applications are smaller in size to cater to the smaller wave length. DFMA is one of the few methods available which leads to design optimization on point of view of manufacturing. By adopting DFMA, the design of ridged horn antenna (RHA) is optimized against ease of manufacture and assembly upholding the functional requirement. The paper focuses on the application of DFMA to Electronic Warfare Antennas under development in an R&D environment where the quantity of production is limited and the desired design intends has to be strictly adhered to in a short time frame. The development of Ridged Horn Antenna using DFMA approach is discussed.**

Keywords*— *Microwave Horn antenna, DFMA, Electronic warfare, Design efficiency, CNC

I. INTRODUCTION

DFMA is an amalgamation of two widely accepted methods; “Design for Manufacture (DFM)” and “Design for Assembly (DFA)”. The aim of DFMA is mainly to simplify the Manufacturing and Assembly of a Product. Design for manufacture and assembly is the process by which designs and assembly sequences and procedures are altered to increase the ease and effectiveness of automated assembly (1). There are various means of doing this like simplifying the parts, reducing the number of parts etc. By doing this, finally the price of a product tends to decrease and the functional requirement of the product tends to reach optimum levels.

Eskelinen et al (2000) presented Novel DFMA-Tools for Passive MW- and RF-Components in Cost-Effective Mass Production during 30th European Microwave Conference (2). Harri Eskelinen and Pekka Eskelinen (2003) presented an interdisciplinary approach that combines design and manufacturing, mechanical and electrical design, and microwave component performance and productivity (3). PF Bariani et al (2004) in their paper discusses about how new approach which combines Design for Manufacture and Assembly (DFMA) and Theory of inventive problem solving (TRIZ) is being used for redesign of a Satellite Antenna (4). Harri Eskelinen et al (2004) applied DFMA effectively for the design of coaxially fed standard gain horn antenna. They utilized cross-technological approach method to arrive at an optimum design for the Antenna and discussed practical design guidelines for horn antenna manufactured were arrived at applying DFMA (5).

In Electronic Warfare, Antennas are the eyes and ears of Surveillance or Counter Measure System. Wide ranges and types of antennas are being used depending on the type of application and the frequencies of operations (6). These antennas are basically a mechanical structure which transforms electromagnetic waves into electrical pulses or vice versa. Hence the mechanical structure or housing of an antenna is of prime importance and its design and development requires careful and meticulous plan. In the initial developmental stages, the quantity of production is limited. A costly and time consuming Die or Fixture is undesirable overhead in this scenario. Hence a tool which can simplify the design and manufacturing process of an antenna yet simultaneously take into account design goals and constraints is required during its Research and Development. DFMA is found to be the most effective tool to achieve this requisite. Conventionally, the design and manufacture of a product were viewed as two entirely different activities performed by experts in those fields. DFMA pulls the Mechanical Designer and Manufacturing Engineer as well as the Antenna Expert on to same work table. The manufacturability and assembly of the antenna is therefore thought about by the electrical and mechanical designer right from the design stages of an Antenna.

Design for manufacturability and assembly concepts were successfully applied in development of exponential ridge integrated horn antenna.

II. ROLE OF DFMA IN THE CASE OF ANTENNAS

Development of Antennas requires involvement of experts from multi-disciplinary background. This is indeed a basic requirement of DFM termed as cross-function team (CFT). A cross-functional team is a team composed of at least three members from diverse functional entities working together towards a common goal. This team will have members with different functional experiences and abilities, and who will likely come from different departments. Fig. 1 represents a cross function team structure for development of antennas. In most cases the majority of a product's costs are committed very early in the design and development process. Therefore cross-functional teams are formed at the onset of a project to ensure that all of the key functional perspectives are able to give input into the original concept design.

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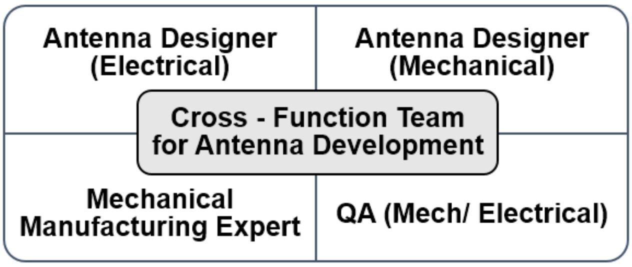

Fig. 1. Cross - Function Team for Antenna Development

The teams assimilate the requirements of the antennas like the band width of operation; the gain required etc and interacts among each other. At this stage, the Antenna Designer formulates the geometry of the transmission line which would give the desired antenna performance. The major dimensions that need to be strictly adhered to are educated to other members. Sketches, drawings are the most commonly used tools. Design alternatives, material alternatives, understanding of the production and assembly process, volume of production and manufacturing costs are the major information flow that takes place within a cross - functional team. A pictorial representation of the evolution of an antenna design incorporating DFMA is given in Fig. 2. Most antennas are invariably assembly of many individual components. Even though the cost of assembly of an antenna may be a very small fraction of the cost of antenna, due attention is to be advocated to achieve the positional accuracies. Properly designed individual components of an antenna keeping the assembly in mind not only takes less time to assemble but also help to achieve the desired design intends like exact symmetry, concentricity, spacing etc. which has high bearing on the performance of the antenna.

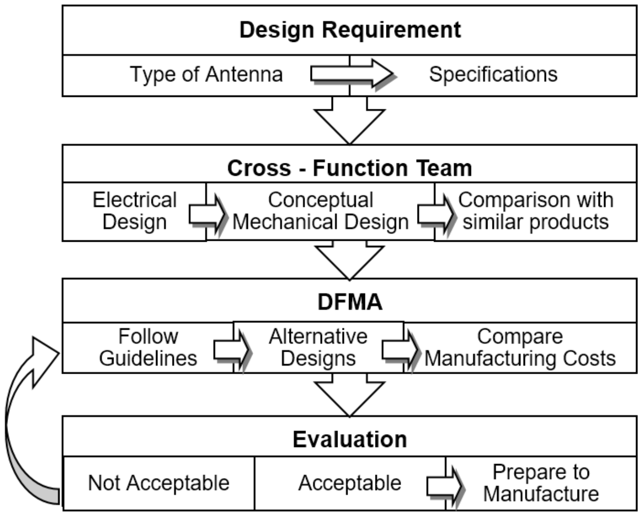

Fig. 2. DFMA Flowchart for Antenna Development

III. RIDGED HORN ANTENNA

Horn Antennas are widely used for calibration and gain measurements. Major attributes of horn antennas are that they can be excited easily and have a fairly larger gain and directionality. However, they can operate only in limited bandwidth. To increase the bandwidth of horn antennas, Ridges are introduced which can be elliptical, conical, hyperbolic, exponential or parabolic in construction (7).

A. Functional Requirements of Horn Antenna

In Horn antenna, a sinusoidal voltage source is applied through a connector across a two conductor transmission line, which in this case is the co-axial feed. Sinusoidal electric fields are created due to this voltage, which in turn produces electric lines of forces as shown in Fig. 3. The free electrons in the coaxial transmission line are displaced by these electric lines of forces causing current flow and creation of magnetic field. Since the electric and magnetic fields thus produced are sinusoidal electromagnetic (EM) waves are created between the co-axial feed. These waves then enter the antenna transition region which in this case is the region between the ridges and are guided into the free space. The cavity, the flare and wedge all plays an important role in transmission of the EM Waves.

Hence the design requirement of horn antenna is to provide a mechanical housing which can:

- Hold the transmission lines which is the co-axial conductor assembly in space.
- Provide a suitable reflective cavity for the waves created.
- Make available a transition line to direct the EM waves into free space.

B. Factors affecting performance of Horn Antenna

The performance of horn antenna depends on the dimensional accuracies of the individual components, quality of their surface, form accuracies like concentricity, perpendicularity, and symmetry of the entire assembly and positional accuracy of the transmission line, transition region and the cavity.

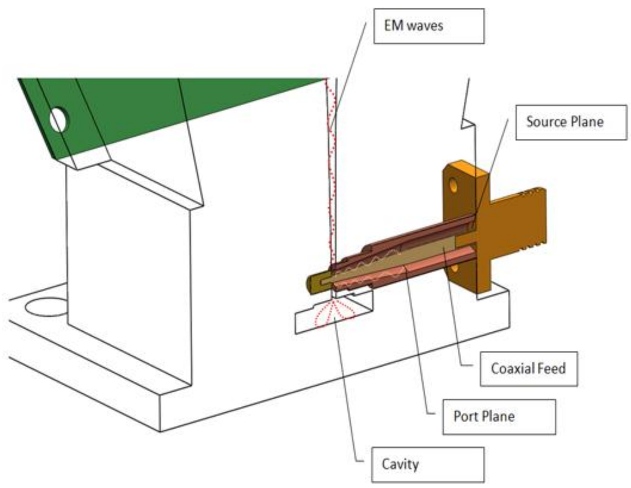

Fig. 3. Working Principle of Horn Antenna

C. Ideal List of Components of Ridged Horn Antenna

If manufacturability is not taken into account, the ideal number of parts that would consist in a Ridged Horn Antenna is as shown in Fig. 4 and as listed in Table I.

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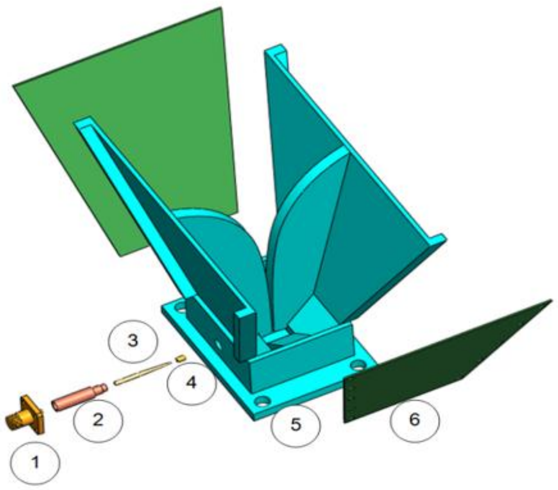


Fig. 4. Ideal number of parts for Ridged Horn Antenna

TABLE I. IDEAL LIST OF COMPONENTS FOR RIDGED HORN ANTENNA

Part No.	Part nomenclature	Qty (Nos)	Remarks
01.	Connector	1	Electrical part
02.	Outer Conductor	1	Electrical part
03.	Inner Conductor	1	Electrical part
04.	Inner Conductor Bush	1	Electrical part
05.	Mechanical Housing	1	Mechanical part
06.	Printed Circuit (PC) Card.	2	Electrical part
07.	Fasteners	24	4 for connector, 20 for PC card assembly

IV. CONVENTIONAL DESIGN OF RHA

The mechanical parts of horn antenna manufactured using conventional design are shown in Fig. 5. The components of ridged horn antenna are sub divided into two categories namely mechanical parts and electrical parts for source plane, coaxial feed and PC card. The list of mechanical parts is given in Table II.

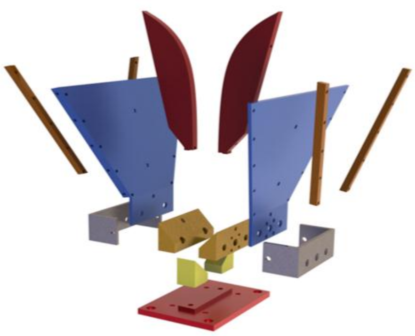


Fig. 5. Exploded view of RHA conventional design (Mechanical parts)

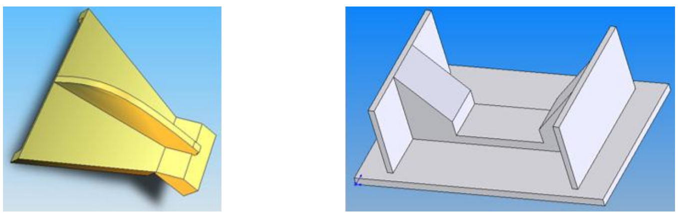
TABLE II. LIST OF MECHANICAL PARTS OF CONVENTIONAL RHA DESIGN

Part No.	Part nomenclature	Qty (Nos)
01.	Bottom Flange	1
02.	Side Cover	2
03.	Lower Flare	2
04.	Wedges	2
05.	Wedge Base	1
06.	Upper Flare	2
07.	Upper Flare Flange	4
08.	Ridge	2
09.	Fasteners requirement for assembly of :	
	a) Upper Flare Flange	24
	b) Ridge	6
	c) Lower Flares + Wedges	2
	d) Side Cover	12
	e) Bottom Block	10

V. DFMA DESIGN OF HORN ANTENNA

One of the main considerations of the DFM principle is to reduce the number of components (8). The mechanical housing discussed in Section III.C is a single integrated entity which is an ideal condition. Manufacturing of this integrated part is a difficult and uneconomical. In the conventional design, the housing is broke down into a number of components of simpler geometries. To achieve desired performance of the antenna, strict tolerances have to be maintained to all the parts in the conventional design which is a costly and time consuming overhead in manufacturing. From functional point of view of the antenna, the electrical parts as mentioned in Table I were kept constant as they are not permissible to modify.

Horn was redesigned applying DFMA principles for ease of manufacture together with use of standard fasteners and cutters. The redesigned horn provided with guide features, incorporation of symmetry aspects, use of proven manufacturing methods and minimum assembly planes. The exponential ridge integrated with top / bottom plates and wedges along with mounting flanges, forming the three dimensionally elevated part as shown in Fig. 6(a). The bottom flange, side covers, wedges and wedge base have been designed as single wedge block housing as shown in figure 6(b). The redesigned mechanical parts after applying DFMA is listed in Table III.



a) Ridge integrated plate b) Wedge block housing

Fig. 6. Redesigned parts after implementing DFMA

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TABLE III. LIST OF MECHANICAL PARTS OF DFMA DESIGN

Part No.	Part Nomenclature	Qty (Nos)
01.	Ridge Integrated Plates Each consisting of Lower Flare (1No) + Upper Flare (1No) + Upper Flare Flanges(2Nos) + Ridge (1No)	2
02.	Wedge Block Housing Each consisting of Bottom Flange (1No) + Side Covers (2Nos) + Wedges (2Nos) + Wedge Base (1No)	1
03.	Fasteners required for assembly of Ridge integrated Plates with Wedge block housing	2

VI. DESIGN EFFICIENCY CALCULATIONS

The application of DFMA rules properly is of utmost importance in order to achieve the desired positive results. Further, there has to be a scale of measure to rank the degree of optimization achieved. There are several methods available which gives step by step procedure to quantify and rate the manufacturability of the Design. Some of the methods being used popularly by the manufacturing fraternity are:

a) Boothroyd-Dewhurst Method

b) Hitachi assembability Evaluation Method (AEM)

c) Lucas DFA Method

In this research, Boothroyd-Dewhurst (B-D) Method was used for computing and quantifying the improvement in design of horn antennas by applying DFMA guidelines. This method defines design efficiency (Ema) as the ideal assembly time divided by the estimated assembly time as given below (9).

$$E_{ma} = \frac{N_{\min}\, t_a}{t_{ma}} \qquad (1)$$

Where:

- N_{min} is the theoretical minimum number of parts
- t_a is the basic assembly time for one part (The basic assembly time is the average time for a part that presents no handling, insertion, or fastening which is equal to 3 Secs).
- t_{ma} is the estimated time to complete the assembly of the product

The Design efficiency was calculated as per the Boothroyd – Dewhurst Method and using equation (1) for both the designs and given at Tables IV and V respectively.

TABLE IV. DESIGN EFFICIENCY CALCULATION FOR CONVENTIONAL DESIGN

Part No.	No of repeats	Handling code	Handling time	Insertion code	Insertion time	Total time t_{ma}	Esse-ntial ? N_{min}	Part Nomenclature
01	01	00	01.50	00	01.50	03.00	1	Bottom Flange
02	02	03	02.18	00	01.50	07.36	0	Side Cover
03	02	32	02.70	00	01.50	08.40	0	Lower Flare
04	02	32	02.70	00	01.50	08.40	0	Wedges
05	01	03	02.18	06	05.50	07.68	0	Wedge Base
06	02	33	02.51	02	02.50	10.02	0	Upper Flare
07	04	30	01.95	08	06.50	33.80	0	Upper Flare Flange
08	02	33	02.51	13	06.00	17.02	1	Ridge
09	01	11	01.80	06	05.50	07.30	1	Connector
10	01	00	01.50	01	02.50	04.00	1	Outer conductor
11	01	08	02.45	01	02.50	04.95	1	Inner conductor
12	01	09	02.98	21	06.50	09.48	1	Bush
13	02	33	02.51	00	01.50	08.02	1	PC Card
Fasteners								
14	24	12	02.52	00	01.50	96.48	0	Upper Flare Flange
15	06	12	02.25	00	01.50	22.50	0	Ridge
16	02	10	01.50	06	05.50	14.00	1	Lower flares +wedges
17	12	12	02.25	00	01.50	45.00	0	Side Cover
18	10	12	02.25	00	01.50	37.50	0	Bottom Block
19	04	12	02.25	00	01.50	15.00	1	Connector
20	20	12	02.25	00	01.50	75.00	1	PC Card
					Total	434.9	10.00	
Design Efficiency (E_{ma}) = 3*10/434.9 = 6.89								

TABLE V. DESIGN EFFICIENCY CALCULATION FOR DFM DESIGN

Part No.	No of repeats	Handling code	Handling time	Insertion code	Insertion time	Total time tma	Esse-ntial ? Nmin	Part nomenclature
01	01	00	01.50	00	01.50	03.00	1	Wedge block housing
02	02	03	02.18	00	01.50	07.36	1	Ridge integrated plate
03	01	11	01.80	06	05.50	07.30	1	Connector
04	01	00	01.50	01	02.50	04.00	1	Outer Conductor
05	01	08	02.45	01	02.50	04.95	1	Inner Conductor
06	01	09	02.98	21	06.50	09.48	1	Inner Conductor Bush
07	02	33	02.51	00	01.50	08.02	1	PC Card
Fasteners								
08	02	10	01.50	06	05.50	14.00	1	Lower flares + wedges
09	04	12	02.25	00	01.50	15.00	1	Connector
10	20	12	02.25	00	01.50	75.00	1	PC Card
					Total	148.1	10.00	
Design Efficiency (E_{ma}) = 3*10 / 148.11 = 20.25								

VII. MANUFACTURING ASPECTS OF RIDGED HORN ANTENNA

The DFMA based new design was examined for its manufacturability. The challenge was to manufacture these components in lesser number and smaller time frame. The exponential profiled ridged top and bottom plates are three dimensionally elevated parts. Successful manufacture of this part depends on operation sequencing and work piece holding. Operation sequence was planned such that, without any special holding fixtures the machining of work piece was completed. The machining sequence, work holding positions and tool path are depicted in Fig. 7. The ridge profile at horn throat is an important requirement and it was machined taking utmost care. The tapered wedge portion dialed to achieve positional accuracy in drilling the hole for outer-conductor.

The wedge block housing, ridged top & bottom plates are manufactured on CNC milling machine and extension pin on Mini-CNC lathe. The solid model of parts generated using Computer Aided Design (CAD) software was imported into Computer Aided Manufacturing (CAM) software and Numerical Control (NC) codes were generated for combined top and bottom ridge plates. The wedge block housing was machined in three settings compared to thirteen settings of conventional design version. The work piece was kept vertical and the material of required depth scooped-out. The wedge profile was machined by holding the job in perpendicular plane and removing the material by pocket milling from both sides of the wedge.

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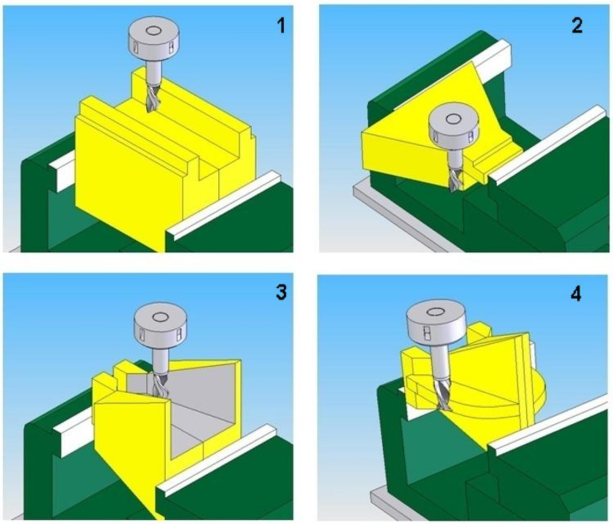

Fig. 7. Work holding and machining sequence of Ridge plate

The functional requirement of antenna assembly was maintenance of predefined gap between the ridges, axial gap between coaxial probes and PC card contact with mounting surface of ridges. Dimensional accuracy of Wedge block housing central web is prime criteria and corresponding ridge plates mating webs lapped to form required gap.

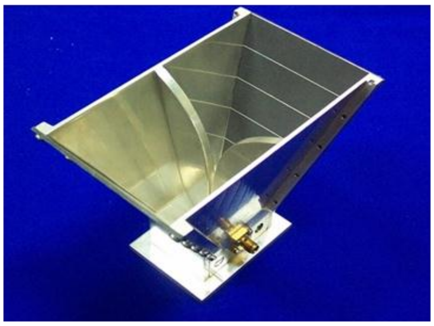

Fig. 8. Photograph of Ridged Horn Antenna

The other obligation in antenna assembly is mounting of PC card on ridged plate surfaces. As the ridged plates are oriented in three dimensions while fixing PC cards on ridged plates, it was making only a line contact. The out-of -phase angle was evaluated and mounting surface machined to requisite angle orientation to convert the line contact to surface contact of mating surfaces. Photograph of Ridged Horn antenna developed adopting DFMA principles is shown in Fig. 8.

VIII. RESULTS AND DISCUSSIONS

DFMA principles applied in development of Ridge horn antenna and the improvements achieved in mechanical and electrical performance are as given below:

- The Ridged horn antenna developed by DFMA approach achieved surface finish of 0.3 microns (Ra) on inner surface, positional tolerance within 10 microns avoiding mismatch and clearance problems. The required gap between ridges and axial gap of coaxial probes was accurately maintained.
- By adopting DFMA design, reduced the work piece setting time for ridged plates and wedge block housing by 60% and 80% respectively compared to conventional design version. Ridge integrated top and bottom plate's internal surface was machined simultaneously to achieve dimensional similarity and machining time reduced by 50%.
- The comparative statement of Design efficiency as well as the number of components and fasteners required for the electrically ideal case and the two design variants are tabulated below in Table VI. From result it is noted that the 3 - fold increase in the design efficiency was achieved with DFMA design compared to the initial conventional design and also DFMA design has only two components more than that of an ideal design.

Sl No	Type of Design	No. of Parts	No. of Fasteners	Design Efficiency (E_{ma})
1	Electrically Ideal Design	7	24	-
2	Conventional Design	22	78	6.89
3	DFMA Design	9	26	20.25

IX. CONCLUSION

In this paper, principles of design for manufacturability and assembly (DFMA) have been successfully applied to the design and manufacturing of ridged horn antenna. The antennas developed by following innovative machining process sequence resulted in elimination of the clearance, mismatch problems and achieved the dimensional accuracy and similarity. Significant improvements were achieved in mechanical and electrical aspects of microwave ridged horn antenna by implementing DFMA guidelines. By adopting DFMA, the design efficiency of ridged horn antenna was increased more than 65%.

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