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OUT OF BAND ANTENNA CHARACTERIZATION

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OUT OF BAND ANTENNA CHARACTERIZATION

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Abstract

The aim of this project is to study the out-of-band performances of the antennas and from there, understand the electromagnetic compatibility of different systems when working together in this electromagnetic rich environment.

During the preparation of this research project, the structural parameters, performance characteristics and antenna measurement theory has been studied. Literature review on antenna out-of-band characteristics and electromagnetic compatibility has been done as the references of this research work.

The airborne L, S, and C band blade antennas are the objects of research of this project. The blade antennas are all monopole antennas which consist of an RF port at the bottom, a metal radiator, a Teflon cylinder load and a dielectric radome covering the antenna. The dielectric radome is found to change the omni-directional monopole antenna into a directional aircraft blade antenna.

The pattern measurement on the blade antennas is done to obtain the far-field radiation pattern measurement. Simulation results of the L, S and C band blade antennas are well matched with the anechoic chamber measurement data. It was found that the blade antennas have both in-band frequencies and higher out-of-band frequencies. Gain and radiation pattern of the blade antennas are found to be influenced by the ground plane and dielectric radome in a way that the blade antennas have two main lobes in the forward and backward directions of the antenna at most of the frequencies.

Equations were built for each antenna to illustrate the relationship between their dimensions and the in-band and out-of-band resonant frequencies. Based on the individual equations, a general equation was derived to predict the out-of-band resonant frequencies with known dimensions of the blade antennas. This will

provide a good reference for future blade antenna design in consideration of avoiding electromagnetic interference at out-of-band frequencies.

Except the relationship between antenna dimensions and the resonant frequency, the maximum gain of the blade antennas at frequencies below 1GHz was found to increase with the frequency by 40dB per decade. A general prediction model has been developed to describe the maximum gain of the blade antenna from the lower out-of-band frequency up to higher out-of-band frequency.

The effects of the dimensional parameters including the antenna length, Teflon cylinder load length, Teflon cylinder load position and the dielectric radome height are investigated as the last part of this research. The impacts of these parameters on the resonant frequency have been studied. Based on the investigations on individual parameters, the resonant frequency equation has been derived to characterize the frequency performance of the blade antennas and reduce the effort in testing simulation models.

At the end of this thesis, recommendations have been made to suggest that more considerations should be put into the relationship between the dimensional parameters and the out-of-band frequency of the blade antennas. It is found that the antenna gain varies sinusoidally with the length of the Teflon cylinder load. However, it is suggested that the relationship between the dimensions and the antenna gain should be studied based on the in-band relationship. At last, although the resources may be limited, it is suggested that the future research in antenna, electromagnetic compatibility and interference should be based on both simulation and measurement in real scenario to obtain better results.

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1. Introduction

1.1 Motivation

Electromagnetic compatibility of the antennas of any communication systems is a very important factor affecting the effectiveness and efficiency of the systems. Among all the system components, the antenna is one of the possible sources for electromagnetic (EM) compatibility and immunity problems. In an electromagnetically rich environment, besides the many sources of radiation from equipment and communication devices, there are also unintended sources of radiations such as transmission lines, clock chips, and power supply. Any system working in such EMC rich environment needs to consider its electromagnetic compatibility and immunity to other systems. Any intended or unintended sources of radiations are received by the antenna of a system and can affect the performance of the system to which it is connected. The motivation of this research project is to examine the electromagnetic immunity and susceptibility of the aircraft and land vehicle communication systems by studying the out-of-band performance of their antennas. Traditionally, the electromagnetic compatibility and interference of a communication system will be tested after it is built on ships or aircrafts. Surrounding environmental conditions, system design or space limit makes it challenging to minimize the possible interference in this case. Meanwhile, due to the complexity of communication system, it is not easy to verify the sources or causes of the interference which causes system failure. Possible sources of out-of-band radiation include the spurious radiation and harmonics from any electronic equipment and transceivers. In this project, the out-of-band property of some typical aircraft antennas will be studied to predict the out-of-band performances of these antennas, so that precautions can be taken to reduce or avoid the electromagnetic interference between antennas even during the design stage.

1.2 Objectives

The aim of this project is to study the out-of-band performance of a few military antennas and from there, understand the electromagnetic compatibility of different systems when working together in an electromagnetically rich environment. In order to predict the out-of-band performance of the antenna, the L, S, and C band airborne blade antennas are selected to be the objects of this study. Based on the study of the in-band and out-of-band performances (based on their S-parameters) and other parameters such as their geometry, feeds and matching networks of these antennas, the purpose is to predict the out-of-band characteristics of these antennas and of similar antennas from their known in-band characteristics. The relationships between the parameters and the out-of-band performances such as gain, beam width and directivity will be analyzed and formulated into relevant prediction functions. This will enable the effective prediction of the antennas' out-of-band performance. By understanding their out-of-band performances, system designers can better handle and avoid problems caused by electromagnetic compatibility and susceptibility. The aim of this study is to help to improve communication systems through the understanding and prediction of possible electromagnetic compatibility (EMC) issues.

1.3 Major contributions

First of all, the gain characteristics, maximum gain direction, radiation pattern and the half power beam width of the monopole blade antennas are studied for both their in-band and out-of-band frequencies in order to understand the out-of-band performance of the blade antennas. The blade antennas are measured in a full anechoic chamber and semi-anechoic chamber with the automated test system and compared with the simulation results. The blade antennas are measured in the full

anechoic chamber from 1 to 18 GHz. Due to the space limit of the full anechoic chamber at NTU, the minimum far field distance requirement cannot be satisfied for lower out-of-band measurement. Therefore, the measurement for lower frequency band from 200MHz to 1GHz is conducted in Electo-Magnetic Effects Research Lab (EMERL), a large semi-anechoic chamber which is near National Institute of Education (NIE). Low frequency microwave absorber is placed on the ground to minimize the multipath reflections.

In order to study the in-band and out-of-band characteristics of a generic blade antenna, the relationship between the dimensions of the antennas (the L, S and C band blade antennas) are examined. The L, S and C band blade antennas were simulated with varying dimensions to examine the effects of each dimension parameter on both the in-band and out-of-band performance of the antenna. Then, the simulation results obtained from the dimension parameter variation are synthesized and analysed using the MATLAB curve fitting tool and surface fitting tool. Regression models relating the dimension parameters, and the in-band and out-of-band resonant frequencies were constructed. Smoothing techniques and interpolation techniques are used in the regression analysis to find the best fit functions. Out-of-band frequencies are separated into bands. Each frequency band has a corresponding prediction function. Based on the individual prediction functions, a generic prediction function has been derived for the blade antennas. A general prediction function is derived for the L, S and C band blade antennas. However, the C band blade antenna performance does not comply with the prediction function completely. This is because, the C band antenna is structurally different from the L band and S band antennas, while the L and S band blade antennas have similar structures.

The maximum out-of-band gain of L, S and C band blade antennas are measured and studied. The common trend of the maximum blade antenna gains are found and formulated into a general prediction function, which can be determined by the in-band resonant frequency and in-band antenna gain. It has been found that at out-of-band frequencies, the radiation patterns of the blade antennas can be seen as omni-directional as the number of main lobes in the radiation field is large.

The dimensional parameters of the L, S and C band blade antennas including the length of the antenna radiator, the length of the Teflon cylinder load, the position of the Teflon cylinder load and the height of the dielectric Radome are examined to study their effect on the resonant frequency. The function derived is able to describe the variation of the in-band and out-of-band resonant frequencies with varied dimensional parameter values.

1.4 Organization of the thesis

The main body of this report includes three chapters. Chapter 2 is on antenna theory and provides a literature review consisting of the important definitions and background of this research study. Discussions on some peer work in this field are reported. Chapter 3 presents the measurement and simulation results of the blade antennas as well as the analysis of the blade antennas on their out of band performances. Chapter 3 is divided into 5 main sections. First, the structure of the blade antennas will be introduced. The components and their functions will be explained respectively. In section 3.1, the measurement setup will be introduced followed by the comparison and analysis of the measurement and simulation results. For the blade antennas, the derivation of the out-of-band resonant frequency prediction function will be explained after the result analysis. The derivation of the maximum gain prediction function will be introduced in section 3.4 and the effects of different dimensional parameters will be studied in section 3.5. Chapter 4 gives a conclusion.

2. Theory and Literature Review

2.1 Antenna characteristics

2.1.1 Definition of antenna

An antenna is an electrical conductor or a group of electrical conductors which transmit (s) the guided electromagnetic waves from the transmission line into free space and/or receive electromagnetic wave which produces a voltage across the feed terminals at the receiver antenna [1]. An antenna is said to be reciprocal if it is able to transmit and receive with the same radiation pattern. Antennas are widely used in commercial and military communication systems such as television broadcasting, radio broadcasting, Wireless Local Area Network (LAN), mobile telephone system, military radar system, satellite communication. The antenna is at the front end of the wireless communication system [2]. It not only acts as an interface between electrical signals and electromagnetic waves, but also acts as a filter, transmitting and receiving only the desired frequencies. Therefore, the antenna plays a crucial role in EMC area [4].

2.1.2 Antenna types

Antennas can be classified into various types based on their structures. There are wire antennas such as dipole antenna, monopole antenna and loop antenna. There is also micro-strip antenna, which is another type of antenna of research interest in this project. Pyramidal horn antenna as another type of typical antennas is used as transmitting antenna in most of the measurements taken during this research. Other types of antennas are not within the study scope of this research; therefore they will not be introduced in detail. These antennas include the reflector antennas, array antennas and lens antennas [2].

Wire Antenna

Wire antennas are extensively used with automobiles, ships, aircrafts, buildings etc. because of their low profile and simplicity of construction. Wire antennas can be further classified based on their shapes into straight wire, loop and helix. Wire antennas studied in this research work include monopole and dipole, which are theoretically half wavelength and quarter wavelength linear wire antennas. Both monopole and dipole antennas have low gain profile, and omni-directional radiation pattern. They have similar feeding mechanism except the monopole antenna requires additional ground. The electromagnetic property of the linear wire antennas is discussed in the antenna theory text by C. Balanis [2]. Typical dipole antenna and monopole antenna is shown in Figure 1.

Figure 1 Typical Monopole Antenna and Dipole Antenna

Microstrip Antenna

Microstrip antenna is another type of low profile antenna widely used in aircraft and satellite applications. Microstrip antenna is manufactured using modern printed-circuit technology with low cost and robust design. They can be installed on planar or non-planar surface. Microstrip antennas can be classified based on shapes of the metallic patch into square, rectangle, circular, elliptical, dipole, triangular, disc sector, circular ring and ring sector (Figure 2). They can be very versatile in

terms of the resonant frequency, radiation pattern, impedance and polarization depending on which shape is selected. The disadvantages of microstrip antennas include low efficiency, narrow bandwidth, poor scan performance, poor polarization purity and high Q. Microstrip antenna radiates from the magnetic current around the periphery of the patch the surface wave which is induced by the dielectric substrate. The fringing field between the microstrip patch and the ground plane excites the low order TM_0 mode surface wave, which contributes to the overall radiation of the patch. Besides the directly radiated power, the ratio of the power in surface wave can be increased by increasing the thickness of the dielectric substrate. Therefore, methods such as increasing the height of the substrate can be applied to increase the efficiency of the microstrip antenna sometimes. However, as the height of the substrate increases, surface wave appears and travels within the substrate, and scattered at surface discontinuities. Surface waves extract the power from being radiated out and degrades the radiation pattern and polarization property. In previous research works, methods have been found to reduce the surface wave and increasing bandwidth, which is explained in detail in the antenna theory text [2].

Figure 2 Typical Microstrip Patch Antenna Shapes [2]

Horn Antenna

Horn antenna is widely used as a feeding element of reflector antenna or lens antenna. Additionally, it can be part of phased array antenna. Horn antenna is widely used in communication system due to its high gain, ease of construction, wide bandwidth, good directivity, ease of excitation and overall performance. Four typical horn antennas are E-plane, H-plane, pyramidal and conical horns (Figure 3). They share the common structure of a hollow pipe of different cross sections which is flared to a large opening. The performance of horn antennas are affected by the direction and amount of flare. Pyramidal horn antenna is flared in both direction and has combined characteristics of E-plane horn antenna and H-plane horn antenna.

Figure 3 Typical Horn Antennas [2]

2.1.3 Directivity and gain

Antenna directivity measures the power density that an antenna radiates in a certain direction versus the power density radiated by an isotropic antenna. Similarly, the antenna gain is measured in dBi and is defined as the ratio of the power radiated in

a given direction to that of an isotropic radiator [1]. Antenna gain can be calculated by multiplying the directivity with the antenna efficiency. Antenna gain (1) is related to the effective area A_e of the antenna in a way that the larger the effective area, the higher the gain.

$$G = \frac{4\pi A_e}{\lambda^2} \quad (1)$$

Antenna effective area is defined as the physical area multiplied by the aperture efficiency. For an isotropic radiator, the effective area A_e is defined can be expressed as $\lambda^2/4\pi$, where λ is the wave length.

2.1.4 Radiation pattern

The electromagnetic wave radiated from the antenna consists of two components, the E-field and the H-field. The energy radiated in a certain direction decreases slowly with the distance in the far-field space because of the free space path loss [1]. The power radiated by the antenna creates radiation field around the antenna. Radiation pattern is an indication of the radiation field strength around the antenna. For example, the radiation pattern of a $\lambda/2$ dipole antenna is in a dumbbell shape [3]. The maximum gain appears at the top of the bell. The three-dimensional radiated field of an antenna can be measured and depicted in two-dimensional pattern cuts. Figure 4 shows the radiation pattern of a half-wavelength dipole antenna. The measurement technique will be introduced later.

Figure 4 Radiation Pattern of Half-wavelength Dipole [2]

Parameters used to describe the antenna's radiation pattern are the main lobe, side lobe, back lobe, null and 3 dB beam width. Main lobe should be the lobe with the highest gain/directivity. 3dB beam width is defined to be the angular separation between the half power points of the main lobe. There is normally a trade-off between the directivity and the 3dB beam width. Large 3dB beam width is always related with low directivity, and vice versa. i.e. dipole and monopole antennas have large 3dB beam width, but the gain is normally only about 1 to 2dB [3]. Vector network analyzer can be used to measure the received power at the antenna under test, so that the radiation pattern of the antenna under test can be obtained.

2.1.5 Frequency of operation

Antennas are designed to operate at different frequencies. The operation frequency is affected by the dimensions of the antenna and the impedance match at the RF port [2]. For example, the length of monopole antenna is normally designed to be about $\lambda/4$. λ is the wavelength at the fundamental resonant frequency. Micro-strip antenna is often designed with a length of $\lambda/2$. For monopole or dipole antenna, radius of the monopole or dipole will affect the operation frequency. Thicker wire antenna has smaller electrical length which lowers the wavelength at resonance. Therefore, wavelength should be increased for thicker wire antenna. Meanwhile,

thicker wire antenna has wider bandwidth than normal wire antenna. For the microstrip patch antenna, the thickness of the ground plane or the microstrip patch is not quite critical.

2.1.6 Reflection coefficient

Reflection coefficient given by (2) is defined as the ratio of the reflected voltage amplitude and the forward voltage amplitude and it measures the impedance match between the input port of the antenna and the transmission line [1]. Normally, the input impedance of an antenna is designed to be matched to one or a few frequencies. However, broadband impedance matching techniques can be applied to make the antenna operate over a wide range of frequencies, such as the UHF whip antenna, which is another type of antenna of research interest in this project. An air coil inductor made using a portion of the transmission line is added in the UHF whip antenna to achieve the broadband characteristics from 225MHz to 420MHz [5]. In commercial applications, most antennas are designed to be matched to 50Ω or 75Ω transmission line [1]. For measurement purposes, the reflection coefficient is given by S_{11} from the S-parameters obtained from the vector network analyzer, where

$$\text{Reflection Coefficient } \Gamma = S_{11} = \frac{V^-}{V^+} = \frac{Z_L - Z_0}{Z_L + Z_0} \quad (2)$$

2.2 Antenna measurement theory

In order to study the performance of an antenna, the above mentioned parameters need to be examined through accurate measurements. First of all, it is necessary to understand the radiation field regions around an antenna. There are several regions surrounding an antenna. Figure 5 defines the distance boundaries for the regions, namely the reactive near-field region, the radiating near-field region, and the radiating far-field region.

Figure 5 Radiation field regions of aperture antenna [6]

As shown in Figure 5, the minimum far-field measurement distance is $\frac{2D^2}{\lambda}$, where D is the largest dimension of the antenna [6]. The far-field region is determined by the minimum distance that has the phase variation of the wave-front arriving at the receive antenna of less than $\frac{\pi}{8}$ (or 22.5°) [7]. Hence, it can be assumed that a plane wave can be received at a distance greater than $\frac{2D^2}{\lambda}$. Most of the time, radiation pattern in the far-field is preferred since the transmission path is often quite long in real applications.

Any antenna can be measured using near-field or far-field with suitable implementation. The general advantages and pitfalls of near-field measurement and far-field measurement are compared in Table 1.

Table 1 Near-field and Far-field Measurement Comparison

	Comparison of Measurement Approach
Far-Field Measurement	<p>Suitable for lower frequency antenna</p> <p>Simple pattern cut measurement</p> <p>Indoor measurement is achievable in anechoic chambers and compact ranges</p>

	Lower measurement cost, except real-estate is required.
Near-Field Measurement	<p>Suitable for higher frequency antenna</p> <p>Complete pattern including polarization measurement</p> <p>Easier to perform indoor measurement than far-field measurement and eliminate the problems due to weather, electromagnetic interference and security concerns</p> <p>Higher measurement cost</p>

Since the blade antennas operates in L, S and C band, which is not quite high, full anechoic chamber with automatic test system is available for computing the far-field antenna gain in NTU, far-field measurement method is chosen to reduce the cost and improve the time efficiency.

For electrically small antennas such as a whip antenna, the radiating near-field region is not present [8]. For such antennas, the far-field distance is normally calculated as $\frac{\lambda}{2\pi}$ [9]. However, a distance of $\frac{2D^2}{\lambda}$ for far-field region is still considered regardless of the type of antenna being used.

Different types of range and scanning methods are available for both the far-field and near-field measurement. Measurements can be performed indoors in an anechoic chamber or outdoor in an open space test site [6]. Experimental work can be performed in any one of the test sites and with any one of the measurement set ups. In this project the anechoic chamber range (Figure 6) is used for the far-field measurements of the antennas [4]. The range is located indoors in the form of a chamber filled with absorbers to minimise reflections. The chamber is shielded to minimise external interference. This is an ideal setup because the external interference source is shielded and reflections from walls are minimized. These are

known as full anechoic chambers. However, full anechoic chambers are limited in size, and therefore, the types of antenna that can be measured are restricted by the lower frequency range, i.e. the larger the size of the full anechoic chamber, the lower the frequency the chamber can start operating.

Figure 6 Anechoic chamber

Vector Network Analyzer (VNA) is often used to record the S-parameters (transmission coefficient, S_{21} , and reflection coefficient, S_{11}) during the measurement. Provided that the gain of transmitting antenna (G_t), the ratio of the power transmitted (P_t) to the received (P_r) and the distance (d) are known, Friis transmission equation (3) can be used to calculate the gain of the antenna under test (G_r) [1]. During the test, cable loss is eliminated by performing calibration on the test system using calibration kit. Since both the transmit horn antenna and the blade antenna are linearly polarized, the polarization loss is not considered in the calculation.

$$\text{Friis Transmission Equation} \quad \frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi d} \right)^2 \quad (3)$$

2.3 Literature review

Out-of-band response of an antenna is an important factor that determines the susceptibility of a communication system to its surrounding environment. While evaluating the compatibility of a communication system, given the power and antenna gain of the transmitting system, the parameter that has substantial effect on

the power received is the receive antenna gain (based on the Friis transmission equation (3)). Therefore, knowing the receive antenna gain and polarization at the out-of-band frequencies is crucial for studying the amount of interference that will be coupled into the communication system. When the polarization of the receiver is matched with the interference source, interference power will be captured.

Despite the fact that the study of the antenna's compatibility and out-of-band performance has started many years back, there are very few literatures in this area.

In 1976 [9], the "Statistical prediction model for EMC analysis of out-of-band phased array antennas" applied statistical analysis technique on the characterization of the out-of-band performance of phased arrays containing ferrite phase shifter on shipboard. Equations are derived for the phased arrays relating the out-of-band pattern scanning properties, relative gain levels, median gain, and standard deviation to the in-band scan and the ferrite phase shifter statistics.

In the "Out-of band response of VHF/UHF airborne antenna" published in 1989 [10], the out-of-band response of the UHF/VHF antennas of the airborne communication/navigation system on aircraft to the Voice of America (VOA) / Radio Free Europe (RFE) / Radio Liberty (RL) broadcast systems has been formulated. It was derived that the out-of-band gain of an antenna and the in-band gain has a 20dB/decade relationship. i.e. $G(\theta, \phi) = G_0 + 20 \log(f)$, where the G_0 is the in-band gain and $G(\theta, \phi)$ is the out-of-band gain. VHF/FM (30 to 88MHz) whip antenna, Dorne & Magolin balanced loop VOR/LOC antenna (108 to 122MHz) and Dorne & Magolin UHF/AM (225 to 400MHz) were measured in the frequency range 5 to 30MHz in a Transverse Electromagnetic (TEM) cell to test the lower out-of-band performance. A TEM cell is an EMC test facility which enables fast and efficient EMC radiated immunity and emission test without interference from the

electromagnetic environment. The measurement results were not always consistent with the analytical data. However, a reliable and repeatable measurement method was provided to test the out-of-band response of the antenna.

One of the most recent studies is on the electromagnetic compatibility of the aircraft communication system in the publication titled “Analysis for phase center of pyramidal horn antennas for out-of-band” in 2010 [11]. It is found that the phase centers affect both the in-band and out-of-band radiation pattern characteristics. Therefore, the characterization framework of the pyramidal horn antennas’ out-of-band phase center was established and theoretical expressions of the phase center was provided. Two types of pyramidal horn antennas with different sizes and operating frequencies are simulated and their phase changes were analyzed using integrated analysis method. It was concluded that the pyramidal horn antenna has higher gain at the high out-of-band frequencies than that at the in-band frequencies. As the frequency increases, the phase center moves closer to the aperture edge of the horn antenna.

For electromagnetic compatibility, many researches focus on the coupling of antennas at in-band frequencies, the designing of electromagnetically compatible antennas, and the near-field interference of antennas. For example, an antenna coupling model was established based on the existing models to predict the coupling level and the probability of interference between neighboring antennas operating in nearby frequencies in “A new antenna coupling model for radar electromagnetic compatibility prediction” published in 2010 [12]. The model proposed was a four level key antenna model which can simulate the far-field radiation pattern with known maximum gain and 3dB beam width. The proposed model was able to extend the applicable frequency range of the antenna coupling model, to simplify the electromagnetic compatibility prediction model and to

improve the computation speed. The band of interest in their study is only for the in-band mutual coupling between antennas, and they are not concerned about the out-of-band performance of the antennas. However, the four level antenna model may be helpful in the prediction of the out-of-band antenna performance. In “A generalized algorithm for antenna near-field computation in EMC prediction” published in 2003 [13], the near-field distribution of the antennas was investigated to reduce the near-field interference for 1D or 2D array antenna and aperture antenna with different aperture contours. The algorithm was based on the fact that the whole antenna aperture can be divided into many elements and the total field of any observation point is the sum of fields due to each element. The far-field distance of the aperture antenna is $\frac{2D^2}{\lambda}$ (D is the largest dimension of the antenna).

Since the element dimension is much smaller than the whole aperture dimension, therefore, even the observation points are in the far-field of all the elements, they may be in the near-field of the whole antenna aperture. Under this condition, the generalized algorithm calculates the near-field radiation of the whole antenna aperture through combining the far-field radiation of all the elements.

In “Electromagnetic Compatibility Test for Aircraft System” in 2000, the EMC safety margin of aircraft is determined on system level and the performances of some important aircraft equipment are evaluated. Various test has been done for investigation of the system compatibility, including AC/DC power line spike test, power line conduction susceptibility safety margin test, AC/DC power line conduction emission test, aircraft radiation field test, airborne antenna radiation field test, airborne antenna coupling test, airborne antenna isolation test, radiation susceptibility test, lightning protection test. [14]

The electromagnetic compatibility problems in digital communication in naval application such as ships are discussed carefully in paper published by Naval EMC

center in Mumbai in 2002. [15] HF, UHF and VHF satellite links are widely used on ships. The causes and effects of the EMI on these satellite links are analyzed. There causes are high ambient level, EMI from near emitters, transmitter or receiver's poor performance, leakage from coaxial transmission cables, etc. The paper concludes that all equipment must be designed in compliance with EMC standard. Standard EMC techniques must be used for grounding, filtering, bonding and shielding the equipment during installation and maintenance.

Paper published by Georgia Institute of Technology presents the study of out-of-band far field radiation pattern of antenna based on near-field measurement. The measurement results show the sensitivity of out-of-band antenna radiation pattern to the frequency and waveguide transmission line components which can excite higher order transmission mode. It is shown that the near-field measurement is useful in determining the complex radiation pattern. This technique is proved to be useful in determine both antenna's near-field and far-field out-of-band radiation pattern as well as spurious mode radiation patterns. [16]

Analysis and prediction of inter-system electromagnetic compatibility (EMC) is presented in paper published in 2003. Five types of EMC control techniques are introduced in the paper, including isolation of antennas by distance or polarization, administration of frequency by providing sufficient frequency isolation or setting up protected frequency band for receiving, RF filtering of transmitting using broad-band fixed tune band filter or narrow band tune band filter, waveform reforming and interference signal counteraction. It is also emphasized that EMC/EMI study should be done in pre-design period to reduce the cost and achieve higher performance. [17]

In the aircraft communication system, cable layout planning is one of the big EMC

concern. Paper published by Moscow Aviation Institute in 2005 considers the potential of using the graphs and the algorithms of their optimization for planning the aircraft and space vehicle networks, considering the requirement of electromagnetic compatibility (EMC). [18]

In “Out-of-Band Response of Antenna Arrays” published in 1987 [19], the response of antenna arrays to out-of-band frequencies has been analyzed using the effective aperture approach. An average value of effective aperture can be obtained by averaging the incidence angle and the polarization of the incident field. Far-field patterns have also been calculated by treating the array element excitations as random variables. The randomness in the element excitation causes a decrease in directivity and an increase in side lobe level. These trends are confirmed by out-of-band measurement using slotted waveguide array. It is mentioned that it is difficult to calculate the impedance mismatch factor at out-of-band frequencies. Therefore this factor or the reflection coefficient must be generally measured at out-of-band frequencies.

In “Military Aircraft Electromagnetic Compatibility” published in 2007 in UK, the evolution of Electromagnetic Compatibility (EMC) test methods used to access UK military aircraft are generally described. [20] The impact of Electromagnetic Interference on aircraft electrical, electronic and armament systems with respect to external radio frequency (RF) environment from 200 kHz to 40GHz is discussed. Additionally, the impact of the aircraft’s self-generated RF environment on its electrical, electronic and armament systems is discussed. For example, the airborne HF, VHF/UHF radios, onboard radar, and electronic counter-measure measure systems may produce large inductive transient, which may cause interference to avionics and cause them to shutdown. The future challenges faced by the EMC community are discussed as well as the potential solutions.

A framework of automatic testing system for electromagnetic compatibility is introduced by Beijing RF & EMC laboratory in 2007. [21] An automated EMC testing system including EMC test units, Database management, EMC test results analysis, and EMC automatic document generation are explained. As traditional EMC test are most manual, which require more human efforts and high technical knowledge by the personnel, the concept of automatic EMC test system may be adopted in the future to enhance the measurement and save cost.

In 2008, paper published by Georgia Technical University investigated the electromagnetic compatibility of an active dipole antenna. The new solution of Hallen's integral equation is given relative to the relative to the axial current of the dipole. It is shown that this solution besides sinusoidal term, considered by the action of e.m.f. applied to the center of the dipole, contains new terms as well, and created by interference of the fields radiated by the different arms of the dipole. The compatibility function is introduced, being the modulus of the integral field in far zone. The analysis of this function makes possible satisfactorily characterize the EMC of the dipole. The great number of numerous results is presented, proving the effectiveness of the method of estimation and improvement of the EMC of the antenna. The suggested method can be used for other types of antennas as well. [22]

In "Out-of-Band of Reflector Antenna" published by David A. Hill, the out-of-band response of reflector antenna is analyzed using optical physical optics. An expression has been derived for its effective aperture. [23] The expression yields both the receiving radiation pattern and the frequency depend on-axis gain. The results are compared with the published measurement results of the radiation pattern and reflector antenna gain to shown good agreement. In the study, the electric and magnetic fields and the Poynting vector in the focal region of the parabolic reflector

is determined by physical optics integration. The receiver power is obtained by integration of the Poynting vector over the aperture of the feeding horn antenna.

In “A New Antenna Coupling Model For Radar Electromagnetic Compatibility Prediction” published in 2010, it is mentioned that most of the interference power from the nearby antenna which operating in the same frequency band comes to the receiving victim antenna by antenna coupling. This paper proposed a four level antenna coupling model which can simulate the far field antenna radiation pattern without knowing the antenna data except the maximum antenna gain and its 3dB beam width. Calculations are done to show that the mutual coupling gain of antenna can be used to calculate the mutual coupling power, and the mutual coupling probability can be used to estimate the veracity of electromagnetic compatibility prediction. The new model improved the computation speed of EMC prediction and the feasibility of EMC prediction [24].

In order to describe the electromagnetic compatibility of aircraft communication problems, electromagnetic interference elements probability space, electromagnetic susceptibility elements probability space, electromagnetic interference correlated pair's information quantity and EMC probability entropy are introduced in “Application of EMC probability Entropy in System Level Electromagnetic Compatibility Study” published in 2010. [25] It is concluded that the bigger the EMC probability entropy of a system, the better the performance of the aircraft system's EMC. Smaller EMC probability entropy will leads to larger uncertainty in the system's EMC and hence the worse EMC performance. This will be an effective method to do quantitative analysis of EMC on system level.

“The method of system level Electromagnetic Self-Compatibility Inspection Based on Orthogonal Experimental Design” published in 2011 performed theoretical analysis of orthogonal design to improve the system-level electromagnetic

self-compatibility inspection method based on orthogonal design. This method successfully solved the problems of the complicated electromagnetic interference relationship. It can also comprehensively, quickly and accurately check and analyze the electromagnetic compatibility of a helicopter system. Additionally, the method introduced provides the reference of the optimization of the system level electromagnetic compatibility. [26]

The out-of-band response analysis in electromagnetic context is a cutting edge and challenging topic, yet a very essential topic to any communication systems. Amongst the previous research work done in this area, the characteristics and electromagnetic compatibility of antennas in aircraft communication systems and ship board are the main areas investigated. The far-field coupling of antennas and near-field interference were also considered in the electromagnetic compatibility prediction. Various analysis method and prediction models were developed to investigate the gain level, radiation pattern, beam width, and phase of different antennas at the out-of-band frequencies. The computational time and complexity of the electromagnetic compatibility prediction is being reduced constantly. However, more accurate, simplified and integrated models needs to be derived in the future based on these previous works to achieve the prediction of the electromagnetic compatibility of antennas at the out-of-band frequencies. This is the main objective of this research work.

3. L, S and C band blade antennas

In Chapter 3, the measurement and simulation of the L band blade antenna will be described. The measurement setups for 200MHz to 1GHz, and for 1GHz to 18GHz are introduced in detail. The measurement and simulation results are analyzed and compared. The prediction models of blade antenna's out-of-band resonant frequency and maximum antenna gain are derived based on the analysis. Lastly, the effects of the dimensional parameters on the in-band resonant frequencies are studied. The relationship between the dimensional parameters and the in-band-resonant frequency is expressed as a formula.

The L, S, and C band blade antennas are based on their frequency of operation. Antennas are designed to operate in different microwave bands. Microwave band ranges from 1 to 100GHz and the names originated from World War II. These military names are adopted by IEEE and are still widely used in military and commercial applications. The nomenclature of microwave bands is shown in the Table 2.

Table 2 Microwave Band Nomenclature

Microwave Band Name	Frequency (GHz)
L band	1 - 2
S band	2 - 4
C band	4 - 8
X band	8 - 12
Ku band	12 - 18
K band	18 - 27
Ka band	27 - 40
V band	40 - 75
W band	75 - 110

For air borne vehicles such as aircrafts a common antenna used is the blade antenna. Blade antennas are used because of their omni-directional properties, relatively good gain performance and relatively wide bandwidth performance. Besides these performance advantages, it also has the advantage of being aerodynamic, with low

wind resistance, light weight and rugged. In order to make the blade antenna aerodynamic and rugged, a dielectric covering is often added outside the antenna structure as shown in Figure 7. This dielectric covering (dielectric radome) can result in a change in the performance of the antenna.

Figure 7 Photo of the L band blade antenna

The L band blade antenna shown in Figure 7 is designed by Defense Science Laboratories (DSO) for research on band blade antenna's in-band and out-of-band characteristics and performances.

Dielectric permittivity and loss tangent of the Radome is measured to examine the effect of dielectric Radome. The effective dielectric constant (ϵ_r) is calculated based on the permittivity and loss tangent, and then used in the simulation. Permittivity and loss tangent versus frequency plots of the L, S and C band blade antennas are shown in Figure 8 and 9.

Figure 8 Permittivity of the LO, S, and C band blade antenna Radom

Figure 9 Loss tangent of L, S, and C band blade antenna Radome

It can be seen that the dielectric constant of the Radome varies with the frequency but not much. Based on investigation, the dielectric constant of the Radome will affect the gain of the blade antenna. Higher dielectric constant will reduce the gain of the antenna due to loss in the Radome.

3.1 Measurement setups

The three blade antennas each operates in L, S or C band and have a narrow bandwidth. However, in this research, the performance of each blade antenna is measured from 200MHz to 18GHz in order to examine their out-of-band characteristics. The blade antennas are measured from 200MHz to 18GHz in order to examine the out-of-band performances both below and above the in-band resonant frequencies. However, since the operating frequency of the full anechoic chamber in NTU is from 1 to 20GHz, the blade antennas are measured in a large semi-anechoic chamber from 200MHz to 1GHz, and measured from 1 to 18GHz in the full anechoic chamber in NTU. The measurement setups and mechanisms are explained in this section. During the measurement, two transmitting antenna, horn (1 to 18GHz) and log-periodic (200MHz to 1GHz) antennas are used to cover the frequency band of interest (200MHz to 18GHz)

3.1.1 Measurement from 1 to 18GHz.

The L, S and C band blade antennas are measured using the automated test system in a full anechoic chamber. The operating frequency range of this test system is up to 20GHz. The equipment setup is shown in Figure 10. A wideband horn antenna is used as the transmitting antenna.

Figure 10 Basic equipment setup for antenna measurement

The automated test system including the Vector Network Analyzer (VNA), cables and the transmitting double-ridged horn antenna were calibrated at an output power of 10dBm for the frequency range of 1GHz to 18GHz. The transmitting horn antenna is connected to Port 1 of the VNA; and the blade antenna, also known as the antenna under test (AUT) is connected to Port 2 of the VNA.

Far-field distance of the blade antennas is calculated using $d_{\min} = \frac{\lambda}{2\pi}$ for the monopole antenna. The maximum wavelength length λ is 0.3m which corresponds to the lowest measured frequency 1GHz. Therefore, the far-field distance $d_{\min}$ required for this measurement is $d_{\min} = \frac{0.3}{2\pi} \approx 0.05m$. Since the distance between the transmit horn antenna and the blade antenna is measured to be 4.06m, the far-field requirement is met.

The L, S and C band blade antennas are all linearly polarized, therefore during the measurement, only col-polarization is measured while the cross-polarization is not considered for the blade antenna. During the measurement, the blade antenna and the transmitting horn/log-periodic antennas are placed so that their E-fields are in alignment. For future work, the cross-polarization of the blade antennas can be measured to investigate their performance at in-band and out-of-band frequencies when the interference source is cross polarized with the blade antennas.

The blade antenna was directly mounted on the rotator with a 52mm by 52mm ground plane (thickness = 1.55mm). The orientation of the blade antenna and the ground plane are illustrated in Figure 11. During the measurement, the blade antenna and its ground plane is rotated while the transmitting horn antenna is fixed (always transmitting towards the negative z direction) to scan the three-dimensional radiation pattern of the blade antenna. Refer to Figure 11, the antenna and its ground plane is placed in xy-plane of the coordinate system, while the top of the antenna is in alignment with the positive z direction. The bottom of the antenna is at the origin point of the coordinate system. The blade antenna rotates clockwise with respect to positive z axis for scanning phi from 0° to 360° in steps of 15°. The blade antenna rotates with respect to positive y axis for scanning theta from 0° to 180° in steps of 15°. In the orientation shown in Figure 11, the top of the antenna is

facing the reader and theta equals to 0° . When the antenna rotates 180° with respect to the positive y axis and the bottom of the antenna is facing the reader, theta equals to 180° . Phi equals to 0° is when the front of the antenna is pointing in the positive x direction, and 180° is when the front of the antenna is pointing in the negative x direction. A frequency sweep measurement done by the network analyzer from 1GHz to 18GHz in steps of 0.01GHz at each specific theta and phi value. In this way, the whole process is repeated until the three-dimensional radiation pattern of the blade antenna is obtained. The S-parameters are recorded automatically at each theta and phi angle.

Figure 11 Blade antenna initial orientation during measurement

With the recorded S-parameters, the gain of blade antenna is calculated by the embedded software in the test system. Both the 2-dimensional and 3-dimensional radiation patterns can be obtained directly from the software interface.

Log-periodic antenna is used as the transmitting antenna from 200MHz to 1GHz, and horn antenna is used as the transmitting antenna from 1 to 18GHz. Gain-frequency response of the transmitting horn antenna and log-periodic antenna are manually type into the software for calculating the gain of the blade antennas. The gain-frequency response of the horn antenna and log-periodic antenna is shown

in Figure 12.

Figure 12 Gain-frequency response of horn antenna and log-periodic antenna

3.1.2 Measurement from 200MHz to 1GHz

L, S, and C band blade antennas are measured from 200MHz to 1GHz using VNA in a semi-anechoic chamber at EMERL. Frequency sweep was done with step of 1MHz. Blade antennas receive power from the log-periodic antenna with a transmitted power of 0dBm. Due to the structural symmetry of the blade antennas, the 3D scan was done from 0 to 180 degree in azimuth direction in step of 10 degree and 0 to 85 degree in elevation direction in step of 5 degree. (0 degree of elevation was not measured due to the system limit of the measurement system. Therefore, 1/4 of the radiation fields of the L, S, and C band blade antennas are measured from 200MHz to 1GHz.

Since the lowest frequency measured is 200MHz, the far-field distance required can be calculated as $d_{\min} = \frac{1.5}{2\pi} \approx 0.24m$. Since the distance between the blade antenna and the log-periodic antenna during the measurement was 5.6m, therefore, the far-field distance requirement was met. Low frequency absorbers are placed in the semi-anechoic chamber to absorb the reflected microwaves from the ground in order to minimize the multi-path signals.

The S21 was recorded in the sum form of numerical real and imaginary parts. The numeric S21 was converted to dBi and phase form in order to perform the gain normalization. Due to the small aperture, the multipath power received by the blade antenna below 1GHz is negligible. Therefore, the Friis transmission equation (Eqn. ?) was used to calculate the blade antenna gain directly. Free space loss is calculated based on the distance between the blade antenna and the log-periodic antenna, which is about 5.6 meter.

$$P_r(dB) = P_t + G_b + G_a + d^2 e^{G_{\log P}} + 20 \log_{10} \left(\frac{\lambda}{4\pi R} \right) \quad (?)$$

S21 (dB) equals to $P_r - P_t$, which means the ratio between the power received and power transmitted numerically. G_{blade} and G_{logP} are the blade antenna gain and the known log-periodic antenna gain respectively. R is the distance between the blade antenna and the log-periodic antenna.

3.2 Measurement and simulation results

The L, S and C band blade antennas are modeled and simulated using CST Microwave Studio. Due to their similar structures, only L band blade antenna's measurement and simulation results are shown in this chapter. In section 3.2.1, the structure of the L band blade antenna will be introduced. In section 3.2.2, the reflection coefficient of the L band blade antenna is examined. Based on the S_{11} plots, it is known that the blade antennas have some resonant frequencies that are out-of-band. In section 3.2.3, the forward gain of the L band blade antennas is plotted with the frequency in order to study the gain pattern with respect to the frequency. In section 3.2.4, maximum gain at different frequencies is plotted to show the worse case of possible EMC problems. In the last section of this chapter, the far-field 2D radiation pattern at both the in-band frequency and some significant out-of-band frequencies are presented for the L band blade antennas.

3.2.1 L band blade antenna structure

The L band blade antenna is a monopole antenna with a bend as shown in Figure 13. The bend is used to reduce the overall height of the antenna and also to form an aerodynamic structure. For impedance matching purpose, a Teflon cylinder load (Figure 13) is added on the antenna. The dielectric radome (Figure 13) covers both the antenna and the Teflon cylinder load to protect the antenna structure. However, this dielectric radome affects the performance of the antenna.

Figure 13 L band blade antenna structures

Since the blade antenna has the bending structure, the effective length of the antenna should be different with the actual total antenna length and varies with the frequency. However, since the actual length of the antenna before the bend (7.55mm) is much smaller compared to the actual length after the bend (19.5mm), the length of the antenna after the bend has more impact on the performance of the blade antenna.

3.2.2 Reflection Coefficient

Figure 14 L band blade antenna reflection coefficient S_{11}

The L band blade antenna which operates between 1.62GHz and 1.92GHz has the best one in-band and two out-of-band resonant frequencies of around 7.72GHz and 12.87GHz according to the measurement result as shown in Figure 14. The wavelengths at 7.72GHz and 12.87GHz are approximately 38.86mm and 23.31mm. The total effective length of the L band blade antenna is about 21.34mm, consisting of the length of the antenna before the bend and the projection of the length after the bend in the vertical direction. Therefore, the ratios between the effective antenna length and the wavelengths are about 0.549 at 7.72GHz and 0.915 at 12.87GHz. It can be seen that the two significant out-of-band resonances are close to the half-wave and full-wave resonances of the L band blade antenna. However, the ratios between the two out-of-band wavelengths are not exactly 0.5 and 1. The discrepancy may be caused by the Teflon cylinder load outside the antenna. It will be shown in section 3.3 that the resonant frequencies are affected by the length of the Teflon cylinder load as well.

At frequencies below 1GHz, the L band blade antenna does not have any resonance and the reflection coefficient is close to 0dB, since the wavelength is much larger than the dimension of the L band blade antenna.

3.2.3 Gain Characteristics

The orientation of the L band blade antennas is shown in the Cartesian coordinate system as in Figure 15.

Figure 15 Orientation of the blade antenna in Cartesian coordinate system

The gain of the L band blade antenna is taken in the direction of the maximum gain at the in-band resonant frequency. For both the measurement and simulation, the ground plane used is 52mm by 52mm. In the previous section, the in-band and out-of-band resonant frequencies in the S_{11} plots have been found for the blade antenna. As shown in the gain vs. frequency plots (Figure 16), it can be seen that the resonant frequencies generally match those found in the S_{11} plots. There are maximum gains of around 4.724dB at 1.748GHz and 4.945dB at 7.33GHz. There is also a local maxima of gain of around 0.12dB at 13.1GHz. Therefore, it can be concluded that the simulation result matches the measurement result.

Figure 16 L band blade antenna maximum gain vs. frequency plot

The gain plotted in the figure is only the gain of the blade antenna. It compares the simulated and measured blade antenna gain at elevation of 60° and azimuth of 0° . The gain of the transmitting antenna and losses has been removed during the calculation. Refer to Figure 12; gain of the horn antenna at L band is between 6dB

to 9dB depending on the frequency. Maximum measured forward gain of the L band blade antenna is found to be located at an elevation angle of 60° instead of 90° for the in-band resonant frequency of 1.748GHz. This is due to the finite ground plane. The ground plane creates an image which results in the gain tilted upwards, which can be seen from the radiation patterns in 3.2.5.

3.2.4 Maximum Antenna Gain

Figure 17 L band blade antenna maximum case gain vs. frequency

It has been found that the blade antenna may have much higher gain at the out-of-band frequencies. However, the highest out-of-band gain normally does not lie in the forward direction of the antenna. This is because at higher out-of-band frequencies, the radiation pattern of the blade antenna becomes quite different from that at the in-band frequency. The highest gain at both the in-band frequencies and the out-of-band frequencies are plotted with the frequency. In Figure 17 the highest gain obtained from the three dimensional radiation pattern is plotted for each frequency, i.e. the maximum gain at each frequency occurs at slightly different elevation and azimuth angles. Figure 17 shows the potential worst case

electromagnetic interference scenario, although at different elevation and azimuth angles. For example, as shown in Figure 17, the highest out-of-band gain of the L band blade antenna is almost 10dB near 8GHz. However, this occurs at an elevation angle of 77° and azimuth angle of 180° , therefore is not in the forward direction and will not cause such a large EMC problem in the forward direction of the antenna. In fact, the gain is only about 3dB in the forward direction.

Figure 18 L band blade antenna maximum gain below 1GHz

The radiation efficiency of the blade antenna is very low at lower out-of-band frequencies such as 200MHz to 1GHz. Refer to the reflection coefficient vs. frequency plot of the L band blade antenna; most of the source will be reflected back at the feed of the antenna at frequencies below 1GHz. Therefore, the radiation efficiency of the L band blade antenna must be very low at frequencies below 1GHz. Radiation efficiency of the antenna can be greatly improved by improving the input impedance matching. It can be seen in Figure 18 that the maximum antenna gain increases from -45dB to about -7.5dB as the frequency increases from 200MHz to 1GHz. The radiation pattern of the L band blade antenna is omni-directional at frequencies below 1GHz, which will be shown later in this

chapter.

3.2.5 3dB Beam Width

Figure 19 3dB beam width of the blade antennas

Besides the gain, the 3dB beam width is also an important criterion to evaluate the potential electromagnetic interference. As shown in the Figure 19, the 3dB beam width of the L band blade antennas decreases when the frequency increases. This implies that as frequency increases, the antennas becomes more directive and radiates mainly in one direction with a beam width of less than 30° . Therefore, it can be concluded that although the maximum gain of the L band blade antenna increases with the frequency, the out-of-band performance of the antenna will only cause electromagnetic interference problems generally in a specific direction over a narrow bandwidth. However, the 3dB beam width at 11.5GHz is 27.1° and at 13GHz is more than 30° . These frequencies might create some serious electromagnetic problems.

3.2.5 Radiation Pattern

As shown in the antenna orientation diagram, the azimuth plane is the xy-plane; the elevation plane is the xz-plane or yz-plane. Forward direction of the blade antenna is in 0° of azimuth, and backward direction of the blade antenna is 180° of azimuth. The radiation patterns of the L band blade antenna at the in-band frequency, two significant out-of-band frequencies and two frequencies below 1GHz are compared in this section to study the out-of-band performance of the L band blade antenna.

i) In-band resonant frequency (1.748GHz)

The L band blade antenna gain for in-band frequencies in the azimuth plane is almost constant and equals to 3.5dB in the forward direction (Figure 20, 21). However, at the higher out-of-band frequencies, the gain in the backward direction in xy-plane is different from that in the forward direction (Figure 22, 23, 24, 25), i.e. the antenna is no longer omni-directional. This asymmetrical property in the azimuth plane for the forward and backward is expected. In fact, as can be seen in Figure 22, 23, the maximum gain in the azimuth plane is in the back of the antenna rather than the front. Also noted is that the antenna becomes more directive with many side lobes as frequency increases. As shown in Figure 20 and 21, the L band blade antenna has omni-directional radiation pattern at 1.748GHz. It is marked out in the simulated radiation pattern in xz-plane that the maximum gain of the antenna at 1.748GHz is at an elevated angle.

Figure 20 xz-plane radiation pattern of L band blade antenna at 1.748GHz

Figure 21 xy-plane radiation pattern of L band blade antenna at 1.748GHz (90° of elevation)

The measurement plane (xz or xy) is indicated on the top of each radiation pattern. “Forward” or “backward” is labeled in these figures to indicate whether that side is the front side or back side of the blade antenna. Refer to the blade antenna structure figure to see the front side or back side of the blade antenna. In the xz-cut plot, 0° to 180° (theta angle) of elevation angle is labeled from the top of the pattern to the bottom. In the xy-cut plot, 0° to 360° (phi angle) of azimuth angle is labeled around

the radiation pattern. The legend of gain in dB is indicated in these plots for checking the antenna gain at different angles. In the simulated pattern in both xz-cut and xy-cut, the two light blues straight lines indicate the 3dB beam width of the simulated radiation pattern at 1.748GHz. The darker blue line indicates the maximum gain direction in the pattern.

ii) Out-of-band resonant frequency (7.92GHz)

At 7.92GHz, the gain of L band antenna is 10.3dB at an elevation angle of 77° , which is nearer to the ground (xy-plane) than that of the in-band performance of the antenna as shown in Figure 22. The maximum gain at 7.92GHz is marked in Figure 22. The gain in xy-plane becomes more directive than that at the in-band frequency. The maximum gain for the in-band frequency is in the forward direction. At this out-of-band frequency, the maximum gain is the highest at 10dB but instead of radiating in the forward direction, it is now radiating in the backward direction as shown in Figure 22 and Figure 23.

Figure 22 xz-plane radiation pattern of L band blade antenna at 7.92GHz

Figure 23 xy-plane radiation pattern of L band blade antenna at 7.92GHz (90° of elevation)

Since the maximum gain is at an elevated angle instead of the ground plane, the maximum gain only appears in the xz-cut.

iii) Out-of-band resonant frequency (12.85GHz)

Another significant out-of-band frequency chosen for this study is 12.85 GHz. The antenna has gain of 4dB at 4° of elevation, almost vertically on top of the antenna (Figure 24). It can be seen that compared to the in-band resonant frequency of 1.748GHz, the gain is slightly higher, but again not in the forward direction but in the upward direction. Compared to the out-of-band frequency of 7.92GHz, this gain is significantly lower. As shown in Figure 25, the forward and backward gains of the blade antenna at 12.85GHz are quite similar but the forward gain is still slightly larger than the backward Gain with the maximum gain on the side of the antenna.

Figure 24 xz-plane radiation pattern of L band blade antenna at 12.85GHz

Figure 25 xy-plane radiation pattern of L band blade antenna at 12.85GHz (90° of elevation)

As can be seen from the xz-cuts and xy-cuts at the 3 frequencies, the radiation in the xy-plane for in-band frequencies is in general omni-directional. However, at the out-of-band frequencies 7.92GHz and 12.85GHz, the antenna becomes more directive in the backward and top directions respectively. However, as the frequency increases, it can also be seen that more side lobes appears.

iv) Out-of-band resonant frequency (250MHz)

Figure 26 xz-plane radiation pattern of L band blade antenna at 250MHz

Figure 27 xy-plane radiation pattern of L band blade antenna at 250MHz (90° of elevation)

As shown in Fig. 22 and 23, the radiation patterns of the L band blade antenna is omni-directional at 250MHz. As the frequency increases, maximum gain direction will slowly be elevated to a direction above the 90 degree elevation plane, which is similar as that at the in-band frequency.

In general, within the in-band frequencies, the radiation pattern of the blade

antennas is more omni-directional. However, at out-of-band frequencies, the main lobe in the elevation planes splits into several lobes and thus reducing the 3dB beam width. From the radiation pattern of the L band blade antennas, it can be seen that the antennas are not omni-directional any more at the out-of-band frequencies. Therefore, the high gain at the out-of-band frequencies may cause serious electromagnetic interference problem in a specific direction. With the investigations on the blade antenna out-of-band radiation pattern and knowing the gain versus frequency or angle characteristics, it will be easy to perform out-of-band link budget calculation for different angles.

3.3 Derivation of the resonant frequency prediction function

In the simulation work, the length of antenna after bend and length of Teflon cylinder load were varied to examine the relationship between these two parameters and the in-band and out-of-band resonant frequencies. The simulations were done with radome on. The dielectric constant of the radome and all other dimensions (the antenna length before bend, ground plane) are the actual measured values. The length of the antenna and the length of the Teflon cylinder are varied individually first to see their individual influence on the in-band and out-of-band frequencies. After that, both the lengths are varied together to examine the interactive and relationship between the length of antenna, the length of the Teflon cylinder load and the resonant frequencies. Only results from the variation of both parameters are presented in this report due to report length limitation. MATLAB surface fitting tool was used to build the regression model of the in-band and out-of-band frequencies. Polynomial regression models are used.

3.3.1 L band blade antenna

Figure 28 Actual dimensions of L band antenna

Length of antenna after the bend as shown in Figure 28 is varied from 17.5mm to 21.5mm in steps of 0.5mm. For each antenna length, the length of Teflon cylinder load (Figure 28) is varied from 32.5mm to 36.5mm in steps of 0.2mm. The in-band and out-of-band frequencies occurred at each combination was recorded. Future investigations can be done to optimize the antenna length and the length of Teflon cylinder load by evaluating the input impedance matching, gain, the radiation pattern and beam width of each combination.

i) In-band frequency (1-2GHz)

Surface fitting results:

$$f(x,y) = p00 + p10*x + p01*y + p20*x^2 + p11*x*y + p02*y^2,$$

where x = length of antenna after bend (mm), y = length of Teflon cylinder load after bend (mm), $f(x)$ = in-band frequency (GHz).

Coefficients (with 95% confidence bounds):

$$p00 = 4.13$$

$$p10 = -0.00843$$

$$p01 = -0.09342$$

$$p20 = -0.00151$$

$$p11 = 0.001707$$

$$p02 = 0.0003649$$

Goodness of fit: RMSE: 0.006204

Figure 29 Surface fitting: Antenna length & Teflon cylinder load length vs. in-band frequency (1-2GHz)

As shown in Figure 29, when the length of the Teflon cylinder load increases, the resonant frequency decreases, which corresponds to a longer wavelength. However, when the length of the antenna after bend increases, the resonant frequency decreases very slowly. This is because at the in-band frequency, the wavelength is very large compared to the variation in the length of the antenna. For example, at 1.7GHz, the wavelength is 176.47mm, while the length of antenna increases by only 4mm from 17.5mm to 21.5mm. Note that in this in-band frequency, due to the relatively large wavelength, the change in frequency due to the change in dimension of the antenna structure is less than 0.3GHz.

ii) Out-of-band frequency (6.746-8.293GHz)

Surface fitting results:

$$f(x,y) = p00 + p10*x + p01*y + p20*x^2 + p11*x*y + p02*y^2,$$

where x = length of antenna after bend (mm), y = length of Teflon cylinder load after bend (mm), $f(x)$ = out-of-band frequency (GHz).

Coefficients (with 95% confidence bounds):

$$p00 = 18.19$$

$$p10 = -1.622$$

$$p01 = 0.5323$$

$$p_{20} = 0.05023$$

$$p_{11} = -0.01311$$

$$p_{02} = -0.006527$$

Goodness of fit: RMSE: 0.05359

Figure 30 Surface fitting: Antenna length & Teflon cylinder load length vs. out-of-band frequency (6.746-8.293GHz)

As shown in Figure 30, the minimum resonant frequency is obtained when both the lengths of the antenna and Teflon cylinder load are the smallest values, 17.5mm and 30mm respectively. The maximum is obtained when both the lengths are the maximum values, 21.5mm and 38mm respectively. When the antenna length is 17.5mm (2mm shorter than the measured value), although the length of the Teflon cylinder increases, the resonant frequency does not vary too much. When the length of the Teflon cylinder load is 30mm (4mm shorter than the measured value), although the length of the antenna increases, the resonant frequency does not vary too much. Therefore, both lengths need to be increased to reduce the resonant frequency. Compared to the in-band resonant frequency, the wavelength is much smaller now. At 7.5GHz, the wavelength is 40mm. As a result, the variation of the resonant frequency becomes more obvious while changing the antenna length and the Teflon length. In the in band frequency, the change in dimension results in a 0.3GHz change in resonant frequency whereas at this out of band frequency, the same change in dimension results in a 1GHz change in resonant frequency.

iii) Out-of-band frequency (12.02-12.25GHz)

Surface fitting results:

$$f(x,y) = p00 + p10*x + p01*y + p20*x^2 + p11*x*y + p02*y^2,$$

where x = length of antenna after bend (mm), y = length of Teflon cylinder load after bend (mm), $f(x)$ = out-of-band frequency (GHz).

Coefficients (with 95% confidence bounds):

$$p00 = 33.25$$

$$p10 = -1.219$$

$$p01 = -0.4836$$

$$p20 = 0.0736$$

$$p11 = -0.05044$$

$$p02 = 0.02119$$

Goodness of fit: RMSE: 0.0249

Figure 31 Surface fitting: Antenna length & Teflon cylinder load length vs. out-of-band frequency (12.02-12.25GHz)

As shown in Figure 31, when both the lengths of the antenna and the Teflon cylinder load increases, the resonant frequency will decrease. This is due to the correspondingly changed wavelengths. Larger antenna dimension corresponds to larger wavelength (at lower frequency). However, when increasing either dimension individually, the resonant frequency decreases first then increases. Keeping the length of Teflon load unchanged (especially at shorter Teflon load), the increase in antenna length will cause significant increase in resonant frequency. This may be due to the same reason mentioned before, the increase of antenna length jumps from one half wavelength to next half wavelength. Therefore, the frequency decreases

then increases when the length of the antenna is varied. In this case, although the change in frequency is only 0.3GHz, the frequency decreases then increase again.

3.3.2 S band blade antenna

Figure 32 Actual dimensions of S band antenna

As shown in Figure 32, the length of antenna after bend is varied from 12.6mm to 18.6mm in steps of 0.5mm. At each length of the antenna, the length of Teflon cylinder load after bend is varied from 19.82mm to 25.32mm in steps of 0.5mm. The in-band and out-of-band resonant frequencies occurred at each combination was recorded.

i) In-band frequency (2-4GHz)

Surface fitting results:

$$f(x,y) = p00 + p10*x + p01*y + p20*x^2 + p11*x*y + p02*y^2,$$

where x = length of antenna after bend (mm), y = length of Teflon cylinder load after bend (mm), $f(x,y)$ = in-band frequency (GHz).

Coefficients (with 95% confidence bounds):

$$p00 = 6.157$$

$$p10 = -0.00466$$

$$p01 = -0.2687$$

$$p20 = 2.186e-005$$

$$p11 = -6.113e-005$$

$$p02 = 0.004422$$

Goodness of fit: RMSE: 0.0049

Figure 33 Surface fitting: Antenna length & Teflon cylinder load length vs. in-band frequency (2-4GHz)

As shown in Figure 33, similar to L band blade antenna, when the length of the Teflon cylinder load increases, the resonant frequency decreases, which corresponds to a longer wavelength. There is an increase in frequency of 0.8GHz. However, when the length of the antenna after bend increases, the resonant frequency decreases very slowly. This is because, similar to the S band blade antenna, at the in-band frequency, the wavelength is very large compared to the variation in the length of the antenna. For example, at 2.5GHz, the wavelength is 120mm, while the length of antenna increases only 6mm from 12.6mm to 18.6mm. Therefore, the length of Teflon cylinder load dominates in the variation of resonant frequency.

ii) Out-of-band frequency (9.004-10.06GHz)

Surface fitting results:

$$f(x,y) = p00 + p10*x + p01*y + p20*x^2 + p11*x*y + p02*y^2$$

where x = length of antenna after bend (mm), y = length of Teflon cylinder load after bend (mm), $f(x,y)$ = out-of-band frequency (GHz).

Coefficients (with 95% confidence bounds):

$$p00 = -19.5$$

$$p10 = 3.645$$

$$p01 = 0.06836$$

$$p_{20} = 0.0278$$

$$p_{11} = -0.2008$$

$$p_{02} = 0.0677$$

Goodness of fit: RMSE: 0.1423

Figure 34 Surface fitting: Antenna length & Teflon cylinder load length vs. out-of-band frequency (9.004-10.06GHz)

As shown in Figure 34, when both the lengths of the antenna and the Teflon cylinder load increase, the resonant frequency decreases. The resonant frequency decreases because the lower frequency corresponds to longer wavelength. However when the resonant frequency starts to increase, the increase of the dimension jumps from current half wavelength to next half wavelength, because at high frequency such as 10GHz, the wavelength is much shorter. Due to the change in dimension being close to the wavelength in this out of band frequency, the change in resonant frequency at this frequency range is large, greater than 1GHz.

iii) Out-of-band frequency (11.8-11.9GHz)

Surface fitting results:

$$f(x,y) = p_{00} + p_{10}x + p_{01}y + p_{20}x^2 + p_{11}xy + p_{02}y^2$$

where x = length of antenna after bend (mm), y = length of Teflon cylinder load after bend (mm), $f(x,y)$ = out-of-band frequency (GHz).

Coefficients (with 95% confidence bounds):

$$p_{00} = 2.214$$

$$p_{10} = 1.484$$

$$p_{01} = -0.05882$$

$$p_{20} = -0.05423$$

$$p_{11} = 0.0007493$$

$$p_{02} = 0.001217$$

Goodness of fit: RMSE: 0.01233

Figure 35 Curve fitting: Antenna length & Teflon cylinder load length vs. out-of-band frequency (11.8-11.9GHz)

As shown in Figure 35, similar to the resonant frequency band 9.004GHz-10.06GHz, the resonant frequency increases first when either dimension is increased. This is also because the increase of dimension jumps from current half wavelength to next half wavelength. At this frequency, the change in dimension only causes a small change in resonant frequency of less than 0.1GHz.

3.3.3 C band blade antenna

Figure 36 Actual dimensions of C band antenna

As shown in Figure 36, the length of antenna is varied from 10.25mm to 19.25mm in steps of 1mm. At each antenna length, the length of the Teflon cylinder load is varied from 9.65mm to 18.65mm in steps of 1mm. As shown, the structure of the C band antenna differs from those of the S and L band antennas. The C band antenna does not have a bend in its structure.

i) In-band frequency (4-8GHz)

Curve fitting results:

$$f(x,y) = p00 + p10*x + p01*y + p20*x^2 + p11*x*y + p02*y^2,$$

where x = length of the antenna (mm), y = length of the Teflon Cylinder load (mm),

$f(x,y)$ = resonant frequency (GHz).

Coefficients (with 95% confidence bounds):

$$p00 = 8.639$$

$$p10 = -0.006053$$

$$p01 = -0.37$$

$$p20 = 0.002769$$

$$p11 = -0.005416$$

$$p02 = 0.01242$$

Goodness of fit: RMSE: 0.03488

Figure 37 Curve fitting: Teflon cylinder load length & antenna length vs. in-band resonant frequency (4-8GHz)

As shown in Figure 37, keeping the length of antenna constant, when the length of Teflon cylinder load is increased, the resonant frequency decreases. However, keeping the length of Teflon load constant, when the length antenna is increased, the resonant frequency does not vary too much. This is because, at in-band frequency 4 GHz to 8GHz, the increase in the length of antenna (9mm) is not comparable to the wavelength about 60mm (at 5GHz), but the increases of Teflon load length will increase the impedance matching at lower frequency. The frequency variation is less than 1GHz.

ii) Out-of-band frequency (3.244-4.196GHz)

Curve fitting results:

$$f(x,y) = p00 + p10*x + p01*y + p20*x^2 + p11*x*y + p02*y^2,$$

where x= length of the antenna (mm), y = length of the Teflon Cylinder load (mm),

f(x,y) = resonant frequency (GHz).

Coefficients (with 95% confidence bounds):

$$p00 = 7.579$$

$$p10 = -0.1017$$

$$p01 = -0.3278$$

$$p20 = 0.004388$$

$$p11 = -0.002987$$

$$p02 = 0.009221$$

Goodness of fit: RMSE: 0.03007

Figure 38 Curve fitting: Teflon cylinder load length & antenna length vs. in-band resonant frequency (3.244-4.196GHz)

As shown in Figure 38, keeping the length of antenna constant, when the length of Teflon cylinder load is increased, the resonant frequency decreases. This is because increasing the length of Teflon load will increase the impedance matching at lower resonant frequency. However, keeping the length of Teflon load constant, when the length antenna is increased, the resonant frequency does not vary too much. This is because at out-of-band frequency 3.244GHz to 4.196GHz, the wavelength becomes even larger than the wavelength of in-band frequency. Therefore, the increase of antenna length (9mm) is less comparable with the wavelength (85.7mm at 3.5GHz). In this frequency range, due to the larger wavelength, the frequency variation is also less.

iii) Out-of-band frequency (8.089-10.54GHz)

Curve fitting results:

$$f(x,y) = p00 + p10*x + p01*y + p20*x^2 + p11*x*y + p02*y^2,$$

where x= length of the antenna (mm), y = length of the Teflon Cylinder load (mm),

f(x,y) = resonant frequency (GHz).

Coefficients (with 95% confidence bounds):

$$p00 = 10.43$$

$$p10 = 0.5586$$

$$p01 = -0.4149$$

$$p_{20} = -0.02289$$

$$p_{11} = 0.006154$$

$$p_{02} = 0.002461$$

Goodness of fit: RMSE: 0.1179

Figure 39 Curve fitting: Teflon cylinder load length & antenna length vs. out band resonant frequency (8.089-10.54GHz)

As shown in Figure 39, keeping the length of antenna constant, when the length of Teflon cylinder load is increased, the resonant frequency decreases. This is because increasing the length of the Teflon load will increase the impedance matching at lower resonant frequency. However, keeping the length of Teflon load constant, when the length of antenna is increased, the resonant frequency increases first then decreases. This is because the increase of antenna length jumps from half wavelength to next half wavelength. Again, due to the variation in dimension being close to this frequency range, the variation in frequency is large (2GHz).

iv) Out-of-band frequency (13.97-16.42GHz)

Curve fitting results:

$$f(x,y) = p_{00} + p_{10} * x + p_{01} * y + p_{20} * x^2 + p_{11} * x * y + p_{02} * y^2,$$

where x = length of the antenna (mm), y = length of the Teflon Cylinder load (mm),

$f(x,y)$ = resonant frequency (GHz).

Coefficients (with 95% confidence bounds):

$$p_{00} = 14.59$$

$$p_{10} = 0.3615$$

p01 = 0.08104
p20 = -0.01064
p11 = -0.002371
p02 = -0.01429

Goodness of fit: RMSE: 0.2662

Figure 40 Curve fitting: Teflon cylinder load length & antenna length vs. out band resonant frequency (13.97-16.42GHz)

As shown in Figure 40, keeping the length of antenna constant, when the length of Teflon cylinder load is increased, the resonant frequency decreases. This is because increasing the length of the Teflon load will increase the impedance matching at lower resonant frequency. However, keeping the length of Teflon load constant, when the length of antenna is increased, the resonant frequency increases first then decreases. This is because the increase of antenna length jumps from half wavelength to next half wavelength. Again, since the wavelength at 13.97GHz to 16.42GHz is small, the change in antenna dimensions causes a 3GHz change in resonant frequency.

3.3.4 Derivation of the Prediction Function

The out-of-band resonant frequencies of three blade antennas are analyzed using curve fitting technique in the previous sections. Functions of the length of antenna and the length of Teflon cylinder load are derived to predict the resonant frequency for each antenna at significant frequency bands. After that, a generic function is be

derived for the prediction of out-of-band performance. The functions derived to predict the in-band and out-of-band resonant frequencies are shown as following:

L-Band Blade antenna

i) In-band frequency 1GHz – 2GHz

$$f(L,T) = 4.13 - 0.00843*L - 0.09342*T - 0.00151*L^2 + 0.001707*L*T + 0.0003649*T^2,$$

L = Length of antenna (mm), T = Length of Teflon cylinder load (mm).

f(L,T) = Resonant frequency (GHz).

ii) Out-of-band frequency 6.746GHz - 8.293GHz

$$f(L,T) = 18.19 - 1.622*L + 0.5323*T + 0.05023*L^2 - 0.01311*L*T - 0.006527*T^2,$$

L = Length of antenna (mm), T = Length of Teflon cylinder load (mm).

f(L,T) = Resonant frequency (GHz).

iii) Out-of-band frequency 12.02GHz - 12.25GHz

$$f(L,T) = 33.25 - 1.219*L - 0.4836 *T + 0.0736*L^2 - 0.05044 *L*T + 0.02119*T^2,$$

L = Length of antenna (mm), T = Length of Teflon cylinder load (mm).

f(L,T) = Resonant frequency (GHz).

S-Band Blade antenna

i) In-band frequency 2GHz – 4GHz

$$f(L,T) = 6.157 - 0.00466*L - 0.2687*T + 2.186e-005*L^2 - 6.113e-005*L*T + 0.004422*T^2,$$

L = Length of antenna (mm), T = Length of Teflon cylinder load (mm).

$f(L,T)$ = Resonant frequency (GHz).

ii) Out-of-band frequency 9.004GHz - 10.06GHz

$$f(L,T) = -19.5 + 3.645*L + 0.06836*T + 0.0278*L^2 - 0.2008*L*T + 0.0677*T^2$$

L = Length of antenna (mm), T = Length of Teflon cylinder load (mm).

$f(L,T)$ = Resonant frequency (GHz).

iii) Out-of-band frequency 11.8GHz - 11.9GHz

$$f(L,T) = 2.214 + 1.484*L - 0.05882*T - 0.05423*L^2 + 0.0007493*L*T + 0.001217*T^2$$

L = Length of antenna (mm), T = Length of Teflon cylinder load (mm).

$f(L,T)$ = Resonant frequency (GHz).

C-Band Blade antenna

i) In-band frequency 4GHz – 8GHz

$$f(L,T) = 8.639 - 0.006053*L - 0.37*T + 0.002769*L^2 - 0.005416*L*T + 0.01242*T^2,$$

L = Length of antenna (mm), T = Length of Teflon cylinder load (mm).

$f(L,T)$ = Resonant frequency (GHz).

ii) Out-of-band frequency 3.244GHz - 4.196GHz

$$f(L,T) = 7.579 - 0.1017*L - 0.3278*T + 0.004388*L^2 - 0.002987*L*T + 0.009221*T^2,$$

L = Length of antenna (mm), T = Length of Teflon cylinder load (mm).

$f(L,T)$ = Resonant frequency (GHz).

iii) Out-of-band frequency 8.089GHz - 10.54GHz

$$f(L,T) = 10.43 + 0.5586*L - 0.4149*T - 0.02289*L^2 + 0.006154*L*T + 0.002461*T^2,$$

L = Length of antenna (mm), T = Length of Teflon cylinder load (mm).

f(L,T) = Resonant frequency (GHz).

iv) Out-of-band frequency 13.97GHz - 16.42GHz

$$f(L,T) = 14.59 + 0.3615*L + 0.08104*T - 0.01064*L^2 - 0.002371*L*T - 0.01429*T^2,$$

L = Length of antenna (mm), T = Length of Teflon cylinder load (mm).

f(L,T) = Resonant frequency (GHz).

Based on the above prediction functions, it can be seen that all the prediction functions are in the same order (2nd order of L and T). Therefore, a generic prediction function (4) can be derived as following:

$$f(L,T) = p00 + p10*L + p01*T + p20*L^2 + p11*L*T + p02*T^2 \quad (4)$$

-L = Length of antenna (mm), T = Length of Teflon cylinder load (mm).

-f(L,T) = Resonant frequency (GHz).

-p00, p10, p01, p20, p11, p02 are the coefficients of the generic equation.

After examining all the prediction equations, it can be concluded that:

- a. Coefficients of the 1st order terms (p10, p01) must be larger than the coefficients of the corresponding 2nd order terms (p20, p02, p11). This shows that the 1st order term has larger influence than the 2nd order term.
- b. For all the out-of-band prediction equations, coefficients (p10, p20) of the antenna length (L) are generally larger than the coefficients (p01, p02) of the Teflon

load length (T), or at least p_{10} is larger than p_{01} . In other words, antenna length has larger effects on the out-of-band frequency than Teflon load length.

c. There is only one exceptional case, which is the prediction function of C-Band antenna at out-of-band frequency 3.244GHz - 4.196GHz. In this equation, p_{10} and p_{20} are smaller than p_{01} and p_{02} . This is because this out-of-band frequency band is lower than the in-band frequency of C-Band antenna (4-8GHz). In this case, the wavelength is even larger than that of the in-band frequency. Therefore, the effect of antenna length is less comparable to the wavelength such that the effect of antenna length on resonant frequency decreases dramatically. For the tree blade antennas, significant out-of-band frequencies mainly occur at the upper out-of-band frequencies.

d. The coefficients (p_{10} , p_{01} , p_{20} , p_{02} , p_{11} , p_{00}) are different for different frequency bands, because the coefficients are dependent on the frequency. However, the patterns of the equations are similar.

3.4 Out-of-band prediction on maximum antenna gain

3.4.1 Maximum gain below 1GHz

The L, S and C band blade antennas are all measured from 200MHz to 18GHz. It is found that the L, S and C band blade antennas have very low gain below 1GHz, which is because of the low efficiency of the radiator at low frequencies. However, the radiation pattern is still omni-directional. The measured and simulated maximum gain of the blade antennas versus frequency are compared and plotted in Figure 41. It can be seen in Figure 41 that for each blade antenna, the maximum antenna gain increases by approximately 40dB as the frequency increases by a decade.

Figure 41 L, S, C band blade antenna maximum gain versus frequency results

As shown in Figure 41, the maximum gain of the L, S and C band blade antennas all increases gradually from 200MHz to 1GHz. It can be seen that the L band blade antenna has the highest maximum gain at all the frequencies, then the S band antenna and the lowest is the C band antenna. The simulation results have shown that the efficiencies of the three blade antennas are different at each frequency, which may be due to the different antenna lengths. For example, the efficiencies of the L, S, and C band blade antennas at 500MHz are all very low. However, even the efficiency of the blade antennas are very low that the gain is very low, it can be seen that the gain increases exponentially with the frequency up to 1GHz. Although due to the low gain at lower out-of-band, the blade antennas are not quite vulnerable to the interferences at these frequencies, the prediction of the lower out-of-band gain is performed in case that the interference sources are quite strong and the out-of-band link budget needs to be investigated.

A general prediction equation has been derived for the L, S and C band blade antennas respectively, based on the 40dB/decade relationship between the

maximum blade antenna gain and the frequency. The coefficients of the general equation are determined by the in-band blade antenna gain and the in-band resonant frequency. The models derived for the L, S and C band blade antennas are compared to the measured maximum gain in Figure 42.

Figure 42 L, S C band blade antennas prediction models

As shown in Figure 42, the prediction models of the three blade antennas all fit the measurement data well along the frequencies. The general equation is derived as eqn. (2):

$$G = a * f^4 \quad (2)$$

G is the maximum antenna gain in numeric form and **f** is the frequency in GHz. Coefficient **a** is determined by the in-band maximum antenna gain and the in-band resonant frequency. For example, for the L band blade antenna, the in-band maximum antenna gain is 3.5dBi, which is 2.24 numerically. Since the in-band resonant frequency is 1.75GHz, the coefficient **a** can be calculated as

$$a = \frac{10^{0.35}}{1.75^4} \approx 0.240.$$

Therefore, the corresponding prediction equation for the L band blade antenna

should be $G_L = 0.240 * f^4$. In a similar way, the coefficients of other blade antennas can be calculated. This equation is effective to predict the out-of-band blade antenna gain below 1GHz, and is useful to study the potential interference power coupled from other blade antennas in the worst scenario case.

The coefficients of the L, S and C band blade antennas are calculated and presented in Table 3.

Table 3 Prediction coefficients of the L, S and C band blade antennas

Antenna Type	Frequency (GHz)	Gain (dBi)	<i>a</i>
L band Blade Antenna	1.75	3.5	0.240
S band Blade Antenna	2.25	3.8	0.094
C band Blade Antenna	5.54	6.8	0.005

Measurement and simulation has been done to investigate the reflection coefficients of the L, S and C band blade antennas and to find that the best in-band resonant frequency of the three antennas are 1.75GHz, 2.25GHz, and 5.54GHz accordingly. These in-band resonant frequencies are used to determine the value of coefficient **a** in Eqn. (2) for L, S and C band blade antennas respectively.

3.4.2 Maximum gain above 1GHz

The measurement and simulation of the blade antennas are completed in previous works. Based on the investigation, it is found that there are a few main lobes at most of the frequencies above 1GHz, including the out-of-band frequencies. Meanwhile, the differences among the magnitudes of those main lobes are within 3dB at most of the frequencies. Assuming the worst case gain at the out-of-band frequencies, the blade antennas are assumed to be omni-directional at the out-of-band frequencies

above 1GHz. In order to illustrate the worst case antenna gain at frequencies above 1GHz, the maximum gain threshold of the L, S and C band blade antennas are plotted based on the measurement and simulation in Figure 43, 44, 45.

Figure 43 L band blade antenna maximum gain threshold above 1GHz

As shown in Figure 43, the in-band antenna gain of the L band blade antenna at 1.75GHz is 3.5dBi, while the gain at out-of-band frequency 11.71GHz is 9.632dBi. Therefore, the difference between the maximum out-of-band antenna gain threshold and the in-band antenna gain threshold is about 5 dB.

Figure 44 S band blade antenna maximum gain threshold above 1GHz

As shown in Figure 44, the maximum out-of-band antenna gain of the S band blade antenna is 9.945dBi at the 15.38GHz, while the in-band gain at 2.25GHz is 3.8dBi. Therefore, the difference between the out-of-band and in-band maximum gain threshold is about 5dB as well.

Figure 45 C band blade antenna maximum gain threshold above 1GHz

For the C band blade antenna, the maximum out-of-band antenna gain at 7.19GHz is 11.76dBi, while the in-band antenna gain is 6.8dBi at 5.54GHz.

Based on the investigation, the worst case gain of the L, S, and C band blade antennas is generally 5dB higher than the in-band antenna gain (eqn. 3) and the blade antennas are assumed to radiate omni-directionally.

$$G_{high} \approx G_0 + 5dB \quad (3)$$

G_{high} is the maximum blade antenna gain at the out-of-band frequencies above 1GHz and G_0 is the in-band antenna gain, which is known normally.

3.4.3 Maximum gain prediction model of blade antennas

Combined with the general prediction equations for frequencies below and above 1GHz, the complete out-of-band prediction model of the blade antennas can be summarized as following:

- i. At frequencies below 1GHz, the blade antenna maximum gain increases exponentially according to eqn. (1).
- ii. At frequencies above 1GHz, the maximum first follow the trend of eqn. (1), until the maximum gain is 5dB higher than the respective in-band maximum gain. Thereafter, the maximum gain of the blade antenna will be constant.

The prediction models of the L, S, and C band blade antennas from 200MHz to 18GHz are compared with their measurement results in Figure 46, 47, and 48 to show the effectiveness of this prediction model. The prediction model can predict the worst case gain of the blade antennas in aircraft communication system applications for electromagnetic compatibility purposes.

Figure 46 L band blade antenna maximum gain prediction model

Figure 47 S band blade antenna maximum gain prediction model

Figure 48 C band blade antenna maximum gain prediction model

3.5 Effects of dimensional parameters on in-band resonant frequency

The effect of the length of the antenna radiator and the length of the Teflon cylinder load of the blade antennas are discussed in section 3.3. A generic equation has been derived to show the relationship between the resonant frequency and the antenna

length & Teflon cylinder load length for the L band and S band blade antennas.

In this section, the effects of the different dimensional parameters of the L band blade antenna will be investigated and analyzed. A prediction model will be derived for the L band blade antenna in order to predict the in-band resonant frequency with known dimensional lengths.

3.5.1 Define the L band blade antenna structure

Figure 49 L band blade antenna model (antenna length=26.2mm, Teflon cylinder load length=31.85mm)

As shown in Figure 49, the antenna radiator has a diameter of 0.8mm and a total length of 26.2mm. The upper portion of the antenna radiator is tilted to the back of the antenna at angle of 45 degree, which makes the antenna structure dynamic in the aerospace environment. The bending angle of the blade antennas is determined considering the aerodynamic loading effect, and it can be varied slightly based on design. The L band blade antenna is designed by DSO according to exactly the same structure of a real L band blade antenna installed on the aircraft for research purpose. The upper portion and lower portions of the antenna radiator are covered by two separate Teflon Cylinder loads (effective dielectric constant = 2.08) with diameters of 3mm and 4.6mm respectively. For the ease of read, the Teflon cylinder load which covers the lower portion of the blade antenna radiator is named as “Teflon cylinder

load 1” and the Teflon cylinder load which covers the upper portion (tilted portion) of the antenna radiator is named as “Teflon cylinder load 2”. There is metal shield with thickness of 0.5mm outside Teflon cylinder 1 & 2. If not specified in later discussion, the length of the metal shield is changed by the same amount as the length of Teflon cylinder load. The metal base on which the antenna radiator is fixed serves as the conduction ground of the monopole antenna, although in actual systems, the aircraft itself performs as the ground.

In this section, the parameters discussed include the antenna length, the length of Teflon cylinder load 2, the position of Teflon cylinder load 2 and the radome height. The diameters of the antenna radiator and both Teflon cylinder loads have not been discussed yet due to limited time. Since the Teflon cylinder load 2 can be moved both up or down along the antenna radiator, and the movement affects the antenna resonant frequency significant, which will be discussed later, the effective antenna length is changed accordingly with Teflon cylinder load 2’s movement. Therefore, in later discussion about antenna length effect, where the phrase “effective antenna length” appears, it means the position of Teflon cylinder load 2 is changed while the antenna length is modified. In contrast, the phrase “antenna length” means the position of Teflon cylinder load 2 is kept unchanged while the antenna length is modified.

3.5.2 Analyze the effects of dimensional parameters

3.5.2.1 Effect of antenna length

The effect of the antenna radiator length is examined in two ways: First, the antenna length is increased or reduced from the top of the radiator, while all other parameters are kept unchanged. Second, when the length of the antenna radiator is increased, for example by 4mm from the top, Teflon cylinder 2 is moved up by 4mm accordingly.

In the opposite, when the length of the antenna radiator is reduced by 2mm from the top, Teflon cylinder load is moved down by 2mm. In this way, the effective antenna length is changed accordingly with the Teflon position. This section aims to examine the effect of the effect of antenna radiator length under different conditions.

Figure 50 shows the relationship between the antenna length & the resonant frequency and the relationship between the effective antenna length & the resonant frequency of the L band blade antenna.

Figure 50 Examine antenna length and effective antenna length effects

It can be seen that the length of antenna radiator is varied from 21.2mm to 31.2mm, which is equally $\pm 19\%$ variation based on the original length of 26.2mm. Within this $\pm 19\%$ range, the resonant frequency varies with the antenna length linearly from 1.868GHz to 1.764GHz (0.106GHz reduction), while the resonant frequency varies with the effective antenna length from 1.858GHz to 1.641GHz (0.217GHz reduction). The results show that changing the antenna radiator length solely has effect on the resonant frequency.

However, if Teflon cylinder load 2 is moved while the antenna length varies, the effect is magnified and leads the relationship to a curly manner. Therefore, the position of Teflon cylinder load 2 should also be taken into consideration while predicting the resonant frequency.

3.5.2.2 Effect of Teflon cylinder length

The length of Teflon cylinder load 2 is 31.85mm for the original L band blade antenna model. The effect of Teflon cylinder load 2 is examined in this section, while all other parameters are kept constant. Due to the limited space between the top of Teflon cylinder load 2 and the top of the radome, the length of Teflon cylinder load 2 can be maximally increased to 36.85mm, which is equivalently +16% of the original length. On the other hand, the length of Teflon cylinder load 2 is reduced to 18.85mm, which is equivalently -41% of the original length. Refer to Figure 51. Consider a similar variation range as the antenna length (total 38% variation), the resonant frequency decreases from 2.135GHz at 24.85mm (-22%) length to 1.617GHz at 36.85mm (+16%). The frequency reduction is 0.518GHz within the total 38% length variation of Teflon cylinder load 2. Compared to the effective antenna length, the frequency reduction is only 0.217GHz within a total effective antenna length variation of 38%, which is nearly half the effect of Teflon cylinder load 2. Based on the observation, it is concluded that the length of Teflon cylinder load 2 has dominant effect over the antenna length on the resonant frequency.

Figure 51 effect of the length of Teflon cylinder load 2

3.5.2.3 Effect of Teflon cylinder position

Refer to section 3.5.2.2; the position of Teflon cylinder load 2 has effect on the resonant frequency. In this section, the effect of the position of Teflon cylinder load 2 is examined based on the modified model with antenna length of 24.2mm (Figure 52).

Figure 52 effect of Teflon cylinder load position (antenna length=24.2mm)

The behavior of the resonant frequency is studied by moving the Teflon cylinder load 2 upward by 2mm and downward by 2mm respectively, while all other parameters are kept unchanged. From Figure 52, it can be seen that the position variation leads to the convergence of the three curves.

3.5.2.4 Effect of Radome height

The height of the radome can be varied according to the design requirement. The dielectric radome made of dielectric materials protects the antenna structure and has slight influence on the antenna resonant frequency. The effective dielectric constant (ϵ_r) of the dielectric material between 1 to 4 GHz is around 4.11 to 3.87. The height of the dielectric radome is varied from 33.6mm to 37.6mm, but only slightly affects the resonant frequency (Figure 53). Therefore, the radome height parameter is omitted during the prediction model derivation.

Figure 53 Effect of radome height

3.5.3 Derivation of the in-band resonant frequency prediction model

The dimensional parameters of the L band blade antenna analyzed includes the length of antenna radiator, the length of Teflon cylinder load 2, the position of Teflon

cylinder load 2 and the height of the dielectric radome. The initial stage of the model derivation takes only two parameters into consideration: the length of the antenna radiator and the length of Teflon cylinder load 2.

First, based on the original structure of the L band blade antenna (antenna length = 26.2mm), the length of Teflon cylinder load 2 is varied from 18.85mm (-41%) to 36.85mm (+16%). In order to investigate the effect of the antenna length, the simulation has been done for antenna lengths of 24.2mm, 26.2mm, 28.2mm, 30.2mm, 32.2mm, and 34.2mm and the simulation results are shown in Figure 54. For 24.2mm simulation, the antenna length is reduced by 2mm based on the 26.2mm model; while for the rest simulations, the antenna length is increased by 2mm, 4mm, 6mm, and 8mm respectively.

Figure 54 Effect of antenna length and Teflon cylinder load 2 (antenna length=24.2mm, 26.2mm, 28.2mm, 30.2mm, 32.2mm, 34.2mm)

The position of Teflon cylinder load 2 is not changed in the above simulations. First, it can be seen that despite of the antenna length, the resonant frequency decreases exponentially as the length of Teflon cylinder load 2 increases. Refer to Figure 54, the curves show that under this condition, the antenna length has very little effect on the resonant frequency, since all the curves are quite close to each other. It also can be seen that when the length of Teflon cylinder load 2 is between 26.85mm (-16%) and 36.85mm (+16%), the curves of different antenna length are nearly

parallel.

Since the antenna length is exponentially related to the length of Teflon cylinder load 2, the relationship can be expressed using the length of Teflon cylinder load 2 as in Eqn. 1:

$$f_1 = a * L^b \quad (1)$$

The italic f stands for the resonant frequency in GHz and L stands for the length of Teflon cylinder load 2 in mm. Due to the parallel of the curves, curve 3, 4, 5, 6 can be obtained approximately by shifting the curve 2 downwards by a distance c .

Since the distances between the adjacent curves are similar, c can be roughly calculated using the increment or decrement in antenna length in mm as in Eqn. 2.

$$c = -9.681 \times 10^{-3} \times \Delta R + 1.724 \times 10^{-3} \quad (2)$$

ΔR stands for the increment (positive sign) or decrement (negative sign) in length based on the original antenna length, which is 26.2mm. Since the coefficient of curve 2 (original L band blade antenna model) are: $a=20.29$ and $b=-0.7001$, the equation of curve 3 to 6 can be expressed by Eqn. 3:

$$f_2 = 20.29 * L^{-0.7001} - 9.681 \times 10^{-3} \times \Delta R + 1.724 \times 10^{-3} \quad (3)$$

The approximate curve functions are plotted and compared with the simulation results in Figure 55.

Figure 55 Comparison: approximate equation value and simulation (antenna

length=26.2mm, 28.2mm, 30.2mm)

As shown in Figure 55, Eqn. 3 approximately models the trend of the resonant frequency at antenna length 26.2mm, 28.2mm and 30.2mm. It is also shown that the equations slightly under estimate the resonant frequencies, but the equations can be effectively used for deriving the final prediction model, which will be explained later.

In the previous discussions in this chapter, the position of Teflon cylinder load 2 is fixed, no matter whether the antenna length is reduced or increased. However, the effect of the position of Teflon cylinder load 2 has already been verified to cause the convergence of the resonant frequency curves. Therefore, in order to add in the effect of the position of Teflon cylinder load 2, the position of Teflon cylinder load 2 is changed accordingly when the length of antenna is changed. Hence the effective antenna length will be changed as well.

Similarly, based on the L band blade antenna model (effective antenna length=26.2mm), the length of Teflon cylinder load 2 is varied from 18.85mm (-41%) to 36.85mm (+16%). In order to evaluate the effect of effective antenna length, simulations have been done for effective antenna lengths of 23.2mm, 24.2mm, 26.2mm, 28.2mm, 30.2mm, 32.2mm, and 34.2mm. i.e. During the simulation of effective antenna length=24.2mm, the length of antenna radiator is reduced by 2mm and at the same time, Teflon cylinder load 2 is moved down by 2mm. Or when the effective antenna length is increased to 28.2mm, Teflon cylinder load 2 is moved up by 2mm. Due to the space limit between the bottom of Teflon cylinder load 2 and the metal base of the blade antenna, Teflon cylinder load 2 can be moved down by 3mm at most. Otherwise the metal shield outside Teflon cylinder load 2 will be grounded to the metal base.

Therefore, the shortest measurable effective antenna length under this condition is

23.3mm. The simulation results of different effective antenna lengths are plotted in Figure 56.

Figure 56 Effect of effective antenna length and Teflon cylinder load 2 (effective antenna length=23.2mm, 24.2mm, 26.2mm, 28.2mm, 30.2mm, 32.2mm, 34.2mm)

It can be seen from Figure 56 that as the length of Teflon cylinder load 2 increases, the curves continue to converge. The curve “effective antenna length=34.2mm” stops at 34.85mm because Teflon cylinder load 2 has been moved up by 8mm, further increasing the length will cause Teflon cylinder load to extend beyond the radome. However, when the effective antenna length is reduced, the curve shifting trend is not regular, i.e. As the effective antenna length changes from 24.3mm to 23.2mm, the curve shifting is negligible. Since the behavior of the resonant frequency is not regular when the effective antenna length is reduced, only effective antenna lengths between 26.2mm and 34.2mm are considered in the prediction model.

Except the effect of the position of Teflon cylinder load 2, another possible factor that causes the convergence is the ratio of the effective antenna length over the length of Teflon cylinder load 2. For the same effective antenna length, the ratio decreases as

the length of Teflon cylinder load 2 increases. Thus the ratio can be defined as in Eqn. 4:

$$ratio_1 = \frac{R}{L} \quad (4)$$

R is the effective antenna length (mm) and L is the length of Teflon cylinder load 2 (mm).

However, the effect of Teflon position should also be added into the ratio to model the convergence of frequency curves. After investigation, it is found that the adjusted ratio which matches the original L band blade antenna curve is as in Eqn. 5:

$$ratio_2 = \frac{R}{L - 1.2} \quad (5)$$

When the effective antenna is increased from 26.2mm to 34.2mm, a biasing factor d should be added into Eqn. 5 as the Teflon position movement factor.

Therefore, the final ratio equation should be adjusted and written as Eqn. 6:

$$ratio_3 = \frac{R}{L - 1.2 + d}, \text{ with} \quad (6)$$

$$d = 4.4 + \left(\frac{\Delta P}{2} - 1 \right) \times 6$$

The biasing position factor d is defined using the position increment (mm) based on the position of Teflon cylinder load 2 in the original L band blade antenna model. i.e. If Teflon cylinder load 2 is moved up by 2mm, $\Delta P = +2\text{mm}$.

Based on the approximation of parallel exponential frequency curves and the factors that cause curve convergence, the final prediction function is written as Eqn. 7:

$$f_3 = \left(20.29 \times L^{-0.7001} + c \right)^e \times \frac{R}{L - 1.2 + d} + g \quad \text{with } e=0.2 \quad \text{and } g=0.83 \quad (7)$$

Coefficient e determines the slope of the exponential function. The larger e is, the faster the resonant frequency decreases. Coefficient g is a weight constant, which

balance the shifting of resonant frequency due to the modeling. The value of Eqn. 7 is compared with the simulation results in Figure 57.

Figure 57 Comparison: prediction model and simulation (effective antenna length=26.2mm, 28.2mm, 30.2mm, 32.2mm, 34.2mm)

Eqn. 7 applies within +31% range of the effective antenna length and $\pm 16\%$ range of the length of Teflon cylinder load 2 of the L band blade antenna model. However, it can be seen that at Teflon length below 26.85mm, the equation still fits the trend of the curves well until the discrepancies start to become larger at 21.85mm.

3.6 Summary

The airborne L, S, and C band blade antennas are the objects of research of this project. The blade antennas are all monopole antennas which consist of an RF port at the bottom, a metal radiator, a Teflon cylinder load and a dielectric radome covering the antenna. The L band and S band blade antennas have bending structures while the C band blade antenna has a straight metal radiator. However, the research results of the L band blade antenna are presented in this thesis because the three blade antennas have similar structures and performances at the operating frequency band. The L band blade antenna consists of a bent antenna structure, a

Teflon cylinder load surrounding the antenna and a dielectric radome. The critical parameters found to affect the antenna resonant frequencies are the length of the metal radiator and the length of Teflon cylinder load. The dielectric radome is found to change the omni-directional monopole antenna into a directional aircraft blade antenna.

The pattern measurement on the blade antennas is done in an anechoic chamber which isolates all the external interference for far-field radiation pattern measurement. Log-periodic antenna and double-ridged horn antenna are used as the transmitting antennas during the measurement. Vector Network Analyzer (VNA) was used to record the transmission coefficient. The measurement system was calibrated to minimize the system loss and inaccuracy. The antenna gain was calculated based on Friis Transmission Formula and free space loss equation and compared with the simulation results. The blade antennas were simulated using CST microwave studio. The simulation results obtained from the software include the reflection coefficient, the 2D and 3D radiation patterns, gain, the 3dB beam width, and the side lobe levels. Simulation results of the L, S and C band blade antennas are well matched with the anechoic chamber measurement data. It was found that the blade antennas have both in-band frequencies and higher out-of-band frequencies. Gain and radiation pattern of the blade antennas are found to be influenced by the ground plane and dielectric radome in a way that the blade antennas have two main lobes in the forward and backward directions of the antenna at most of the frequencies. The main lobes of the blade antennas have an elevation angle, which is varying with the frequency. The directivity of the blade antenna becomes possible cause of EMC problems in certain direction at higher out-of-band frequencies.

The relationship between the antenna length and Teflon cylinder length of the L, S

and C band blade antennas and their performances was examined through parameter sweep simulation. Equations were built for each antenna to illustrate the relationship between their dimensions and the in-band and out-of-band resonant frequencies. Based on the individual equations, a general equation was derived to predict the out-of-band resonant frequencies with known dimensions of the blade antennas. This will provide a good reference for future blade antenna design in consideration of avoiding electromagnetic interference at out-of-band frequencies.

Except the relationship between antenna dimensions and the resonant frequency, the maximum gain of the blade antennas at frequencies below 1GHz was found to increase with the frequency by 40dB per decade. At frequencies higher than the in-band frequencies, the blade antennas are found to radiate omni-directionally again so that maximum gain thresholds are drawn to describe the higher out-of-band gain of the blade antennas. A general prediction model has been developed to describe the maximum gain of the blade antenna from the lower out-of-band frequency up to higher out-of-band frequency.

The effects of the dimensional parameters including the antenna length, Teflon cylinder load length, Teflon cylinder load position and the dielectric radome height are investigated as the last part of this research. The impacts of these parameters on the resonant frequency have been studied. It has been found that both the Teflon cylinder load length and the antenna length affect the in-band resonant frequency while the Teflon cylinder load length dominates. With different Teflon length and antenna length, the function of the resonant frequency and the length can be drawn into a set of parallel curves, which will converge if the Teflon cylinder load is moved along the metal radiator. Additionally, the height of the dielectric radome is found to have negligible effect on the resonant frequency. Based on the investigations on individual parameters, the resonant frequency equation has been

derived to characterize the frequency performance of the blade antennas and reduce the effort in testing simulation models.

4. Conclusion

At the beginning of the report, antenna was defined and the basic parameters used to describe the antenna performances were introduced. After that, the antenna measurement theory and the measurement method used in this study were explained. This is followed by the antenna theories, the literature review in the area of antenna's out-of-band performance prediction, electromagnetic compatibility and some relevant researches.

The airborne L, S, and C band blade antennas are chosen to be studied in this project as the representatives of the monopole antenna type. The blade antenna have similar structures which consist of an RF port at the bottom of the antenna, an antenna radiator, a Teflon cylinder load and a dielectric radome covering the antenna. Due to the similarity of the structures of the L, S and C band blade antennas, the study of the L band blade antenna is selected to be presented in this report. The L band blade antenna has a bending antenna structure and a Teflon cylinder load surrounding the antenna. It was found that not only the length of the antenna but also the length of the Teflon affects the performance of the L band blade antenna. In addition, the dielectric radome is also found to have impact on the radiation pattern and the gain of the blade antenna.

The measurement setup for measuring the blade antennas are introduced as well. The measurement of the blade antennas were completed in an anechoic chamber which isolates all the external interference and satisfies the far-field requirements of the blade antennas. Vector Network Analyzer (VNA) was used to record the transmission coefficient during the test while the antenna gain was calculated by the automated test system.

The L band blade antenna was simulated using CST microwave studio which is a

specialist tool for the 3D simulation of high frequency component. The simulation results obtained from the software include the reflection coefficient, the 2D and 3D radiation patterns, gain, the 3dB beam width, and the side lobe level. The simulation results were compared with the measurement results in the anechoic chamber and comply with the measurement results quite well. It was found that the L band blade antenna not only has resonances at the in-band frequencies but also have higher-order resonances at higher out-of-band frequencies. The simulated and measured gain of the L band blade antenna was plotted with the frequency to show that the gain results match the reflection coefficient. Moreover, it was found that ground plane size does affect the gain of the blade antenna. The L band antenna radiation pattern is omni-directional at the in-band frequencies but becomes more directive at the higher out-of-band frequencies, which may lead to serious out-of-band EMC problems in certain direction.

The relationship between the dimensions of the L, S and C band blade antennas was examined through parameter sweep simulation. The length of the antenna after the bend and the length of the Teflon cylinder load were varied to investigate the variation of both the in-band and out-of-band resonant frequencies. Regression models were built for each antenna to show the relationship between the dimensions and the resonant frequencies. Based on the individual equations, a generic equation was finally derived to predict the out-of-band resonant frequencies with known dimensions of the blade antennas.

Besides, the maximum gain of the L, S and C band blade antennas are measured from 200MHz to 18GHz. The maximum antenna gain below 1GHz for the blade antennas was found to increases with the frequency with a 40dB per decade relationship. An exponential function was derived to predict the maximum gain at frequencies below 1GHz. At frequencies higher than the in-band frequencies, the

blade antennas are found to radiate omni-directionally so that maximum gain thresholds are drawn to describe the higher out-of-band gain of the blade antennas.

The effects of the dimensional parameters such as the antenna length, Teflon cylinder load length, Teflon cylinder load position and the dielectric radome height are investigated to study their influences on the in-band resonances of the blade antennas. It has been found that as the Teflon cylinder load length has dominant effect over the antenna length. Meanwhile, the position of the Teflon cylinder load needs to be taken into consideration since it causes the resonant frequency trend curves to converge. The height of the dielectric radome is found to have negligible effect on the resonant frequency. Based on the investigations on individual parameters, the resonant frequency prediction equation has been derived considering the effect of all the dimensional parameters. The equation can be used to characterize the frequency performance of the blade antennas and reduce the effort in testing simulation models.

There are some key contributions in this study. First, the relationship between the antenna length and the Teflon cylinder load length is studied. Based on investigations, generic prediction equations have been derived to show the relationship between the dimensions and the in-band and out-of-band frequencies of the blade antennas. Based on the simulation and measurement results, the performances of the L band blade antenna are investigated. A prediction model is derived to predict the out-of-band maximum antenna gain of the L band blade antenna using frequency. Lastly, the effects of the dimensional parameters including the antenna length, Teflon cylinder load length, Teflon cylinder load position and the dielectric radome height are investigated to study their influences on the in-band resonances of the blade antennas. A mathematical equation is derived to calculate the in-band resonant frequency of the antenna. The performance of performance off the

equation is compared with simulation results and good agreement is shown.

Recommendations:

The antennas chosen as the subject of interest in this study includes the airborne L, S and C band blade antennas. In this thesis, the in-band and out-of-band performances of the blade antennas were studied. There are a few recommendations for the future works in this research area:

1. For the blade antennas, relationships between the dimensional parameters and the resonant frequencies have been studied. The dominant dimensional parameter has been found to be the length of the Teflon cylinder load, the position of the Teflon cylinder load and the ratio between the antenna length and the Teflon cylinder load length. The prediction function is able to describe the variation of the in-band resonant frequency. However, more efforts need to be put in investigating the effects of the dimensional parameters on the out-of-band resonant frequencies. The current prediction equation may be helpful for finding an equation for out-of-band cases.
2. The maximum gain of the L, S and C band blade antennas are closely examined in a wide frequency range from 200MHz to 18GHz. The out-of-band antenna gain below 1GHz is found to increase exponentially as the frequency increases. However, the out-of-band maximum gain threshold is found to be 5dB higher than the in-band maximum gain. However, the study of the maximum out-of-band antenna gain is not related to the dimensional parameters. The author has found that the dimensional parameters actually can affect the gain of the blade antennas to certain extent. For example, the in-band antenna gain varies sinusoidally with linearly increasing/decreasing Teflon cylinder load length. More investigations are suggested to be done in the future to examine

the effect of the dimensional parameters on antenna gain. A general prediction equation can be found possibly to characterize the behavior of the maximum blade antenna gain at different resonant frequencies.

3. The study of the L, S and C band blade antennas are based on the far-field measurement and simulation of the blade antennas only in this research. In order to better characterize the blade antennas in EMC environment, simulations and measurements should be done in real-time scenarios. For example, the blade antennas should be installed and tested in aircraft communication systems to study the feasibility of the prediction functions derived. Simulation can be done for the real scenario as well to compare with the test results. However, these can't be achieved in current research due to both software and hardware resources limitation. It is suggested that the antenna EMC research should be conducted with the participations of external parties such as the Ministry of Defense so that proper equipments such as real aircraft can be provided to assist the research work.
4. The interference study should be done at system level in the future, specifying the type of the receiver antenna the blade antennas are connected to, the filter mechanism of the system, and the interference signal which may from different direction. Thorough interference analysis in system level will be more useful analyzing antennas characteristics independently.

Author's publication

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L. Wang, W. J. Koh and Y. H. Lee, "Out-of-Band Gain Prediction of Blade Antennas for EMC Purpose", Asia-Pacific Electromagnetic Compatibility (APEMC) Conference 2012, Singapore.

Paper Submitted

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