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A Study and Modeling of High Pressure Radome with Uwb Frequency Coverage in Submarine Communications

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ABSTRACT - *Modern submarines require high reliability communication systems for communicating the strategic and tactical information to the shore and other participating units during the operations. Traditional submarines having the retractable masts for fitment of various communication sensors and these masts were lifted during the operation, when submarine is diving at periscope depth. This leads to exposure of submarine to the aircraft attacks and aircraft can easily destroy the submarine operations. Many techniques have been in use to counter these operations. However, a concept i.e. "anywhere and anytime" communications is the need of the hour for survival of the submarines. This is basically, when submarine in diving, the communication needs to be established with the external establishments like, satellites, ships, submarines, base stations, etc.,. Many research labs are working on these concepts to develop the system and the electronics sensors like antennas, need a high pressure radome to house them. The challenge is to have a high pressure radome with ultra wide band frequency coverage with low loss tangent. The author has designed and developed a high pressure radome covering frequencies from 15 KHz to 18 GHz to meet the submarine applications. The details are presented in this paper.*
Key words**:** Band width Ratio (BWR), Electronic Warfare, Impedance, Fiber Reinforced Plastic, Loss tangent, Ultra Wide Band (UWB)

I. INTRODUCTION

Submarines need to communicate with external agencies during strategic and tactical operations. The operations include line of sight communications, satellite communications, Intelligence gathering, maritime distress operations and safety operations. These systems operate in various frequency bands covering from 10 KHz to 18 GHz. A typical frequency ranges are given below at Table-1.

Table 1 Frequency ranges of various sensors on submarine

S. No.	Sensor	Typical global frequency ranges
1.	VLF / HF	Reception 15 KHz – 30 KHz & Reception 3-30 MHz
2.	V/UHF	Transmission & Reception 110 – 160 MHz & 200 - 400 MHz
3.	IFF	Transmission & Reception from 1030 – 1090 MHz
4.	UHF SATCOM	Tx 290–320 MHz, Rx 240 – 270 MHz
5.	S Band SATCOM	Tx 2670-2690 MHz & Rx 2500-2520 MHz
6.	GPS	Reception 1575.42 MHz
7.	GLONASS	Reception 1602 - 1610 MHz
8.	IRNSS	Reception 2.49 GHz
9.	GMDSS	Transmission 121.5 MHz, 156.8 MHz, 402 MHz
10.	ESM	Early Warning Receiver from 1-18 GHz

Typically these systems are WB and UWB systems [1] operating beyond 500 KHz bandwidths. The details of systems are like ESM, Satellite communications, etc., are presented in [4-5]. The radome covering these sensors is also UWB as the radome is covering from 15 KHz to 18 GHz.

The basic function of a RADOME is to protect the antenna from the external environment with minimal impact on the electrical performance of the antenna. This means, ideally, the radomes should be electrically transparent. The matching of material composition to a particular application and the RF frequency range decides the performance of the radome for its intended use. The development of radome for submarine applications is a challenging task due to various constraints like size, weight, corrosive atmosphere, leak proof joints and strength etc.,. The task involves meticulous material selection, design and analysis based on the strength and functional requirements, manufacturing, testing and proving the hardware. Many researchers have succeeded in designing of radomes for various communication purposes for platforms like aircrafts, satellites, ships and submarines and many of these applications are narrow band systems. The design and development of radome for submarine applications covering a very wide band of operation is presented in this paper.

II. LITERATURE SURVEY

Many researchers have succeeded in design submarine based radomes for strategic and tactical communication purposes, but for narrow band applications only. Radomes for ultra wide band frequency requirements for submarines are undergoing many studies. An extensive literature survey is undertaken in this area and many academic journals, publications, scholarly articles are referred. The details of literature survey are presented in the following paragraphs.

Anil Prakash and SkAbhishek [6] have presented the design and analysis of airborne radomes, explaining the strength and pressure requirements. The authors

have presented deformation profiles when the radome with thickness of 1.6mm and 5.6 mm, are subjected to wind velocity of 0.8 mach. The authors have concluded through wind tunnel test that radome with 5.6 mm thickness with synthetic foam is suitable for airborne applications

Mr. N. V. Srinivasulu et al., [7] presented paper on design and analysis of submarine radome. The paper explains that E glass/epoxy radomes are inferior compared to Aramid fibres in strength and dielectric constant. The dielectric constant and loss tangent of the aramid/epoxy composite measured by free space measurement method were 3.742 ad 0.018 and E-glass/epoxy composite were 4.686 and 0.015 and preferred aramid material to E glass. However, to meet the requirements of RF transparency and high stress requirements, hybrid composites were suggested by authors for submarine based systems

Dr. Dirk baker [8] SAAB Avionics has presented a paper at AOC conference and explained that A sandwich radome is suitable for UHF frequency ranges. The author has developed model and tested the radome for RF transparency, high pressure capability of 75 bar and presented the results and thus suggested that the radome with foam core is suitable for UHF band of frequencies

Mr. Ch. Viswanadham [9] Bharat Electronics Limited, has presented various material properties used for radomes for ultra wide band frequency of operation. The author has mainly concentrated on thin wall radome used for EW applications and the use of absorbing material placed inside the radome for shaping beam of the antenna. Many equations related to radome are presented by the author. The author has clearly brought the relation between material properties and the construction methodologies in radome technologies.

Mr. Mikko Kurri and Mr.AskoHuuskonen [10] have presented in their paper the effect of rain intensities on the loss of transmission. The paper brought out that water running on a surface of a radome has great impact on transmission loss. A 3 dB two way transmission loss of a radome is achieved at the rain intensity of 15.1 mm/h. The paper also presented the measurements for the reduction of transmission loss by waxing the radome through 1.5 dB.

Competition Composites Inc (CCI), Canada [13] presented a paper on various types and classes of radomes based on the frequency of operation. It was discussed that the core thickness would vary from 1 in at 3 GHz to ¼ in at 8GHz in order to maintain minimum transmission losses.

Eli Levine [14] has discussed in a presentation on selection of wall thickness for different radomes. He has suggested that mechanical aspects dominate in the design of radomes for broad beam sensors and EW systems

M. Madhusudhana Rao et al., [15] studied about the failure of underwater shells subjected to high external pressure due to buckling and observed that the specific stiffness of the reinforcing fibre plays an important role and suggested high strength carbon epoxy shells with ultra high modulus fibres in the thickness portion and also for the circumferential stiffening rings would augment buckling strength considerably without any weight penalty.

III. DESIGN METHODOLOGY

3.1. Design Specifications

The design specifications of the product i.e., the Radome, are derived from the operational parameters of the end product. These requirements are built-into the.

design to make it completely comply with the desired intended use. Thus the Radome specifications are derived from system specifications, which are explained below respectively.

3.1.1. System operational conditions are

- Maximum depth of operation: not less than 300m
- Maximum tow speed : 25 knots
- Recovery speed : 25 knots
- Continuous operation – 8 hr
- Two way Tactical and Satellite Communications
- Frequency scanning

3.1.2. The operational parameters of Radome are

- Maximum pressure : 75 sustained
- Temperature range: -5 to +65 degrees Centigrade
- Maximum compressive force: 10 kN
- Radome RF transparency up to 18 GHz.
- Insertion loss(< 3dB) and insertion loss variation over 360° azimuth (<1 dB)
- Light weight, to be 30-35 kg with outside diameter not to exceed 300mm and to accommodate antenna system of diameter 265mm
- Material should withstand impact damage without abruptly cracking, when subjected to explosive forces or on direct impact of shrapnel.
- Material to have low creep and low fatigue characteristics

Based on the above specifications, following design method is implemented for this work.

- Basic Material selection
- Study of various RF transparent materials
- Selection of the material
- Coupon manufacturing
- Design validation (mechanical and Electrical)
- Finalization of wall thickness
- Simulation & analysis of Radome
- Simulation for mechanical properties
- Electrical parameters
- Fabrication and Testing

3.2. Material Selection

Based on the above requirements, various materials have been studied for selection. A variety of materials have been used for construction of radomes like Balsa and Plywood etc., But the demanding requirements of mechanical and electrical properties led to the invention of composite materials. Various fibre reinforced plastics came into existence. The study and comparison of commonly used FRP material like E-glass with the specialized material is carried out to finalize the most suited option for this design application.

3.2.1. Composite Selection Criterion

A composite is a structural material with two or more constituents combined at macroscopic level and are not soluble in each other. One constituent is called 'Reinforcing Phase' and the one in which it is embedded is called 'Matrix'. The reinforcing phase material may be in the form of fibres, particles or flakes. The matrix phase materials are generally continuous.

3.2.2. Reinforcement

The main function of reinforcement is to improve the overall mechanical properties of the composite. In general, these reinforcement materials will have higher tensile strength and young modulus than that of matrix material and used in the form of materials. Many materials like glass fibres (E, A, C, S, Z, M & D), carbon fibre, graphite, boron fibre, asbestos, whiskers, kelvar etc., are in use as reinforcement materials [12]. The various design consideration for selection of Reinforcement are:

- Part curvature
- Ply thickness
- Laminate ply orientations
- Machining
- Weaving styles (drape)
- Matrix Systems

The plastic phase which holds together the reinforcing fibres is called Matrix. The plastic material acts as the medium, through which load is transferred from one fibre to the other fibre. Also the matrix protects the reinforcing fibres from weather and provides shape and finish to the composite material. There are variety of matrix materials available, some additives are loaded to the matrix to get desired improved properties like hardness, temperature resistance etc., and these additives include curing agents, fillers and stabilizers. The two types of resins are Thermoplastics resins and thermosetting resins. Thermo plastic resins play a very important role in composite industry – Polyster, Vinyl Ester, Epoxy, Phenolic resins and Cyanate Ester etc are the mostly used matrix materials. Various design considerations for selection of resin compatible to fibres are

- Fiber sizing compatibility and wetting
- ILSS (inter laminar shear)
- Water absorption
- Cure temperature and related items: laminate residual stresses, tooling expansion, upper use temperature, composite glass transition temperature and micro cracking
- Flow characteristics and processing method
- Mechanical properties: shear and tensile strength, modulus and strain compatibility with the reinforcing phase
- Physical properties: out gassing, moisture absorption/diffusivity/swelling
- Toxicity and health concerns
- Cost, availability, lead time, and stable supply source

3.2.3. Matrix Selection

Although epoxy is more expensive than other resin systems, the advantages outrun the disadvantages [11]. Epoxy has much better physical and adhesion properties compared to polyester and/ or vinyl ester. Based on its properties, this resin system is used in various industries including the aerospace, automotive and marine industries.

The mechanical properties and its resistance for environmental degradation and water resistance makes the epoxies most suitable for marine applications. The adhesive properties and the low shrinkage are further benefits of epoxies. Finally, epoxies cure easily and quickly making them beneficial for numerous projects. These epoxies need a hardener in order to start curing process and therefore, needs skill to handle this material. Due to its outstanding advantages, it is the most suitable for marine applications and therefore, chosen as resin for the present design.

3.2.4. Fiber Selection

The designer has a wide range of fibres to make suitable selection. Often a fibre is selected because of physical properties. For example, graphite or carbon fibres are electrically and thermally conductive, while aramid (Kevlar®) and glass fibres are non-conductive. In certain applications, such as an antenna reflector, electrical conduction is required. Hence, graphite (carbon) fibres are generally chosen for reflector-type applications. In other applications, for example a radome, radar transmissibility is desired. Here, Kevlar® and glass fibres are the materials of choice. Though Kelvar is a stronger material than glass fibres, its disadvantage of moisture absorption and poor compressive strength put them on lagging line for the present application of submarine radomes [7]. Fibre selection should also consider mechanical and thermal properties. The salient mechanical properties are modulus and strength. Those for thermal properties include coefficient of thermal expansion

(CTE) and thermal conductivity. Below Table -2 presents typical properties of some commercially available fibers presently utilized for space, spacecraft and marine structures.

Table 2 Material composition of different Glass Fibers [9]

Composition	E glass	H glass	S glass
Silica SiO_2	54%	94%	65%
Alumina AL_2O_3	14%	Nil	25%
Calcium oxide CaO+ Magnesium Oxide MgO	22%	2%	10%
Boron oxide B_2O_3	5 to 8%	Nil	-
Na_2O+K_2O	<2%	3%	0.1%
Fe_2O_3	0.5%	---	0.1%

The important characteristics of these materials are enumerated below.

E glass Fibers

(a) E-Glass or Electrical grade glass was originally developed for stand-off insulators for electrical wiring. It was later found to have excellent fiber forming capabilities and is now used almost exclusively as the reinforcing phase in the material commonly known as fiber glass. Glass composition (Weight %): E-Glass is a low alkali glass with a typical nominal composition of SiO_2- 54wt%, Al_2O_3- 14wt%, CaO + MgO-22wt%, B_2O_3- 10wt% and Na_2O+K_2O less then 2wt%. Some other materials may also be present at impurity levels.

(b) Properties that have made E-glass so popular in fiber glass and other glass fiber reinforced composite include:

- Low cost
- High production rates
- High strength and High stiffness
- Relatively low density
- Non-flammable and Resistant to heat
- Good chemical resistance and Electrical insulation
- Relatively insensitive to moisture
- Able to maintain strength properties over a wide range of conditions.

(c) The advantageous properties of E-glass generally outweigh the disadvantages which include:

- Low modulus
- Self abrasiveness if not treated appropriately leading to reduced strength
- Relatively low fatigue resistance
- Higher density compared to carbon fibers and organic fibers.

Hollow glass fibers (H-glass)

(a) Hollow glass fibres are made of a proprietary blend of alkali-free alumina-borosilicate glass using unique precision manufacturing technology and platinum multi-spin dyes resulting of special "tube like" continuous structural glass fibres with an outer diameter of 10 - 12 µm and inner capillary „tunnel" of 5 - 6 µm [14]. Continuous hollow glass fibres manufacturing process is patented. With their unique properties, combining low weight, high specific strength and energy absorption capabilities, H-glass fibres became very attractive engineering materials for use in the advanced composites and aerospace/ naval industries. Glass composition (Weight %) H-Glass has a typical nominal composition of SiO_2- 94% with Al_2O_3- 0%, CaO+MgO- 10%, B_2O_3- 0% and Na_2O+K_2O less then0.1wt%. Some other materials may also be present at impurity levels.
Characteristics

(b) H-glass is a lower density fibre in comparison with 'solid' E-glass or S-2 Glass, thus reducing the overall weight of cured laminates by up to 40 %! H-glass is more elastic, has higher compression strength and specific strength characteristics compare to 'solid' E-glass fibres. The hollow structure of H-glass fibres is responsible for significant improvement in their dielectric, thermo-insulating and acoustic insulation properties in comparison to standard 'solid' glass and carbon fibres.

(c) H glass fibre based composites serve as a very efficient energy and shock absorbers. There are two variants normally used (density variants –grams sq meter) in H glass fibres – 160 gsm and 220 gsm

S-glass fibers (S-glass)

(a) Though E-Glass has been used extensively in polymer matrix composites, which exhibit good mechanical properties, these have not been sufficient in some instances. Consequently, the E-glass composition has been modified to produce more desirable properties. A higher stiffness material resulting from this is S-Glass. Glass composition (Weight %). S-Glass has a typical nominal composition of SiO_2 65%, Al_2O_3 25%, MgO 10%. Some other materials may also be present at impurity levels.

(b) Key Properties Properties that have made S-glass so popular in fibre glass and other glass fibre reinforced composite include:

- High production rates
- Improved mechanical properties compared to E-glass
- High strength
- High stiffness
- Relatively low density
- Non-flammable
- Resistant to heat
- Good chemical resistance
- Relatively insensitive to moisture
- Able to maintain strength properties over a wide range of conditions

(c) The advantageous properties of S-glass generally outweigh the disadvantages which include:

- Significantly higher cost compared to E-glass
- Self abrasiveness if not treated appropriately leading to reduced strength
- Relatively low fatigue resistance
- Higher density compared to carbon fibres and organic fibres.

3.3. Coupons Testing – Mechanical properties

Having studied different reinforcement materials and matrix materials, standard coupons of sizes 25 x25 x10 cm are made for E glass, S glass and H-glass with Epoxy with two variants viz., 160 gsm and 220 gsm . The coupons were tested for mechanical properties.

The summary of the properties are presented in Table 3. The results revealed that H glass is most suitable for the present application. Both variants of H glass almost exhibit the same performance with little superior characteristics of H 220 gsm. To arrive at the optimum solution, accordingly, H-glass with two variants (160 gsm and 220 gsm) with Epoxy matrix is chosen for further analysis through modelling and simulation for the project under study –Ultra Wideband Radome for submarine.

Table 3 Test Results of Coupons – E glass, H glass and S glass

Description of structural parameters		E-Glass	H-Glass		S-Glass
			160gsm	220gsm	
Mechanical properties					
Density (kg/m^3)		2100	1600	1600	2000
Tensile (Mpa)	Strength	240	178.8	196.4	225
	Modules	45000	15620	17620	50000
Compression (Mpa)	Strength	220	248	232.5	215
	Modules	12000	17180	21350	8000
Flexural (Mpa)	Strength	---	314.6	320.33	---
	Modules	---	15000	15966.6	---
ILSS (Mpa)	Strength	46	35.76	38.78	42
RF Properties					
Dielectric constant		4.06	2.9	2.9	4.6
Dielectric loss factor		0.02	0.01	0.01	0.02

3.4. Coupon Testing - Electrical properties

The coupons (16 mm and 18mm thick) are tested for electrical properties also for dielectric constant and loss factor (loss tangent). The results reveal that H glass has the lowest factors. The H glass coupons are also tested for insertion loss, using network analyzer, for the frequency band of 15 kHz to 18 GHz - both in horizontal polarization mode and vertical polarization mode. The insertion loss for one measurement is presented below at Figure--1 for understanding the performance. The samples with 16mm thick and 18mm thick coupons exhibited same electrical performance over the frequency ranges [10]. Therefore, the thickness of wall, meeting the mechanical strength requirements plays an important role in the design of Radome.

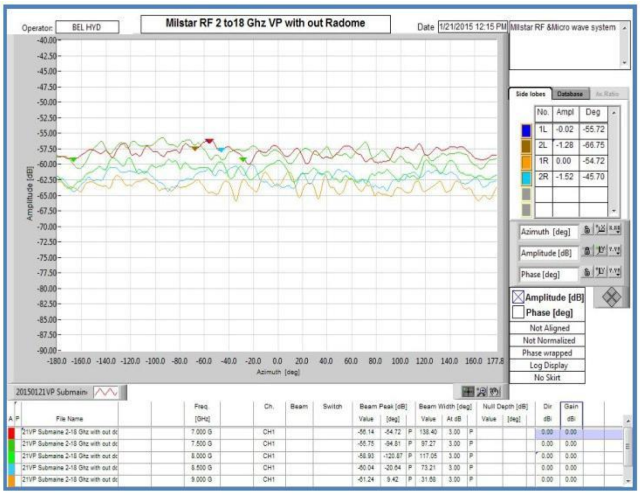

Figure 1 Insertion loss properties – Vertical polarization

3.5. Finalization Radome wall thickness

The case under study requires the radome to function electrically transparent for the following frequencies (multi-function antenna)

- Communication and reception over VLF (15 to 30 KHz) and HF (3-30MHz)
- Transmission and reception in VHF (110-160 MHz), UHF (200-400 MHz)
- Satellite communication – low power voice and data communication over UHF (200-400MHz) and S band (2.5-3.5 GHz)
- ESM reception over 1-18 GHz

The above would reveal that the requirement is spread across a very high band from 15 KHz to 18 GHz - and the radome should support ultra wide band multi frequency antenna system. Literature Survey revealed that various types of radomes are exclusively made for different frequency bands with narrow bandwidth, as follows [13].

- For Frequencies of 10–20 GHz, appropriate selection is thin or thick radome with suitable loss tangent dielectric material
- λ/2 solid laminate is the natural choice.
- A thick sandwich type also gives good result
- For narrow beam radars, the radome structure and shape is extremely important with composite material of loss tangent <0.004. Plastics with special fibre matrix recommended.
- For broad band, EW systems and communications, mechanical aspects are dominant with loss tangent <0.02 [15].

Since the present case study falls under EW system with ultra wide band and mechanical aspects play vital role, the wall thickness estimated based on mechanical loads is considered suitable for electrical parameters also. Further, the coupons of 16mm and 18mm are meeting the electrical parameters. Therefore, the minimum wall thickness of 16 mm is concluded.

3.6. Simulation & analysis of Radome

Based on the above coupons studies, Radome properties are finalized. Radome wall constructions are typically the following categories –

1. Solid (monolithic) or single layer wall
2. Thin Wall monolithic with wall thickness equal to or less than 0.1λ wavelength at highest operating frequency.
3. A sandwich multilayered wall – consisting of 3 layers - two high density skins and a low density core. Dielectric constant of skin is greater than core material – for 0.25λ wavelengths
4. Multi layered wall having 5 or more dielectric layers. As the number increases, performance in broadband frequency improves.
5. Other constructions not fitting in the above with dielectric constant of skins is less than that of the core.

Though the literature survey reveals recommendation of Radome with solid laminate as well as multi layer sandwich type wall for good strength and electrical properties over wide band frequency, it is preferred to use solid laminate cross section in view of the high strength requirements and to avoid susceptibility for failure due to crack propagation, which is aggressive in sandwich radomes when compared to solid wall sections [6]. Further, to withstand the hydraulic pressure of 75 bar, if the wall is of sandwich configuration, the thickness required would be of high order and the design limitation of 16 mm would be defeated. The thickness of 16 mm is very critical in order to maintain the internal diameter as 268 mm to accommodation the multi function antenna.

Therefore, it is proposed to carry out the experiments through modeling and simulation using ANSYS ACP software with the following composite material (H glass Epoxy with loss tangent of 0.016), for validating the design for normal stresses, inter laminar shear stress, buckling strength and failure analysis with H glass 160 gsm and 220 gsm epoxy material with wall thickness of 16 mm. The following table details composite materials, wall thickness and type of wall section of radome under study.

Table 4 Details of radome material and wall configuration

Composite material + matrix	Wall thickness	Thickness of lamina	No of layers in the stack	Type of Wall section
H glass Epoxy -160 gsm	16mm	0.2 mm	80	Solid Multi layer
H glass Epoxy 220 gsm	16 mm	0.3 mm	53	Solid Multi layer

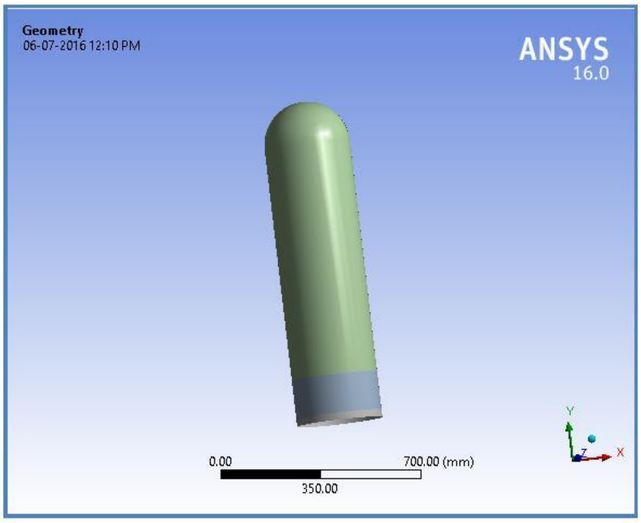

Figure 2 Surface geometry model

Figure 3 Surface geometry model

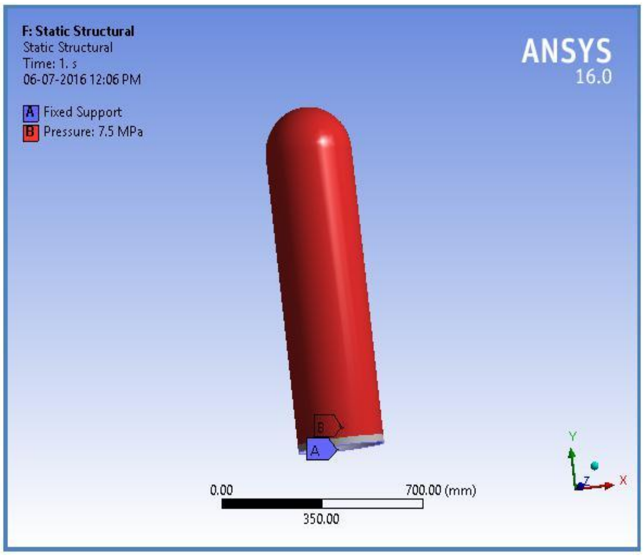

Figure 4 Boundary conditions

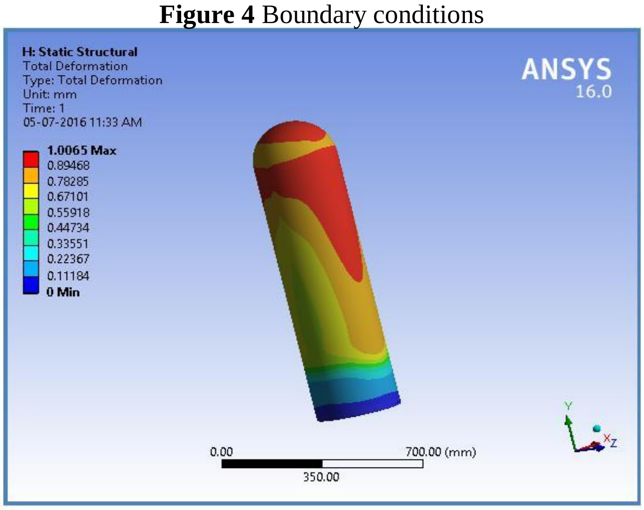

Figure 5 Total deformation (160gsm)

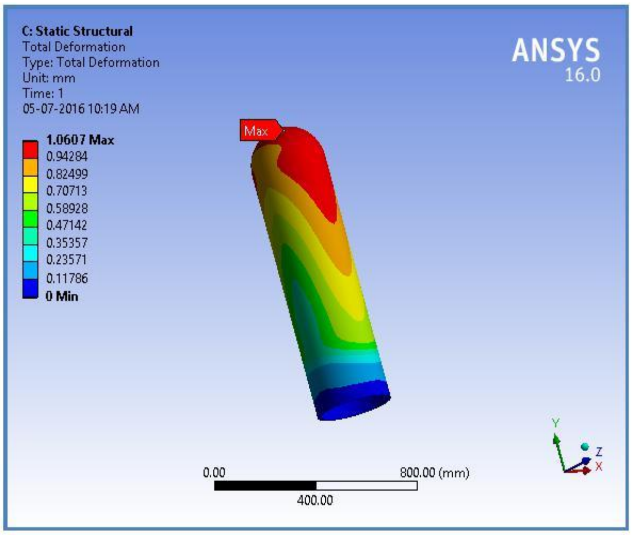

Figure 6 Total deformation (220gsm)

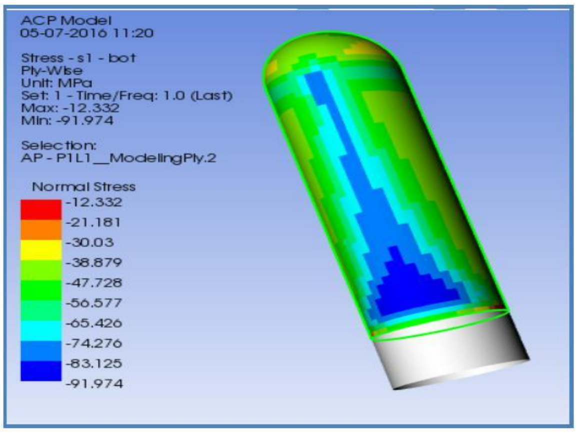

Figure 7 Normal stress (160 gsm)

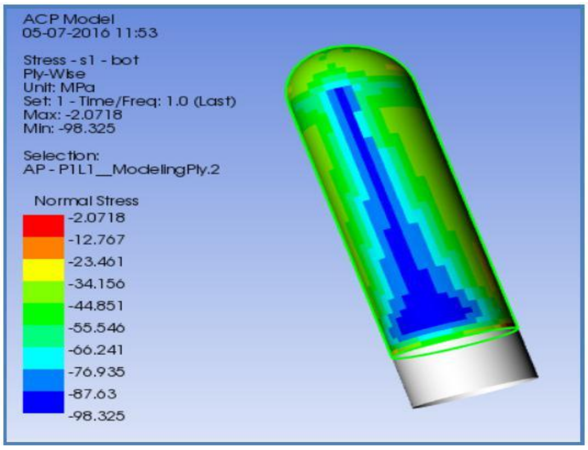

Figure 8 Normal stress (220 gsm)

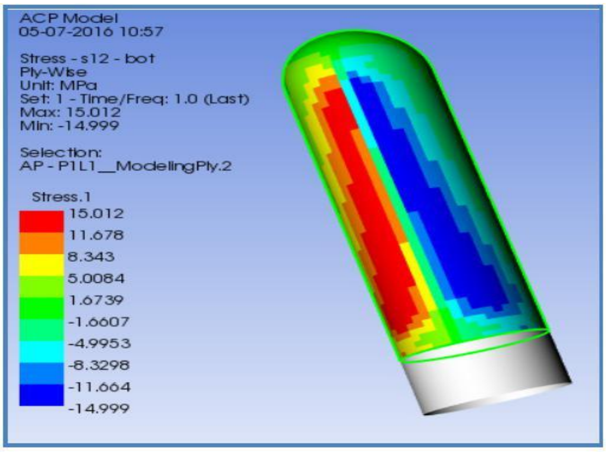

Figure 9 In plain inter lamina Shear Stress (160gsm)

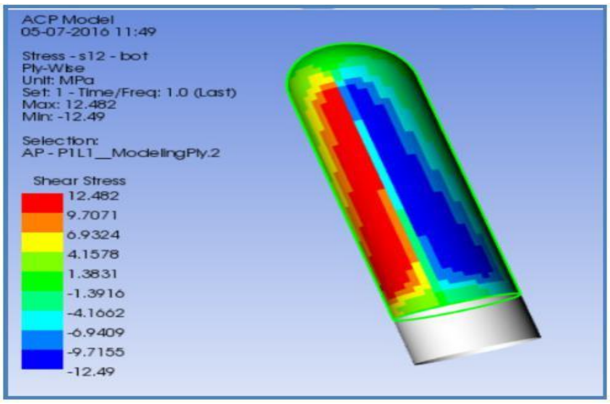

Figure 10 In plain inter lamina Shear Stress (220gsm)

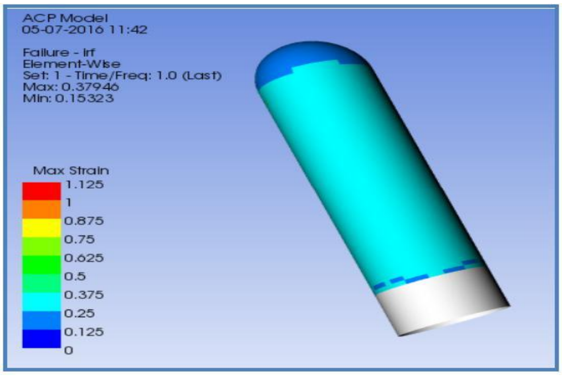

Figure 11 Max strian for 160 gsm

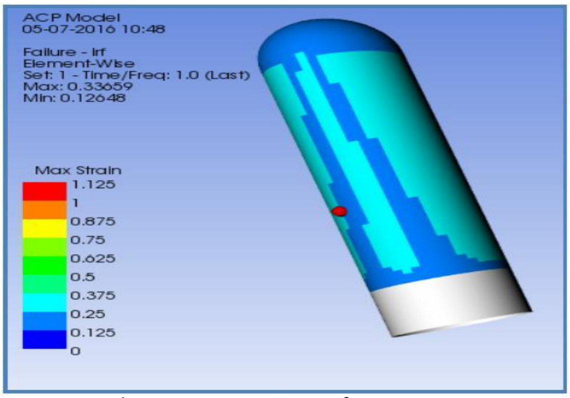

Figure 12 Max strian for 220 gsm

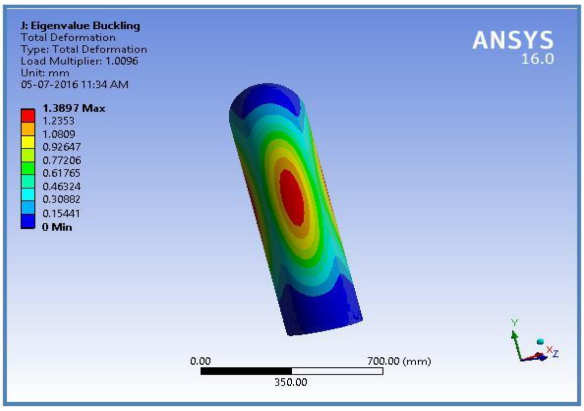

Figure 13 First Buckling for 160 gsm

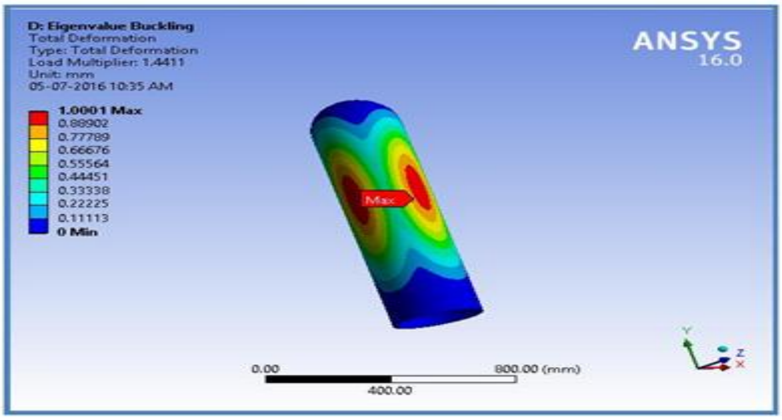

Figure 14 First Buckling for 220 gsm

In addition the above, modal analysis, harmonic analysis and frequency response, etc were simulated and analyzed. Due to space constraint these are presented here.

Simulation of electrical parameters:

The electrical parameters are in agreement with the coupons made with H glass fibers and hence no simulation and analysis has been carried out.

4. FABRICATION & TESTING

Based on the studies, Radome of cylindrical shell with spherical dome of dimensions 300 mm outer diameter and 1400 mm height was manufactured using the standard manufacturing process [8]. The manufactured Radome has a cylindrical shape with wall thickness of 16 mm, pressure withstanding capability of 75 bars and the frequency response of 15 KHz to 18 GHz. The picture of the manufactured Radome is shown at Figure- 15.

Figure 15 H glass Radome with 16 mm thick and 1400 mm height

The above Radome is tested for following mechanical properties.

- Pressure testing in pressure chamber (up to 75 bar, 16 hours)
- Weight measured less than 32 kgs.
- Dimensions 1398 mm height x 299 mmØ
- Thickness: 15.8 mm

The above Radome is tested for electrical parameters at one of the lab in India (Figure- 16 and Figure- 17) and the setup and results are presented at Figure- 18.

Figure 16 Transmitting antenna test setup

Figure 17 Radome with antennas mounted on test platform

The insertion loss at various heights is provided at Figure- 18.

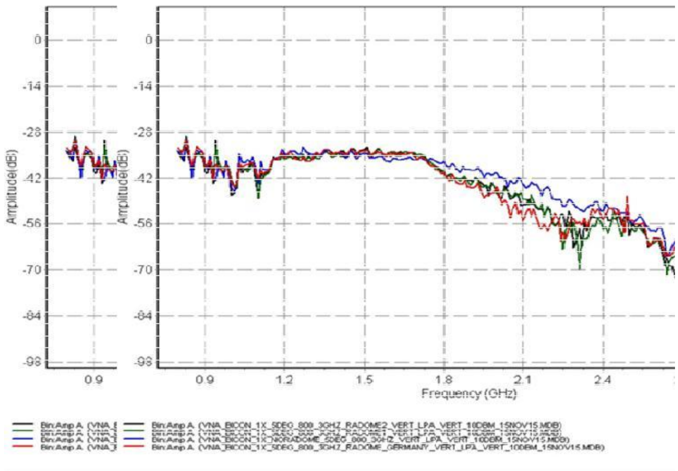

Figure 18 Insertion Loss of radome at various heights

V. CONCLUSION

The UWB Radome for su bmarine based applications with the required specifications is designed, simulated, analyzed, manufactured and tested for perrformance in a systematic approach. Thorough survey of the literature and the inputs from various publications were used foor taking up this work. Further the Radome is suitable for UWB frequency operationns from 15 KHz to 18 GHz and withstanding the pressure of 75 bars for 16 hours.

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REFERENCES

[1] Hans Schantz, Art and Science of Ultra Wide Band antennas, 1st Edition, 2005

[2] Ch Viswanadham, Prof P Mallikarjuna Rao, Experimental Results of Structurally Modified High Power Ultra Broadband Phased Array Antenna for Extending the Operating Frequency Range and Improving the VSWR, ATMS India (16), 01–03 Feb 2016

[3] Ch Viswanadham, Prof P Mallikarjuna Rao, Hybrid tapering and aperture smoothening for improving VSWR of UWB Phased Array Horn Antenna for ECM applications, Submitted for IEEE transactions, Antenna Wave Propagation, 2016.

[4] Richard G. Wiley, Electronic Intelligence: The interception of Radar signals, 1985.

[5] J.D. Walton, JR, Radome Engineering Handbook Design and Principles, McGraw-Hill Book Company, New York, Georgia, Georgia Institute of Technology Engineering Experiment Station, pp. 44–7 – 44–22, 1994

[6] Anil Prakash, SK Abhisheik, Design and Analysis of Radome, International Journal of advanced scientific and technical research, 4(1), Jan–Feb,2014, RS Publications, pp 201–208

[7] N.V. Srinivasulu, Safeeruddin Khan and S. Jaikrishna, Design and Analysis of submarine radome, proceedings of the International Conference on Research and Innovations in Mechanical Engineering, Lecture Notes in Mechanical Engineering, DOI: 10.1007/978-81-322-1859-3-2_Springer India 2014

[8] Dr. Dirk Baker, SAAB Avionics, The challenges of developing a COMINT DF and Monitoring antenna for the High pressure environment of submarine operations, AOC conference, pp. 12–13 Nov, 2008, CSIR, Pretoria

[9] Viswanadham, Ch, A Practical approach for controlling the shape of radiation pattern of Microwave Log periodic Antenna for Wide band applications, IEEE Antenna and Propagation Magazine, 56(5), Oct 2014, PP 304–315

[10] Mikko Kurri, AskoHuuskonen, Measurements and transmission loss of a radome at different rain intensities, Proceedings of ERAD, 2006, Finnish Meteorological Institute, Helsinki (Finland)

[11] Autar K.kaw,"Mechanics of Composite Materials, 2nd Edition, Taylor and Francis Group, New York

[12] R.K. Mallik," Fibre Reinforced Composites, CRC Press, Taylor and Francis Group, New York

[13] Competition Composite Inc (CCI), Radome R&D White Paper, 168, Wescar Lane, Canada, www.fastcomposites.ca

[14] Frederick T. Wallenberger, James C. Watson, and Hong Li, Glass fibres, ASM International, ASM Handbook, 21: Composites.

[15] Ely Levine, Radome and Performance, Presentation

[16] Priya Shukla, Aman Verma, Vidhushi, Neha and Kuldeep Singh Naruka, Dual Band Notched UWB Antenna with A T-Shaped Parasitic Strip and A Defected Ground Plane. *International Journal of Electronics and Communication Engineering & Technology*, 5(5), 2014, pp. 43–47.

[17] Km. Vidushi, Priya Shukla, Neha, Aman Verma And Kuldeep Singh Naruka, Square Monopole Antenna with Two L-Shaped Slots In The Patch For UWB Application. *International Journal of Electronics and Communication Engineering & Technology*, 5(2), 2014, pp. 69–74.

[18] Dr. (Mrs) Mala Thapar Kuthiala and Dr. Sadhana Mahajan, Proposed Value Projection Hierarchy Model For Fibreglass Reinforced Plastic (FRP) Products. *International Journal of Management*, 3(3), 2012, pp. 112–120.

[19] Sathishkumar. S, A.V. Suresh, S.C. Sharma and Radha. H.R, Drill Ability Studies of Jute Fibre Reinforced Plastic Sandwich Structure Using Doe and Anova In Various Surrounding Condition. *International Journal of Industrial Engineering Research and Development*, 5(1), 2014, pp. 1–9.

[20] M Madhusudhana Rao & K KKSanyasi Rao, Composite Materials for under water applications, Proceedings on Seminar on Naval Materials Present and Future Trends, NMRL, Ambernath, 2000.