ANALYSIS AND DESIGN OF KING POST USING STATISTICAL APPROACH

A DISSERTATION

submitted in partial fulfilment of the
requirements for the award of the degree
of
MASTER OF ENGINEERING
in
MECHANICAL ENGINEERING
(Specialization in Machine Design)

By

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the dissertation entitled "ANALYSIS AND DESIGN OF KING-POST USING STATISTICAL APPROACH" in partial fulfilment of the requirements for the award of the degree of MASTER OF ENGINEERING (MECHANICAL) with specialisation in MACHINE DESIGN, of the University of Roorkee, is an authentic record of my own work carried out for a period of about 13 months, from June 1987 to June 1988 under the supervision of DR.V.K. GOEL, Professor, Department of Mechanical and Industrial Engineering, University of Roorkee, Roorkee and SHRI K. KATHIRVEL, Head Antenna and Mechanical Systems Division, Space Applications Centre, I.S.R.O, AHMEDABAD.

The matter embodied in this dissertation has not been submitted by me for the award of any other degree or diploma.

Dated June, 30 , 1988 (A. C. MATHUR)

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Dated: JUNE 30,1988

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SYNOPSIS

The steerable antennas having paraboloidal reflectors are used for Satellite Communications (SATCOM) purposes. For proper functioning of these antennas which are important part of a SATCOM system, their design need to be carefully considered and these antennas should have very high degree of reliability. King Post is an important component of the antenna system.

In the present dissertation, the analysis and design of the King Post of a typically large size antenna, has been presented on the basis of reliability based design. The design variables are considered as random variable and design and analysis is done using statistical design approach. A high amount of reliability or low value of probability of failure is considered for the component.

The statistics of King Post diameter and deflection is found and compared with the results of classical design approach.

LIST OF SYMBOLS

Dm	Diameter of main reflector
Ds	Diameter of sub-reflector
L	Total length of azimuth tube(king-post)
L1	Length of king post between bearings
t	Thickness of azimuth tube
Za	Height of antenna vertex
Za1	Height of antenna subreflector
Xs,Ys,Zs	Coordinates of stowlock
Xr,Yp,Zp	Coordinates of platform c.g.
Ar	Area of equipment room front wall
Cd	Wind drag coefficient
Cl	Wind lift coefficient
Cms	Wind moment coefficient of subreflector
Cmm	Wind moment coefficient of main reflector
V	Wind velocity
ρ	Density of wind
FDa	Wind drag force on antenna
FLa	Wind lift force on antenna
Mm	Yaw moment on main reflector because of wind
Ms1	Yaw moment on subreflector because of wind
FDr	Wind drag force on room
FHs	Horizontal force on stowlock

FVs	Vertical force on stowlock
Ms	Moment on stowlock
Zb1	Distance of lower bearing
Zb2	Distance of Upper bearing
Kb	Shock factor in bending
Kt	Shock factor in torsion
Wp	Weight of platform
Wa	Weight of antenna parts
Mx,My,Mz	Total bending moment on king post in x,y,z directions
Fx,Fy,Fz	Total axial force in x,y,z directions
R1x,R2x	Reaction forces on bearing 1 & 2 in x direction
R1y,R2y	Reaction forces on bearing 1 & 2 in y direction
K	Ratio of internal tube diameter to outer diameter
do	Outer diameter of az. tube
di	Internal diameter of az, tube
I	Moment of inertia
x1,x2..xn	Lengths of tube elements
β	Angle of wind attack
α	Column correction factor
N	Factor of safety
ρ_c	Radius of generation
Sy	Yield stress of the material
S_{smax}	Maximum shear stress
R	Reliability of the component
θ	Deflection angular
δ,D	Deflection linear
$\bar{\ }$,μ	Mean value of variable
σ	Standard deviation of variable

CONTENTS

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CHAPTER -1

INTRODUCTION

1.1 GENERAL

The large size steerable antennas having paraboloidal reflectors are used for SATELITE COMMUNICATIONS. The antennas are the most important single element of typical SATELLITE CONTROL EARTH STATIONS. These antennas are pointed towards the satellite position in the SPACE. The main function of antennas is to collect (receive) and to/transmit radiations from and to satellites in space. The radiations are in the form of radio waves (microwave) of high frequency. The signals are sent through antenna reflectors for communication, satellite tracking and control (Fig.1.1). The antennas track the satellite while in orbit, as well as during launch. These antennas are capable of being steered to any desired/specific satellite position with a minimum response to other satellites in space in order to give minimum interference of signals.

1.2 REQUIREMENTS OF AN ANTENNA SYSTEM

A typical antenna system for a Satellite Communication Ground Earth Station should meet the following requirement :

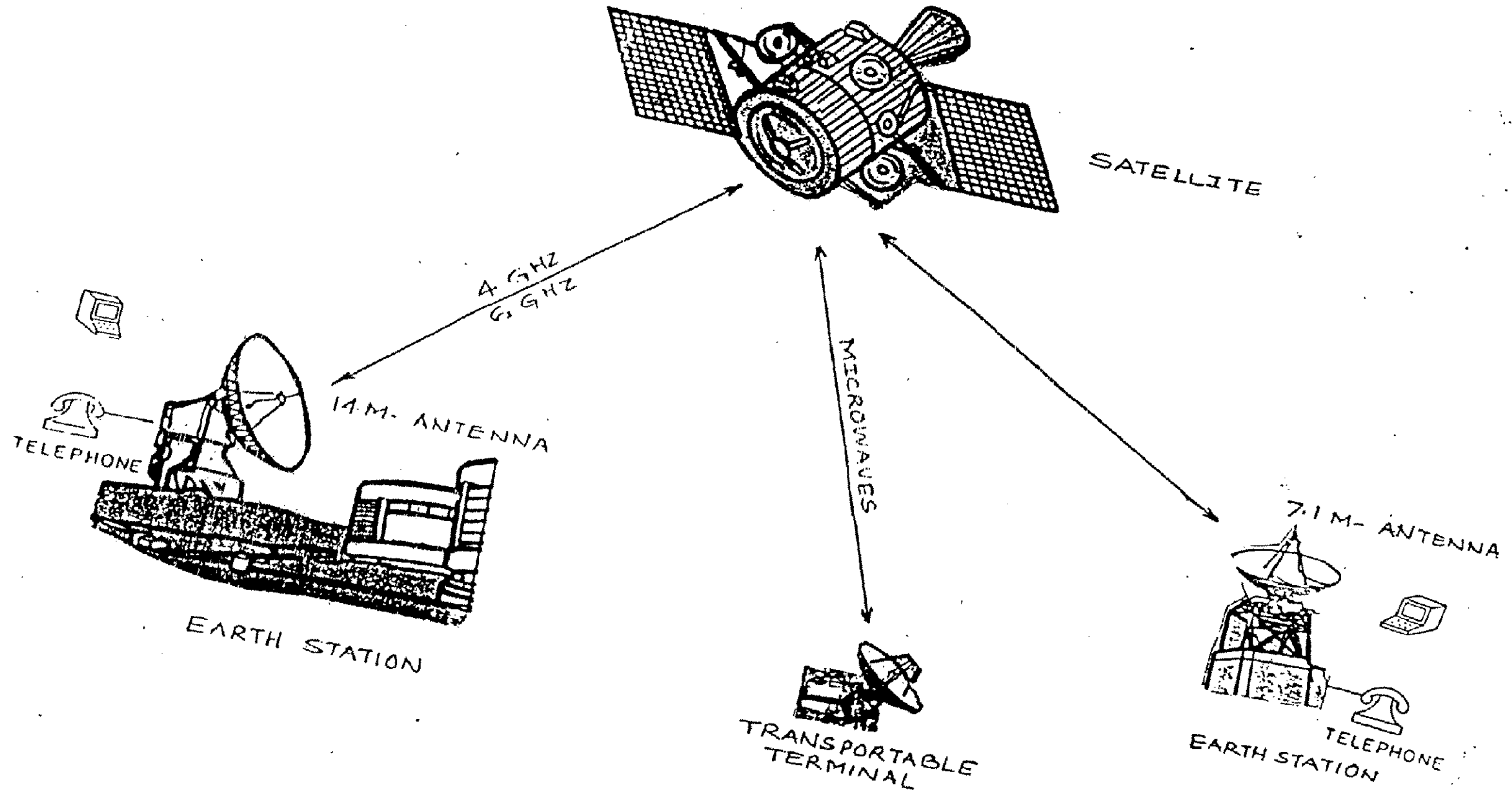


Fig.1.1 Satellite communication system

FIG.1.2: 14 M Ø - Antenna

FIG.1.3: 14 M Ø - Antenna

a. It should possess the required directional properties when functioning at the selected frequency.

b. It should be able to transmit maximum frequency in the required direction.

c. Size and weight of the total system should be minimum.

d. The antenna structure should be rigid enough to take care of wind loads, vibration, gravitational loads etc.

e. It should move and stop quickly.

f. The drive system should have zero backlash.

g. The system should have the capacity to track the satellits in Geosynchronous orbit, transfer orbit and during launch without any failure even for a very small time.

1.3 IMPORTANCE OF THE SYSTEM

The antennas are precision instruments, have large size structural and mechanical parts and are important from

Mechanical Engineering point of view. The system should not fail any time as they have to track the important satellites continuously once the contact is lost between satellite and ground station even for a very short period, the chances of loosing the satellites becomes more. They may change their orbit or can drift from their positions. Once the satellite is lost in space, it becomes impossible to get it back and a huge amount spent on the mission becomes a waste. So, the antenna systems should be highly reliable from mechanical and structural point of view.

1.4 PRESENT STATE OF DESIGN

The basic input for the design of the complete system comes from the loads induced by the environmental factors like wind, earthquake, snow and self weight or gravitational loads. Till now the mechanical and structural systems are designed by most of the design engineers, using the conventional design approach. This approach is popularly known as deterministic design approach and is used not only for SATCOM antennas, but for other mechanical systems also, by majority of design engineers. In this approach a fixed value of the design parameters, like forces, geometry, stresses and strength of the materials etc. is taken and using a factor of safety, (decided on the basis of intution, experience, and design codes the final dimension or value is decided. The results such obtained are approximate.

Modern engineering practice bases the safety factor on the significant strength of the material.

$$N = \frac{\text{Significant strength of the material}}{\text{Corresponding significant stress, due to normal loads}}$$

$$N = \frac{\text{Design overload}}{\text{Normal load}}$$

The factor of safety should be selected considering following factors:

a. degree of loading uncertainty

b. degree of material strength uncertainty

c. uncertainities in relating applied loads to material strength

d. consequences of failure - human safety and economics

e. cost of providing a large safety factor.

When the requirements are stated as a single value, with no indication of the variation to be expected, each design group inflates its computed requirement before releasing it as a design parameters. In a sequence of such steps, the amount of inflation of requirements can become quite large and in any event or at final stage the consequence is certainly an unknown amount of inflation. The net result is (often) overdesign.

The engineers design the systems on conservative side due to lack of information and uncertainty about the behaviour of various parameters and variables. On the basis of deterministic approach the designer cannot say anything about the systems reliability or its probability of failure. In turn he strongly believes or remain under the impression that by using a large value of the factor of safety the systems will not fail. As a result of all above, the systems are overdesigned.

1.5 OBJECTIVE OF STUDY

In modern society, the things are becoming more and more dependent on the proper functioning of increasingly complicated mechanical devices and systems, many of very recent origin, like SATCOM Ground Earth Station Antennas, Radio Telescopes, Radar Antennas etc. Recently designer and engineers have become increasingly concerned about problems of design adequacy and optimisation in various disciplines. In a complex system like antenna, extremely grave consequences can result from the failure of a single component . Designer should choose the best structural and mechanical designs, considering factors such as cost, reliability, weight and volume. RELIABILITY is basically a design parameter and must be incorporated in the system at the design stage itself. Design reliability is relatively a new era and are used to improve design. Recent concern with the reliability of designed mechanical products has led to a revolution of the foundation of design. The response of engineers has led to intense research activity over the past several decades, resulting in, the development of Finite Element Analysis, Fatigue research, fracture mechanics, probabilistic design and optimization.

The PROBABILISTIC DESIGN APPROACH originated in Aerospace engineering and now slowly spreading towards consumer products industry. This approach attracted the interest of engineers in 1950. In probablistic design each design factor is considered as multivalued phenomenon. The design process uses statistics of all random variables and finally gives the results close to actual values.

According to Dr. A.Frendenthal 'a careful and rigorous analysis may be largely deprived of their merits if the accuracy of results is diluted by the employment of empirical multipliers selected rather arbitrarily on the basis of considerations not always rational or even relevant'.

Stevension is of the view that the Luxry of picking up the worst possible load conditions and the minimum strength for design is not longer economically feasible under broad spectrum of load conditions.

Benjamin's views on this aspect are probabilistic concepts have been informly adopted in almost every concept of design office practice. It is time for these informal, but often incorrectly applied, procedures to be put on more rational basis.

It has been demonstrated by several authors that more economy can be achieved by designing the structural members on the basis of probabilistic school of th-ought.

1.6 SCOPE OF STUDY

Environmental loads are the major factors in the design of antenna system. The Wind Earthquakes, Snow load, Gravity loads and the Geometrical dimension, the strength of materials to be used etc , Vary randomly in nature and can be best treated statistically. No deterministic procedure can do justice to quantify these accurately. Total design variables are too many in case of antenna design and analysis.

In this study the analysis of a typical antenna system, having 14 m diameter praboloidal reflector will be done. The systems at present is being used for INSAT-I (INDIAN NATIONAL SATELLITE) Satellite control earth station, at Master Control Facility (MCF), HASSAN in Karnataka.

The forces and moments induced in the various parts of the antenna system, due to wind and self weight have been calculated and then the resultant effect of all the forces on the KING POST (i.e. Centre tube also called as Azimuth tube) which is the most critical part in the system from mechanical engineering design point of view. The analysis and design of king post has been done by both the design approaches and the results are compared. For statistical approach the statistics of the design input variables is collected and used for calculating other variables.

By considering a reasonable amount of reliability, the design of KING POST is done. As none of the system can be 100 percent reliable in the world and that is only possible when no structure is fabricated.

Efforts in the past were primarily limited to reliability predictions and reviews. These reviews resulted in changes in systems configuration rather than change in elements or components. Such changes presumably upgraded reliability, but more effective reliability improvement results from changes in component design. Improvements cannot be effective unless the methodology of designing a specified reliability into a component is known.

1.7 OUTLINES OF THE WORK

In the present study an attempt has been made to design and analyse a 'King Post' of a large size SATCOM antenna i.e. 14 m. diameter, using Statistical Design Approach (Reliability based design). The first chapter deals with the function, types of antennas, its importance, and present state of design approach. SATCOM antenna parts with special reference to 14 m. I.S.C.E.S. antenna have been described. The effects of various design factors on antennas have been discussed. The two main approaches to design viz. classical design approach and probabilistic design approach have been compared with their merits and demerits. The various design variables which are random in nature, are analysed and their statistical properties have been estimated. The analysis of King Post is carried out and the system is designed by both classical and probabilistic approaches.

Finally, the results are reported and validity of statistical approach to design is discussed. The computer programmes for both the approaches to design have been included in the Appendix.

CHAPTER - 2

SATELLITE COMMUNICATION (SATCOM) ANTENNA SYSTEMS

2.1 ELEMENTS OF ANTENNA SYSTEM

A typical antenna system has following three main elements.

Antenna Reflector

It is an important element which performs the dual purpose of radiating radio frequency energy and receiving reflected energy to and from a satellite in space. The praraboloidal type of reflectors are mostly used for SATCOM purposes because of its various advantages over others. Reflector is the most important part of the antenna system from functions point of view. The surface of the reflector is called reflecting surface and is made precisely and accurately to a parabolic form. The surface should be as smooth as possible to get the maximum efficiency or to transmit and receive maximum signals with minimum noise.

A small subreflector of hyperbolic shape is used to get a cassegrain geometry of the systems.

Feed

It is an element which is mainly responsible for transmitting and receiving radio waves to and from reflector surface.

Pedestal

It mainly consists of a support system for reflector, a mechanism for rotating the antenna reflector and control its movements to point it toward a satellite. The important goals of the pedestal are:

a. Sky coverage
b. Movement dynamics (velocity and acceleration required for tracking).
c. Accuracy of movement
d. Structural integrity

To aim the reflector at any point in the sky requires a pedestal mechanism with at least two axis of rotation. This steering function can be fulfilled by following four types of mounts.

Azimuth Elevation (Az-El) Mount

Azimuth axis is fixed and vertical to the earth surface

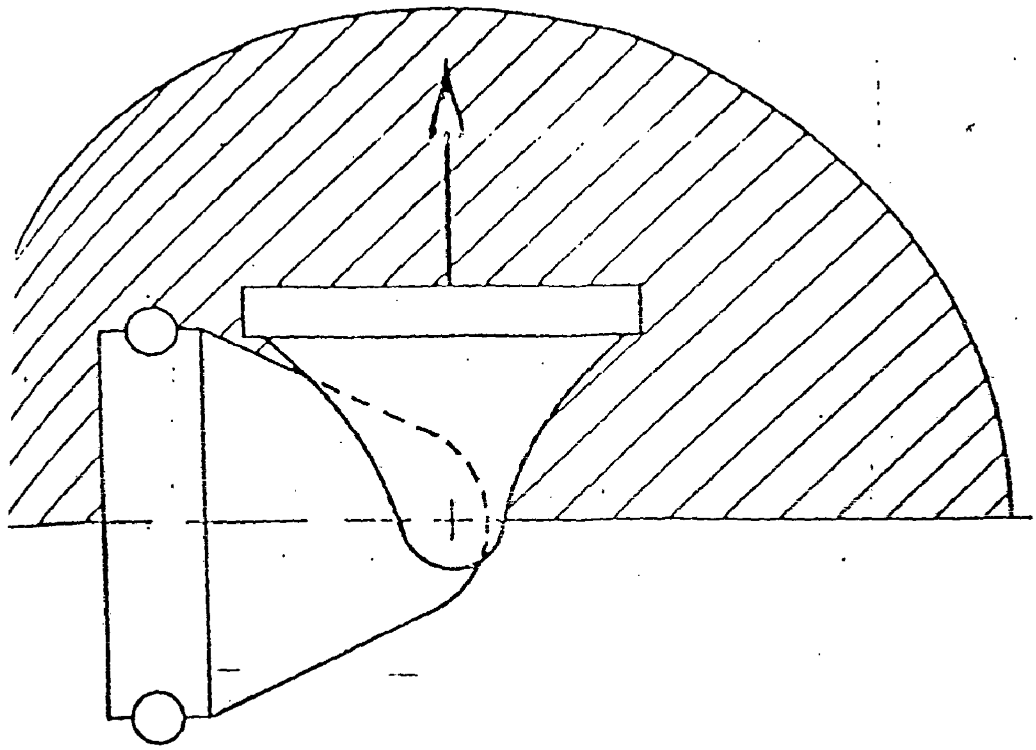


Fig.2.1 X-Y MOUNT

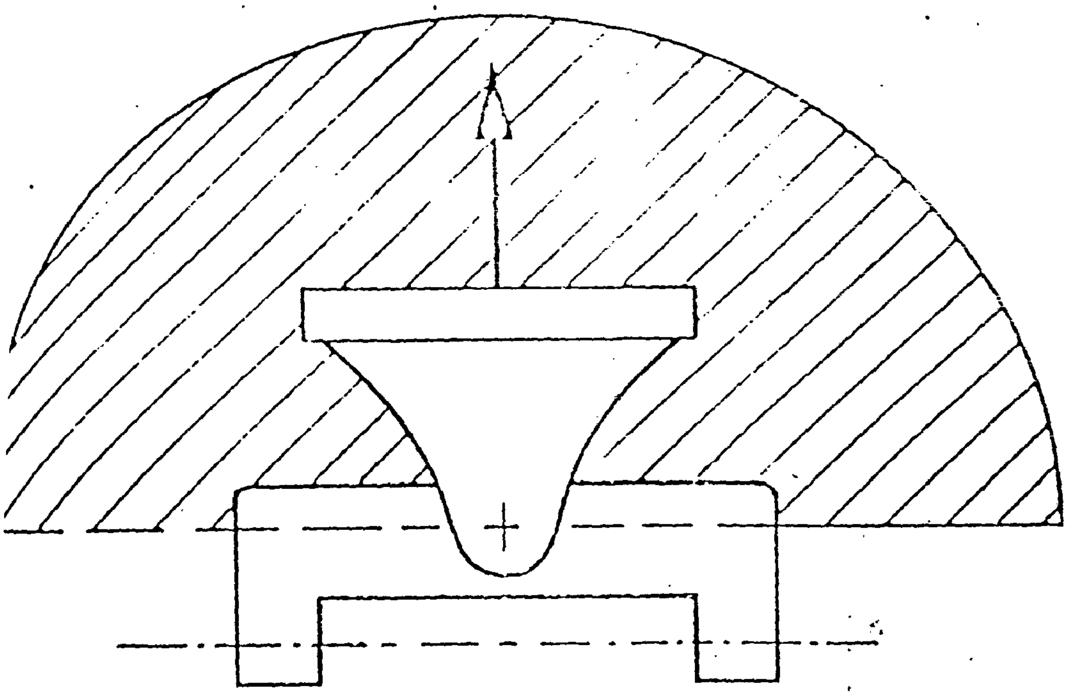


Fig.2.2 X-Y MOUNT

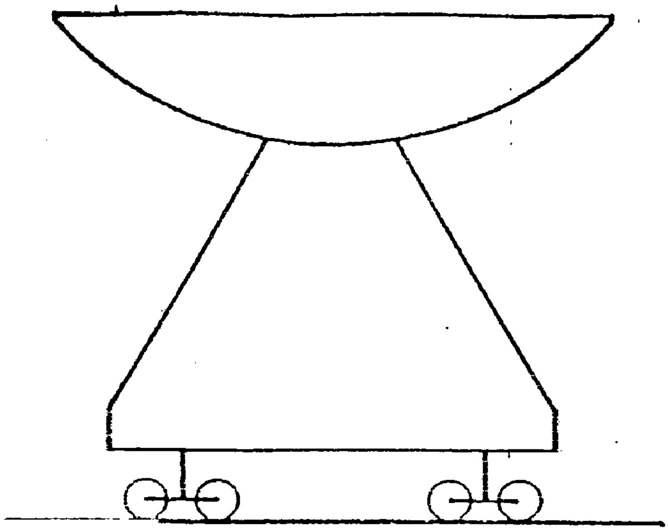


Fig.2.3 BOGIE SUPPORTS

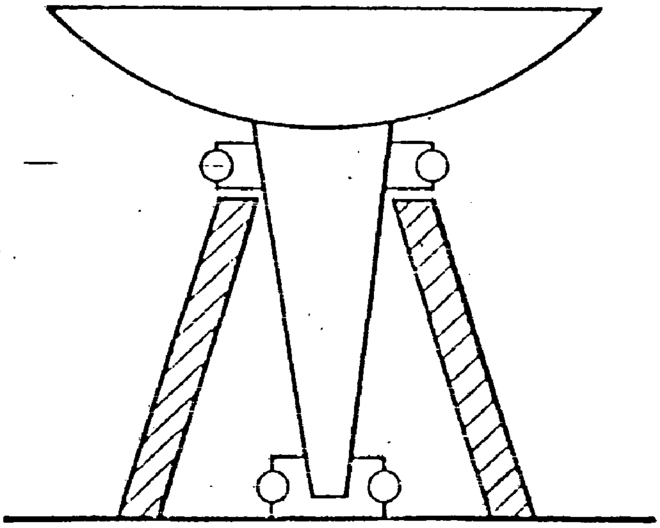


Fig.2.4 KINGPOST SUPPORT

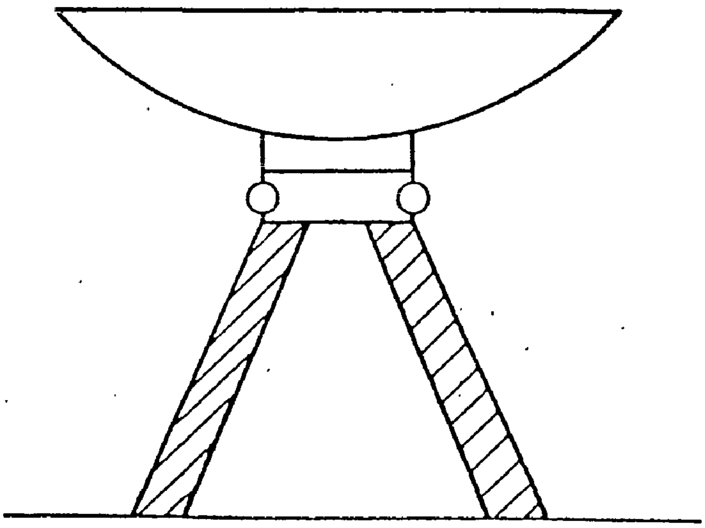


Fig.2.5 ROLLER BEARING SUPPORT

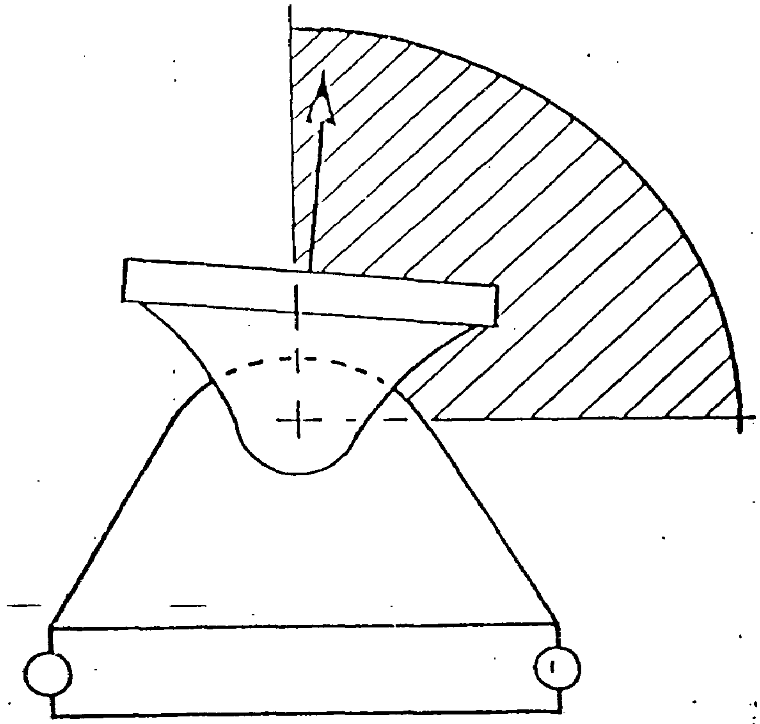


Fig.2.6 ALT.-AZ. MOUNT

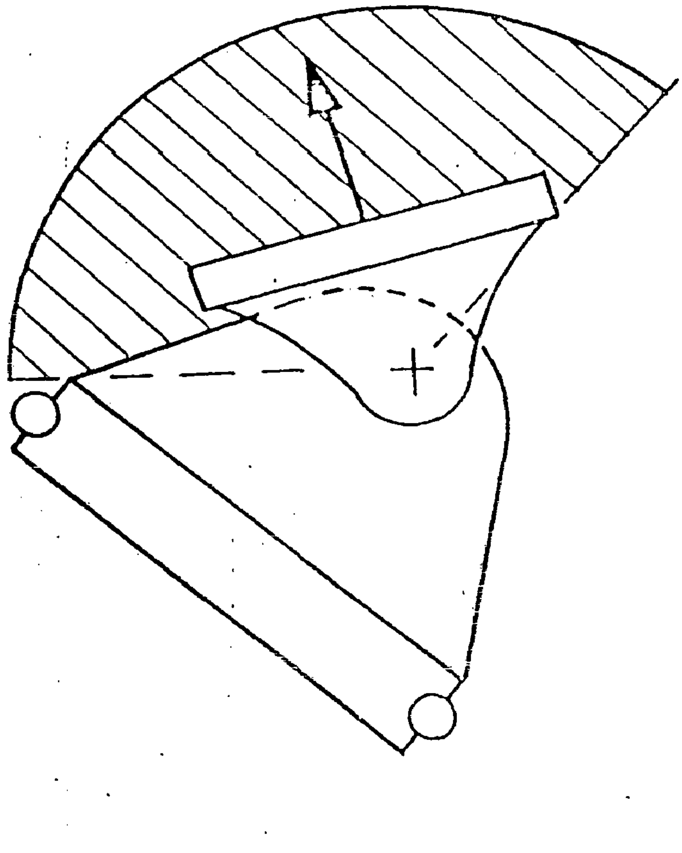


Fig.2.7 INCLINED ALT.-AZ. MOUNT (HADEC)

and elevation axis is vertical to it.

X-Y Mount

'X' axis is horizontal and fixed. The 'Y' axis is perpendicular to it. Figs. 2.1 and 2.2.

Hour Angle Declination Mount (HA-DEC)

Hour angle axis is fixed and parallel to the earth's axis of rotation and the moving (declination) axis rotates in a plane parallel to earth's equator plane. Figs. 2.6 and 2.7.

Oblique and Slant Mount

Fixed axis is vertical and moving axis is inclined at 45 degree to Azimuth.

The Az-El concept is most successful and used for fully steerable antennas.This concept is further used in following three different ways.

a. Wheel and track or bogie support(mount) Fig. 2.3

b. King post support Fig. 2.4

c. Slew ring bearing. Fig. 2.5

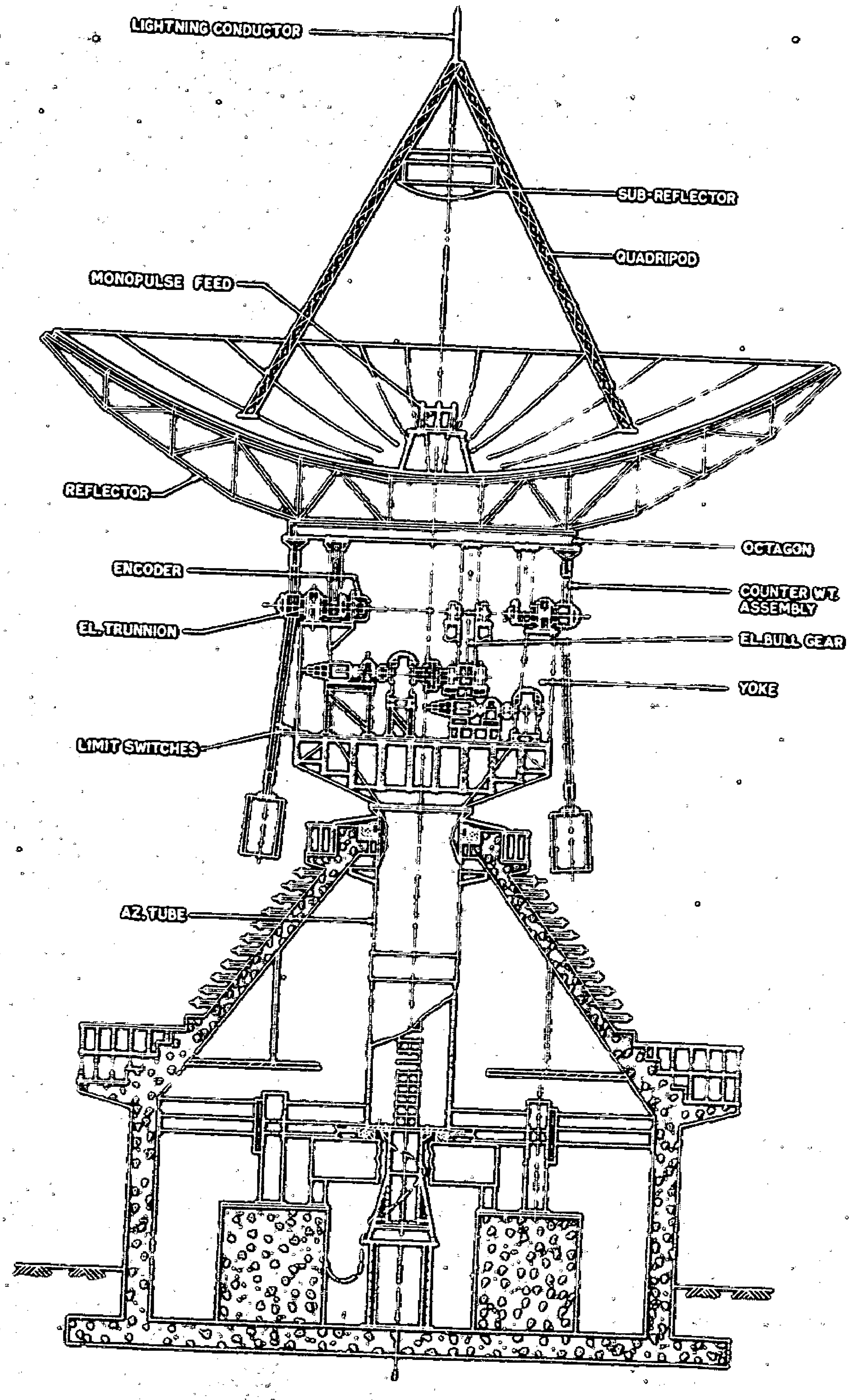
The KING POST type of mount is used mostly in Az-El type arrangement.

2.2 KING POST MOUNT/SUPPORT

A 'King Post' type mount is used to support the antenna reflector and provides freedom of motion in two directions simultaneously. It mainly consists of one vertical centre tube and two bearings, called main bearings. The vertical centre tube, sometime called as 'AZIMUTH TUBE', is subjected to combined axial, bending and torsional loads. The tube is driven by a large gear between two bearings. The main bearings of the system supports the weight of the antenna system and serve as the pivot about which the system is driven. These bearings are most heavily loaded and the lower bearing has to restrain the antenna system against wind overturning moments and also support the dead weight and side shear forces. Both the bearings are usually supported in a RCC tower. The upper and lower bearings establishes the azimuth axis of the KING POST concept.

2.3 INSAT-1 SATELLITE CONTROL EARTH STATION ANTENNA (ISCES)

To control the multipurpose satellites INSAT-IA and B, two earth stations of the international standard have been set up at Master Control Facility (MCF), near HASSAN in Karnataka State. These control earth stations consists



14M MCF ANTENNA

of two fully steerable antenna system. The systems are capable of controlling the INSAT-I satellites during transfer orbit and later on during synchronous orbit. Each antenna system is having a 14 meter diameter solid parabolic reflector, an Az-El type of mount, RCC foundation and servo control system, succh a typical antenna system is shown in Fig.

For the first time, design and manufacturing of such an antenna system is done in our country with the aim of generating technical competence in India for such an antenna work in future. Space Applications Centre, ISRO, Ahmedabad was given the responsibility of design, manufacturing and installation of the two antennas.

The antennas were designed from structural and mechanical stand point. The structural and mechanical problems are counted as major towards program success.

The design, manufacturing and erection of such an antenna system is an example of most complex and advance mechanical engineering and was a challenge to Indian industries.

Specifications

The important specification of ISCES/MCF antenna system are as follows:

Mechanical specifications

1. Diameter main reflector	:	14 meter
2. -do- sub reflector	:	1.612 metre
3. Focal length of reflector	:	5.18 metre
4. Steeribality		
Elevation	:	0 to 90°
Azimuth	:	± 270°
Type of mount	:	El-Az
5. Tracking speed	:	1°/sec.max. in both the axis
6. Tracking acceleration	:	0.2°/sec^2 in both the axis
7. Slew speed	:	1°/sec,max.in both the axis
8. Slew acceleration	:	1°/sec^2,max.in both the axis
9. Tracking error	:	0.04° RSS peak
10. Pointing error	:	0.08° RSS peak
11. Weight of antenna	:	140 Tonnes

Environmental Specifications

1. Wind speed		
a. Operational	:	60 KMPH
b. Occasional	:	80 KMPH
c. Survival	:	200 KMPH
2. Rain	:	80 mm continuous rain fall
3. Temperature	:	0 to 55°C
4. Relative humidity	:	Not specified

5. Snow : Not specified
6. Earth : Not specified
7. Solar and radiation : Not specified

Design Considerations

The major factors, considered are

F/Dm = 0.37, frequency - 3.7 to 6.4 GHz
Wind velocity - 200 KMPH

The wind loads and moments have been calculated on the basis of E.Cohen and J. Vellozi's paper titled 'Calculation of wind forces and pressures on antenna'. The fixed loads on platform attached to king post are as follows:

a. Self weight : 11.4 tonnes
b. Live load : 500 kg/m
c. Weight of equipment room - 4.1 tonnes

The Azimuth tube or KING POST is designed considering axial loads, bending and torsion. The effect of cutout is considered while computing the stresses and deflection by FEM.

It is felt by the designers and other engineers that the system is overdesigned (excess of weight). Not only king post but other mechanical and structural components of the systems can be optimized and a reduction of weight is possible.

CHAPTER - 3

FACTORS FOR ANTENNA DESIGN

The mechanical design of an antenna system is closely linked with its electrical design. The mechanical requiements play an important role in the electrical design.

The important factors which influence the desgin of large antenna systems are as follows:

3.1 FREQUENCY

The antenna reflector surface tolerance or accuracy depends upon the radio frequency at which signals are to be transmitted. At very high frequency the increase in diameter does not improve the gain till the accuracy is increased. Literally the surface tolerance controls the entire design and cost. As the surface tolerance decreases the reflector weight (stiffness) increases Fig. 3.1.

3.2 FOCAL LENGTH TO DIAMETER RATIO

A reflector with long focal length is easier to manufacture accurately and has less deflections when pointing towards the horizon than does a deeper (short focal length)

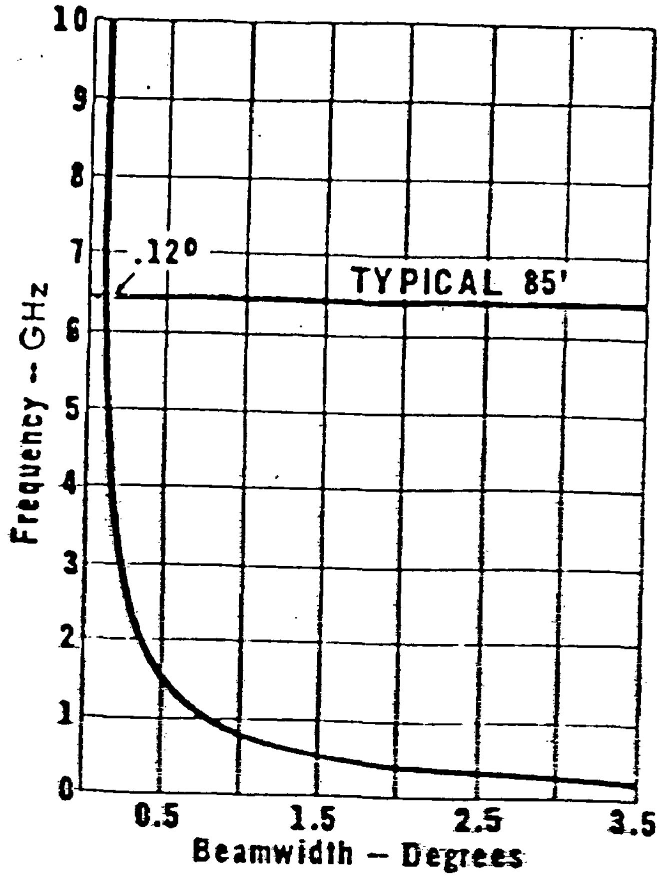
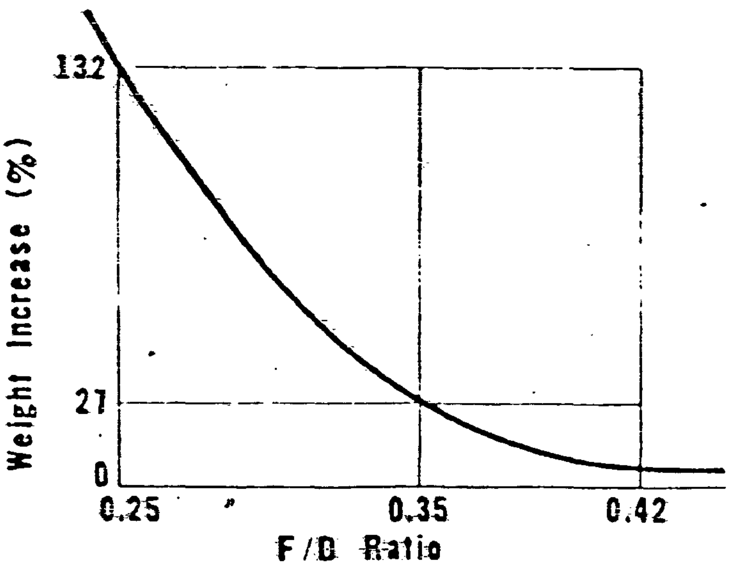


Fig. 3.1 Beamwidth Versus Frequency



'/D Ratio Versus Percentage Weight Increase (Reflector Only)

Fig.3.2

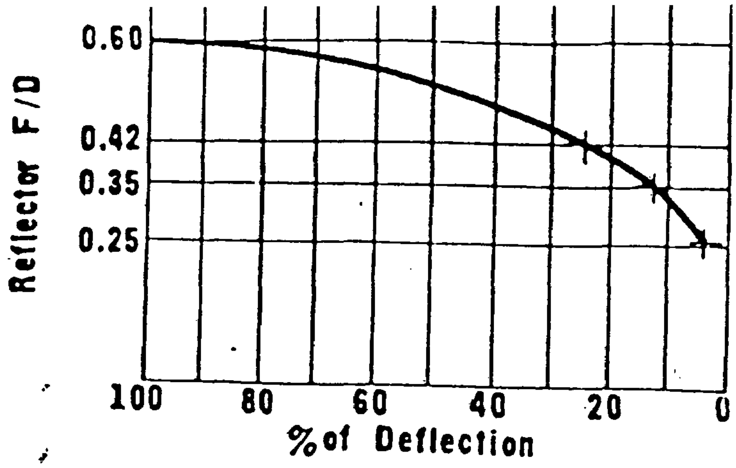


Fig.3.3 Feed Support Structure f/D Versus Percentage of Focal Point Deflection

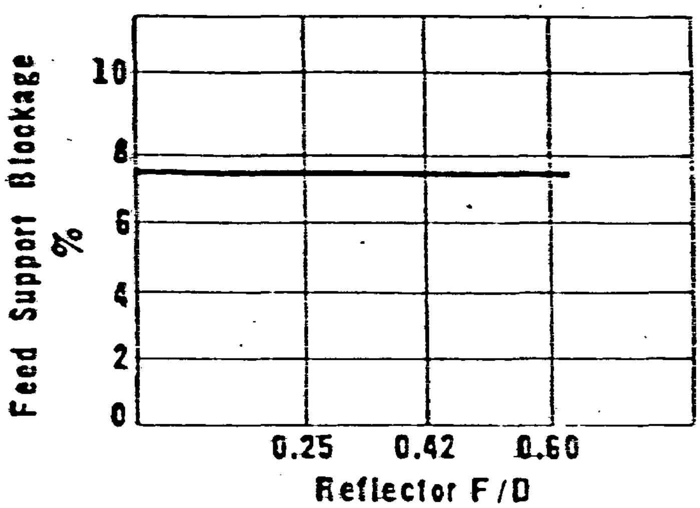


Fig.3.4 Feed Support Blockage Versus f/D

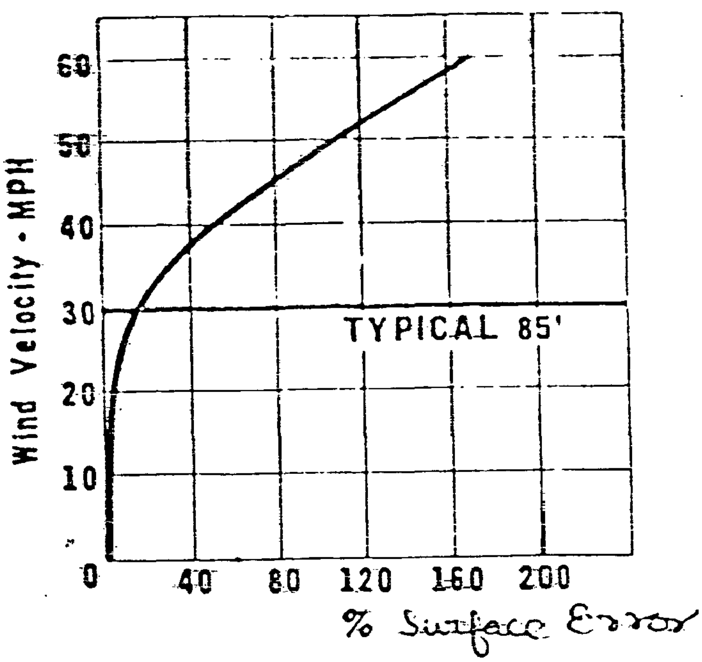


Fig.3.5 Wind Velocity Versus Percentage Surface Error Increase

reflector. A deeper reflector has approximately a 130% increase in weight and 20% higher peak positive moments over the shallow. When f/d ratio increases, the deflection of feed/sub reflector support increases, which results into more pointing error Figs. 3.2, 3.3 and 3.4.

3.3 GEOGRAPHICAL LOCATION

The environmental conditions differ with geographical location of the selected site. The environmental conditions at the selected location must be carefully measured and evaluated if feasible to establish antenna specifications. It is unreasonable to believe that one design is suitable for all locations.

The environmental factors like wind, snow, earthquake, temperature etc. induce loads and moments on antenna structures. The combined effect of all these factors comes finally on the king post.

Wind Loads

It is the most important parameter which has the greatest influence on the design of antenna parts. For an economical design the structure should be designed to a maximum wind load for a given life and then to stable the performance

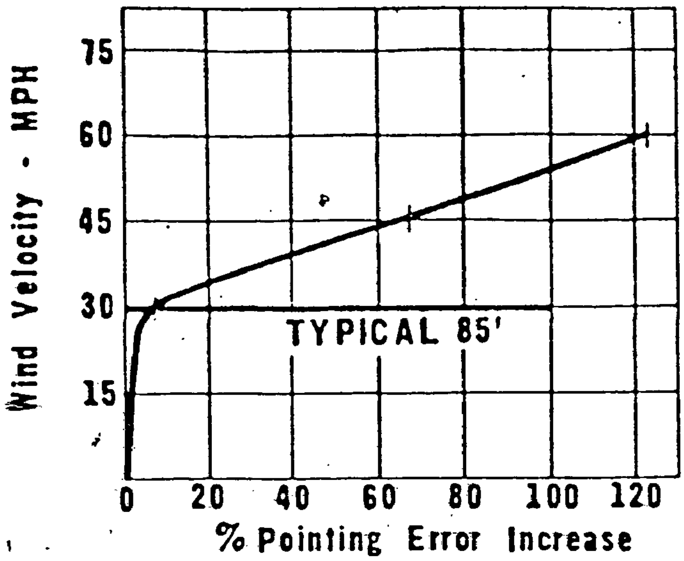


Fig.3.6 Wind Velocity Versus Percentage Pointing Accuracy

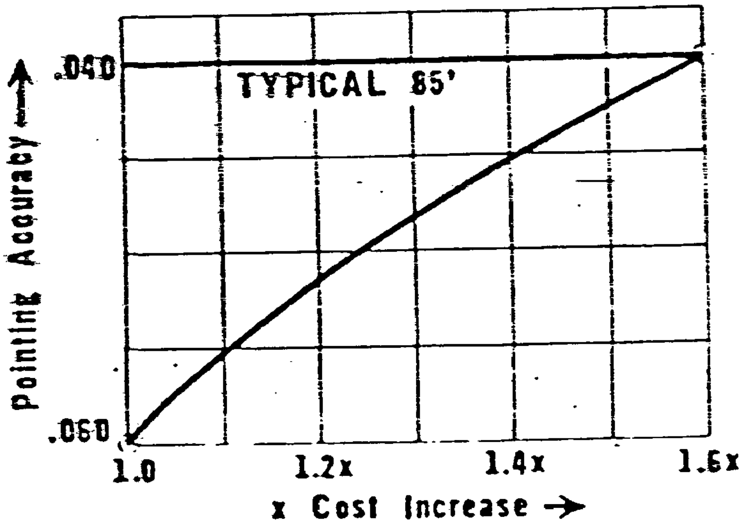


Fig.3.7 85-Foot AZ-EL Antenna Pointing Accuracy Versus Cost Increase

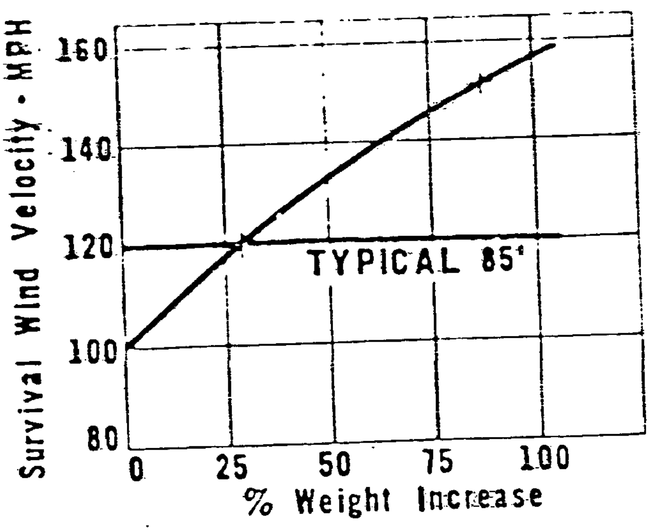


Fig.3.8 Wind Velocity Versus Percentage of Weight Increase

characteristics expected for different wind regions.

Wind velocities of upto 48 kmph (30 mph) have less than 14% effect on performance. Above this the wind error become so large that they over shaddow all of the other error contributors. As the wind velocity increases above 95 kmph (60 mph), and the accuracy remain same, the reflector becomes significantly heavier, because stiffness must be increased to the higher wind loads, the cost is very much affected. Figs 3.5,3.6,3.7 and 3.8.

Earthquake Loads

In case of earthquake, ground shifting and deflection, takes place. But because of the top structure being eleastic the movement of the ground is reduced. The effects of earthquake on ground is also taken care by the RCC foundation of the antenna. The frequency of the structure because of earthquake is very less in comparison to the natural frequency of the structure, so chances of failure of the structure are very less. The stresses developed in the foundation and structures are very low.

If we design the structure on the basis of high intensity of earthquake, the structures become very heavy and uneconomical.

Even if the antenna structure deflects i.e. the reflector electrical axis shifts and it does not track the satellite for a very small period (microseconds) as the earthquake occurs for a short time.

Snow/Ice Loads

Snow or ice loads on a structure vary according to the geographical location (climate) site exposure, shape and type of structure (shape) and of course from one winter to another. Snow or ice loads play an important part in ensuring the safety of structures. The snow/ice increases the dead weight of the structures. The load depends upon the snow ice density. Snow density is a random variable in time and space and its estimation by a numerical constant is quite difficult. The assessment of snow loads can be done in a improved way by probabilistic approach for any structure because of blown off effect at the ground they are maximum.

In a large antenna system, the snow/ice loads mainly effect the paraboloidal reflector and the equipment room's roof. The snow gets deposited on the roof and inside the paraboloidal dish. Antennas which are located in heavy ice formations zone, must be carefully evaluated. The ice loading significantly influence the structural and mechanical component design. The increase in dead weight because of ice deposited cause an extra load on structure and drive system. It causes an extra deflection of reflector surface.

To melt the ice, various methods such as mechanical (scrapping), chemical and electrical are used. Usually the electrical method is used by putting electric heaters (in special curved form) below the reflecting surface.

Much literature is not available for calculating the effects of snow/ice structure. The effect of snow are negligible when antenna design is done for survival condition. The effect of wind at high velocity are much more and the snow deposited is less because of blown off effect.

Thermal/Temperature Effects

The temperature effects vary linearly with diametere of the antenna. The temperature causes some deflection in the structure which affects the RMS surface error and pointing error of the antenna. The errors are usually very small. For 14 m, MCF antenna, the estimated values of temperature effects on RMS error and pointing error are as follows:

RMS error = 14/65 x 0.43 = 0.093 mm

Pointing error = 14/65 x 0.024 deg = 0.005 deg

The above errors are low and hence detailed temperature analysis is not essential. These errors are negligible compared to specified performance critria. The temperature values differ during clear night and noon sun time. In antenna system the reflector is the most sensitive part for temperature.

Because of temperature variation, thermal stresses and strains develop in the structure. These may cause some deflection of the structure, which is very small. The stresses developed are also very small and hence the temperature effects does not contribute significantly for antenna system design.

3.4 GRAVITATIONAL LOADS

The gravitational loads (because of self weight) acts vertically downwards away from the centre axis of the system. It causes an axial load along with a moment (about 140 tons in the 14 M antenna) which are considered while designing the king post, selection of bearing and foundation design.

3.5 INERTIA LOADS

The inertia torque depends upon the acceleration rates and are calculated for various acceleration or slew acceleration. For MCF antenna, the slew acceleration is 1 deg/sec^2 . At operational wind speed the inertia torque [6] on the two axis are

Elevation axis, T_E = 1053 kg.m = 1.053 T-M

Azimuth axis, T_A = 1382 kg.m = 1.3827 T-M (Ton-Meter)

Beyond 100 kmph, the antenna drive system becomes non operational. The inertia torque at the two axis are zero. To know the performance of the system at operational wind speed, the inertia forces may be considered but here also the value is very less as the acceleration of antenna is only 1 deg/sec^2. The inertia torques are usually very less in comparison to wind torques.

CHAPTER - 4

DESIGN APPROACH AND METHODOLOGY

There is now a choice of philosopies available for carrying out mechanical design. However, in many respects engineering design methodology until recently has been slow to change in response to new demand. Theory and methodology sufficient to satisfy former (simpler) requirements have experienced difficulty with some current problems.

At present there are broadly three approaches for the design of mechanical and structural parts. The merits and demerits of each one are mentioned below in brief.

4.1 DETERMINISTIC DESIGN APPROACH

This approach is the oldest, most popular, and most simple. It is still widely used by the designer. This approach is also called as conventional / classical/traditional design approach.

In this approach it is maintained that all the design parameter are single valued and the scattering is zero. It uses concept of safety factor which is decided mainly on the basis of intution and judgement of the engineer till recently. The

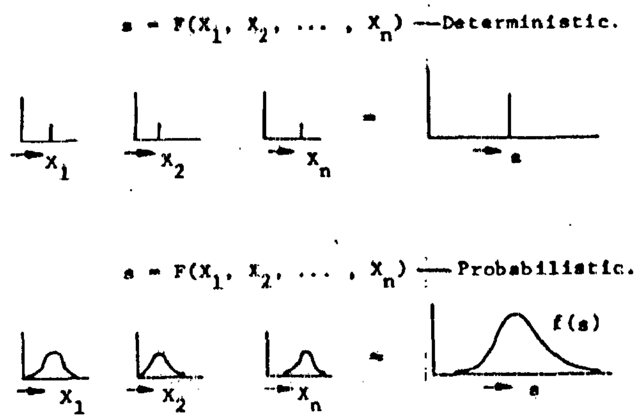
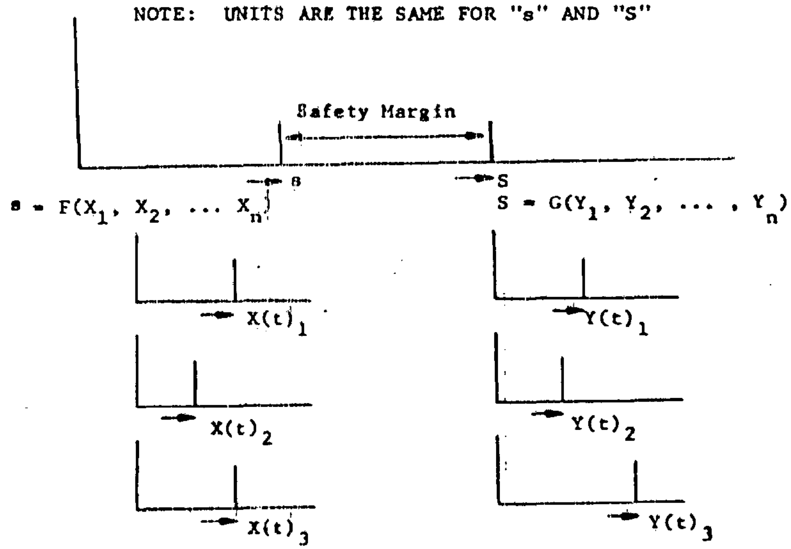
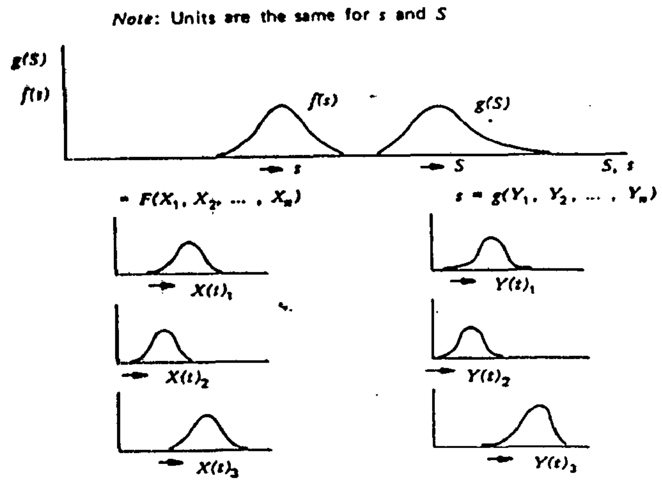


Fig. 4.1 Deterministic versus probabilistic representation.



Note. t refers to service life.

Fig. 4.2 Design–deterministic approach.



Note: Symbol s refers to service life.

Fig. 4.3 Design–probabilistic approach.

accepted criterion for an adequate strength limited design has been

$$S > N.s$$

where S is the deterministic component of system strength, 'N' is factor of safety which takes care of possible errors of omission and commission, 's' denotes single value applied stress.

Merits and Demerits

1. It is most simple and popular design approach.
2. It is not adequate from a reliability design point of view.
3. Statistical nature of design variable is not considered seriously and usually ignored.
4. It gives overly conservative results. The degree of conservation (sometimes reflected in excess of weight) cannot be readily be estimated by this methods.
5. The value of factor of safety specified in the code are so much conservative that probability of their being crossed is very low.
6. It considers that material strength can be exactly known which is never true.

7. It can be compared with worst case analysis as maxima of loading and minima of strength are considered of simultaneous occurrence.

Fallacies in Designing by Safety Facotrs

The nature of the variability of nominal stress and of the stress factors that affect component stress, and of nominal strength and the strength factors that affect component strength, explain the existence of stress and strength distribution. The safety factor concept completely ignores the facts of variability that result in different reliabilities for the same safety factor.

Three possibility exists in which a safety factor may be maintained as failure probabilities varies.

1. Mean stress and mean strength may be changed in the same proportion with no change in the standard deviations.
2. Failure probability varies if the mean values of stress and strength distributions are held constant and the standard deviations are varied.
3. Both mean values and standard deviations varies without affecting the safety factor.

4.2 PROBABILISTIC DESIGN APPROACH

This approach is comparatively new approach and began with the use in aerospace industries. Its importance is being realised by the designers and researchers, all over the world. This approach is a major tool for reliability based designs of mechanical systems. It utilized the probabilistic models of the random variables prepared with the help of statistical data and statistical methods. The probability of failure depends upon statistical numbers for modelling variables and statistical algebra for constructing function.

Merits

The advantage of probabilistic approach are as follows.

1. This approach is adequate from reliability point of view and the component reliability can be calculated at the design stage itself.
2. It identifies explicitly all the design variables and parameters.
3. It forces the designers to quantify uncertainty in the design variables and thus understood the inherent reliability of the design.

Demerits

a. Main drawback is that it requires good knowledge of probability and statistics which every designer does not have.

b. For preparing a probabilistic model statistical data of all the variables are required which in general the designers are not having.

c. A simple procedure for design is not available as the subject is new one or is still at its infancy.

Advantages of Statistical Aproach in Antenna Systems Design

The statistical approach/methods help us in the antenna system design as follows:

1. To model the behaviour of all variables like wind speeds, snow, area, forces, geometrical dimension, material behaviour etc.

2. To specify risk of failure associated with design based on life of the antenna structure.

3. It quantifies design adequacy and reliability.

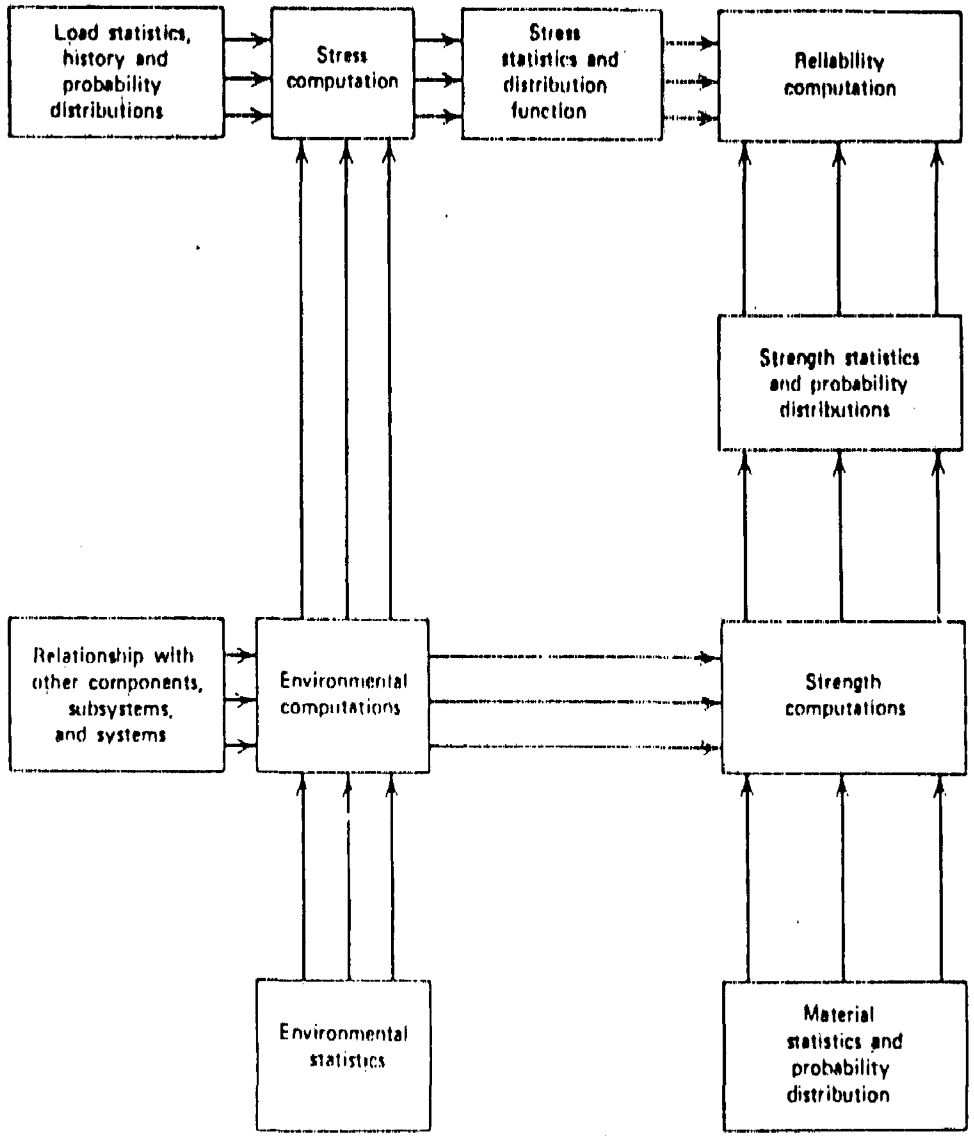


FIG.4.4 : Probablistic Design Methodology

4. The chief merit of the statistical approach is that it is realistic and ensures that similar structure are designed to same level of reliability.

Probabilistic Design Methodology

The probabilistic design methodology is shown through block diagrams in Fig. 4.4. The various steps in the process are :

1. Establishment of a primary design.
2. Estimation of external forces.
3. Analysis of the preliminary system, including force intensity in component expressed as probability density function (pdf).
4. Material selection basedon mechanical and physical properties and on economic feasibility.
5. Description of strength and failure characteristics of the material, incuding its pdf.
6. Quantitative estimates of strength and failure characteristics of components, are functions of

   a. Engineering
   b. Geometric considerations
   c. Anticipated operational loads.
7. Description of collective strength and failure characteristics.

CHAPTER - 5

STATISTICAL ANALYSIS AND ESTIMATION OF DESIGN VARIABLES

The data collected for different design variables are bound to follow a statistical distribution. Most of the statistical methods are based on underlying distributions. Using the distribution theory statistical models are constructed. Static models are used to evaluate possible design configurations and to determine the necessary reliability levels for subsystems and component.

It is generally impossible to obtain a model that would provide an exact fit to the experimental data and what should be aimed for, is the one that fits well enough to provide consistent and reasonable answers in practice.

5.1 STATISTICAL ANALYSIS OF WIND SPEED

The metrological department gives data about the maximum gust and highest mean hourly wind speed for every day. Estimates of a designed wind speed must be based on the most severe wind condition which the structure will encounter during its specified or anticipated lifetime. Since this involves prediction of wind condition for into the future, it is evident that there can be no precise and certain estimates but that probability considerations based on the statistical analysis of previous observations of wind speed must be employed. The probability that contain speed will not exceed in the given time interval is mentioned.

Earlier the designer used to take the maximum wind velocity occured till the time of design on the selected site, as design wind speed. The life of the structure, randomness of wind velocity and direction were not used to be considered. The IS-875 (1964), code of practice for structural safety of buildings, governs the design of structures to resist wind load. The code is entirely deterministic in nature. The ISI has circulated a new revised draft code, so as to present a standard which is consistent with the current design practices as also to remove the anomalies existing in the current code IS:875 (1964).

For an antenna designer, i.e., to the structural and mechanical engineers, modelling the probabilistic behaviour of wind speed is of vital interest on two counts. Firstly an adequate probabilistic model may conveniently be used to specify basic design wind speeds under the action of which, the stresses in structure will not exceed the allowable stress level for the load combination considered in the design. Secondly, from the knowledge of probability distributions of the wind speeds direct inferences may be drawn regarding the safety level of structures subjected to wind loads.

Only the static models of the wind are considered. In the study of probabilistic behaviour of winds, two types of statistics are of interest, those relating to the total population of wind speeds and those related to the properties of extreme.

To find a suitable model for wind, a number of researchers and engineers have studied the wind behaviour extensively. Notably among them, Gumbel (1958), Shellard (1965), Rayleigh (1967), Davanport (1969), Johnson and Kotz (1970), Lebor and Shore (1970), Bury (1975), Puri and Tikku (1986), have worked significantly and have tried both parent wind modelling and extreme wind modelling [16,19,26]. The following models have been proposed.

[A] Parent wind speed distribution model

i. Normal model or Gaussian model
ii. Exponential model
iii. Rayleigh model
iv. Weibull model

[B] Extreme wind speed model

i. Type-I or Gumbel model or Fisher Tippet Type-I
ii. Type-II or Frechet model or Fisher Tippet Type-II

The results from the studies [26] done recently for India are as follows:

a. The mean or the observed peak wind speed can not be used for design.

b. The extreme value type-II (Frechet) distribution seems to be most appropriate to model wind behaviour in the Indian subcontinent.

c. The estimates of wind speeds from type-II distribution are not very high compared to observed peak or the estimated value from type-I distribution.

d. For consistent and reliable estimates of predicted wind speeds, length of record of 25 years or more can be considered as adequate.

e. The study indicated the presence of a fixed shape parameter for each station, which if identified could be used to predict wind speeds even from shorter periods of record (10 to 15 years). These results however, need further authentication and verification.

f. The risk associated using a 50 year return period wind for an average life span of 50 years of a structure were quite high (=0.63).

Wind speed values for the 14 stations considered in the analysis by Tiku[26], are given out by IS 875-1964 and the revised draft code. The return period for these wind speeds is 50 years. Wind speeds data of 28 stations, analysed by Agarwal[1] have been collected from Indian Metrological Department.

The data analysed for Bangalore, Ahmedabad and Delhi is given in Table 5.1.

Table 5.1 WIND ANALYSIS DATA

Place	Length of records years	Sample mean value in KMPH	Sample maximum value in KMPH	Standard deviation KMPH	Predicted extreme wind speed in KMPH for 50 yrs. Return Period
Bangalore	13	72.4	106	17.112	129
Ahmedabad	16	89.5	131	18.243	152
New Delhi	40	104.1	159	18.35	163

Wind speeds recommended by various researchers for 50 years return period are given in Table 5.2.

Table 5.2 RECOMMENDED WIND SPEED

Place	Jain	Ayyer & Goel	Mari & Morley	Puri & Tiku	Revised Draft Code
Bangalore	118	120	100	120	120
Ahmedabad	168	160	147	128	140
New Delhi	176	160	148	170	170

The risk analysis of different stations for which data of more than 15 years were available, was carried out [2,24]. For design wind speed for 50 years return period, the risk that the design wind will be exceeded during the life time of the structure (50 years)p50($>$ V)=0.63. This risk may be regarded as being too high. Decrease in this risk requires either an increase in the design wind speed or a reduction in the designed life of structure. However, world over, the structures designed on the basis of this risk level, have performed satisfactorily.

At a speed of 200 kmph, for 50 years structural life, risk factor reduces considerably or if life is 15 years, the risk is further reduced to 0.01489.

For the deterministic approach the design wind speed is to be considered as 200 kmph maximum wind value, on the basis of extreme value distribution. In the probabilistic approach the mean value of wind speed is taken as 72.4 kmph (for Bangalore) with maximum value as 200 kmph. The standard deviation can be found, considering the normal distribution.

3 standard deviation = Max. wind speed - Mean wind speed

For Bangalore, the standard deviation in wind speed

$$\sigma V = \frac{200 - 72.4}{3} = 42.2 \text{ kmph}$$

5.2 GEOMETRICAL VARIABLES

The component and system dimensions such as reflector diameter, length of king post, thickness of tube, height of antenna vertex, height of sub-reflector, position of stowlock and other physical features are of prime importance in mechanical design. Geometric variations influences,

a. Failure frequency in a component population.
b. Probability of failure of a component selected at random from among many.

The determination of required statistics of geometrical variables is accomplished by appropriate quantitative studies of the manufacturing process. Capability and from actual measurement of typical products. In the absence of data, approximation based on previously related studies (or ranges of values to be expected) are used.

Most of the process operations naturally generate normal distribution if they are controlled [12]. Manually operated processes generate distributions different from those obtained from automatic processes.

Operations where operator work to high side of tolerances, result in distribution that are skewed. A part may be rough machined, milled and then hardened, in which case heat treatment effects will cause a shift in the mean dimensions and increase in variability.

The mean and standard deviation values can be calculated from the following:

Let the collection of values are, d_1, d_2,....,d_n

$$\mu\bar{d} = \frac{d_1 + d_2 + d_3 + \ldots\ldots + d_n}{n} \qquad \ldots \qquad (5.1)$$

$$\sigma_d = \left[\frac{\sum_{i=1}^{n} (d_i - \mu\bar{d})^2}{n} \right]^{\frac{1}{2}} \quad .. \quad (5.2)$$

Main Reflector Diameter (Dm)

The typical variation in the dimension of diameter (Dm) as measured, are given in Table 5.3.

Table 5.3 VARIATION OF DIMENSIONS ON Dm

S.No.	Dm	S.No.	Dm	S.No.	Dm
1.	14.000	17.	14.002	33.	13.878
2.	13.889	18.	14.001	34.	13.880
3.	14.002	19.	13.000	35.	13.880
4.	14.003	20.	13.999	36.	13.881
5.	13.998	21.	13.999	37.	13.881
6.	14.003	22.	13.998	38.	13.880
7.	13.997	23.	13.990	39.	13.882
8.	14.001	24.	14.000	40.	13.882
9.	13.999	25.	13.880	41.	13.882
10.	13.999	26.	13.882	42.	13.887
11.	14.000	27.	13.884	43.	13.878
12.	14.000	28.	13.884	44.	13.878
13.	14.000	29.	13.882	45.	13.879
14.	14.001	30.	13.878	46.	13.879
15.	14.001	31.	13.876	47.	13.880
16.	14.002	32.	13.876	48.	13.880

Using equation 5.1 & 5.2, the mean and standard deviation values comes out to be 13.940 m and 0.02 m.

Sub Reflector Diameter (Ds)

The variation in dimensions of sub reflector diameter (Ds) are given in Table 5.4.

Table 5.4 VARIATIONS IN DIMENSIONS OF Ds

S.No.	Diameter,Ds
1.	1.612
2.	1.614
3.	1.613
4.	1.611
5.	1.611
6.	1.610
7.	1.613
8.	1.614
9.	1.611
10.	1.613

Using equation 5.1 and 5.2, the mean and standard values comes out to be 1.612 m and 0.007 m.

Statistics of Linear Dimensions

From actual manufacturing conditions the following dimensions have variations upto $\pm$ 5 mm or $\pm$ 0.005 meters. So the standard deviations values can be found by considering ($\pm 3\sigma$ limits) normal distribution as follows,

$$S.d. = \frac{0.010}{6} = 0.00166 \text{ meters}$$

Tube Thickness

From actual manufacturing conditions and availability, the variation in the thickness of the tube is considered as $\pm$ 22 mm = $\pm$ 0.0022 m.

$$\text{So the S.d.} = \frac{0.0022}{3} = 0.000666 \text{ meter}$$

Equipment Room Wall Area (Ar)

The area statistics depends upon the statistics of dimensions a_1, a_2, b_1 and b_2, Fig. 5.1.

The mean and standard deviation values of a general function y can be found as follows. y is defined as -

$$y = f(x_1, x_2, \ldots\ldots, x_n) \quad .. \quad (5.3)$$

The mean of function y is given by

$$\mu_y = f[\mu(x_1), \ldots\ldots, \mu(x_n)] \quad .. \quad (5.4)$$

The standard deviation of function y is given by

$$\sigma_y = \sum_{i=1}^{n} \left(\frac{\partial y}{\partial x_i} \right)^2 \sigma^2_{x_i} \quad .. \quad (5.5)$$

Using Eqs.(5.4) and (5.5) the mean and standard deviation of

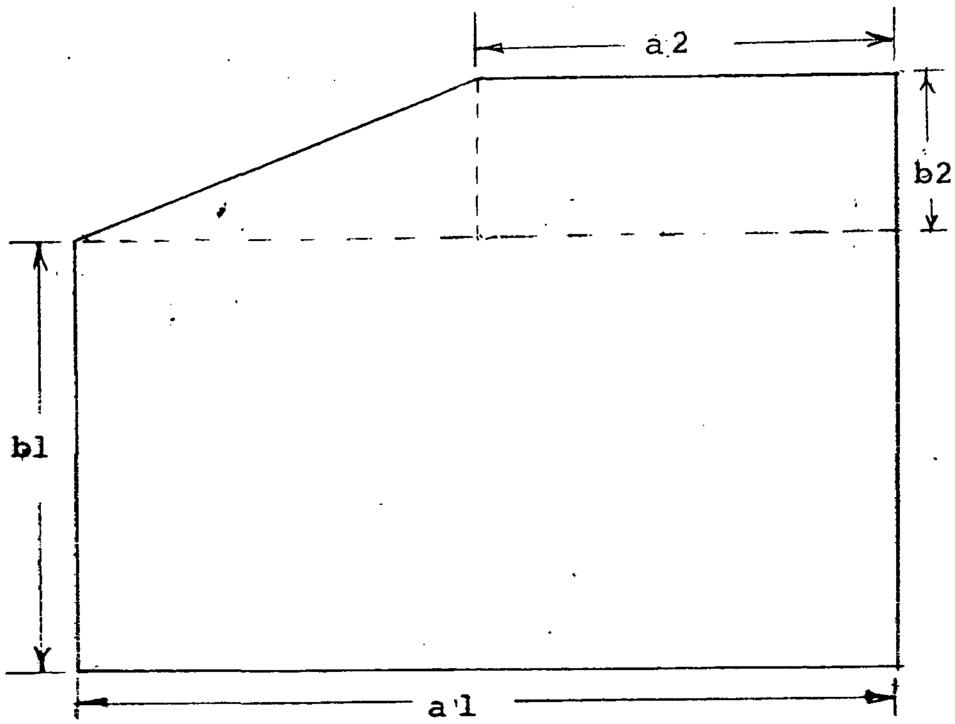


FIG: 5.1 : Equipment Room Wall

equipment room wall area are given by

$$\mu_{Ar} = \bar{a}_1\bar{b}_2 + \bar{b}_1\bar{a}_2 + \bar{b}_1(\bar{a}_1 - \bar{a}_2) \quad .. \quad (5.6)$$

$$\sigma_{Ar} = [\ (\bar{a}_1 \times \sigma a_1)^2 + (\bar{b}_2, \sigma b_2)^2 + (\bar{b}_1\ \sigma b_1)^2$$

$$+ (\bar{a}_2 x\ \sigma b_2)^2 + (\bar{b}_1 . \sigma a_1)^2 + (\bar{a}_1 .\ \sigma a_1)^2$$

$$+ (\bar{b}_1 .\ \sigma a_2)^2 + (\bar{a}_2 . \sigma b_2)] \quad .. \quad (5.7)$$

From actual manufacturing conditions the dimensions a_1, a_2, b_1 and b_2 can vary upto $\pm$ 10 mm.

So the S.d. in linear dimensions = $\frac{0.001}{3}$ = 0.0033 meters

The equations 5.6 and 5.7 gives the mean and standard deviation values of Ar as 11.35 and 0.0181.

5.3 LOADING VARIABLES

Loading in mechanical design influences behaviour of mechanical systems and induce strains in the system. Loading determination involves the identification and measurement of relevant parameters and the use of this information to estimate total forces on the system.

The estimation of load spectra for design usage is done from the data on physical phenomenan or through experiments.

The static loads are often normally distributed, and the dynamic loads are often normally or lognormally distributed.

It is assumed in this dissertation, that the antenna system is subjected to static load only and therefore the distribution of various loads acting on the system is taken as normal. The different loads acting on the system are discussed in the following paragraphs.

Gravitational Loads

Since the dimensions of components and material density vary, the total weight of antenna structure would also vary. As the detailed analysis of gravitational load is not carried out, it is assumed on the basis of past experience that total weight of the system varies by ± 10%. Hence the mean and standard deviation values of gravitational load can be given as,

$$\mu Wp = 140 \text{ T}$$

$$\sigma Wp = 140 \times \frac{10}{100} \times \frac{1}{3} = 4.666 \text{ T}$$

Stowlock Reaction

The operation of stow lock mechanism gives vertical and horizontal reactions and a moment (Fig. 6.3) at the base. The magnitude of these forces [6] depends upon wind velocity, component dimensions, mechanism weight etc. It is assumed that the stow lock reactions vary in magnitude as ± 10%, moment as ± 5%. So the statistics of the FH_s and FV_s can be given as

$$\mu FH_s = 47\ T, \qquad \sigma\ FH_s = \frac{10x47x2}{100x3} = 1.566T$$

$$\mu FV_s = 20.0T, \qquad \sigma\ FV_s = \frac{10x20x1}{100x3} = 0.666T$$

$$\mu M_s = 20.5T, \qquad \sigma\ M_s = \frac{5x20.5}{100x3} = 0.3427\ T\text{-}M$$

Platform Unbalance

The platform weight depends upon weight of equipment (Wp1) self eight (Wp2), Equipment room weight (Wp3) and live loads (Wp4). It is assumed that the variation in Wp4 is ± 5% and in others is ±10%.

Using Equation 5.3 and 5.4, the statistics of the platform unbalance comes as follows,

$$\mu Wp = \mu Wp1 + \mu Wp2 + \mu Wp3 + \mu Wp4 = 33.85T$$

$$\sigma Wp = \sqrt{(\sigma\ Wp1)^2+(\sigma\ Wp2)^2+(\sigma\ Wp3)^2+(\sigma\ Wp4)^2} = 3.825T$$

5.4 OTHER FACTORS AND COEFFICIENT

Modulus of Elasticity

The Kent's Mechanical Engineer Handbook (page 2-57) gives the variation in value of E as ±3.45%, so its mean and S.d. value becomes,

$$\mu E = 2x10^7 \ T/m^2$$

$$\sigma E = 23x10^4 \ T/m^2$$

Shock Factors

The shock factors in bending and torsion are decided by designers, on the basis of experience between 1.00-2.0.

If $\mu K_b = \mu K_t = 1.5$

Then,

$$\sigma K_b = \sigma K_t = 0.166$$

Elevation Angle

At survival wind speed the antenna is stowed towards zenith (ß=0). The exact locking position depends upon systems dimension, actual position of locking pin and hole and manufacturing errors. The variations in ß may be taken ±2° [6].

So, $\mu\beta = 0°$, $\sigma\beta = 0.666°$

Wind Density

It varies from place to place, depending upon the humidity for Indian conditions and the value of acceleration due to gravity. Its variation may be taken between 0.0074 to 0.012 kg/m^3, which gives,

$$\mu\rho = 0.0097 \text{ kg/m}^3 = 0.0000097 \text{ T/m}^3$$

$$\sigma\rho = 0.00077 \text{ kg/m}^3 = 0.0000077 \text{ T/m}^3$$

Drag, Lift and Moment Coefficient

The values of these coefficients are found by actual tests. The work done in this field is very less and hence much data are not available. Its value depends upon the angle ß, height to diameter ratio of reflector. Considering variation in the coefficient values as $\pm$ 0.01 [5] and normal distribution, the value of these coefficients is given as follows:

$$\mu Cd = 0.3, \; \mu Cdr = 1.0, \; \mu Cm = 0.13$$

$$\mu Cms = 1.2, \; \mu Cl = 0.15$$

$$\sigma Cd = \sigma Cdr = \sigma Cmm = \sigma Cms = \sigma Cl = 0.0033$$

5.5 STRENGTH VARIABLES

The examination of numerous histograms indicate that the distributions of static yield strength in [12] are usually approximately normal. It is well known that the statistical characteristics of a given material produced to the same specification will vary from company to company. Material strength varies with the design factors like strength stress modifier, effects of size, temperature, and the theory of failure to be applied.

The IS-2602 does not specify the strength values of mild steel in probabilistic terms. On the basis of various tests, the values can be found and added to the code. The yield strength values given inthe code and considered earlier in the deterministic design approach are 42 kg/mm^2.

The standard deviation can be considered a ± 3 kg/mm^2 or 7.14% equivalent to the standard deviation of structural steel given on page 601 [12].

CHAPTER-6

DESIGN AND ANALYSIS OF KING-POST

6.1 CLASSICAL DESIGN APPROACH

Various forces and moments which act at the King Post and consequently affect its dimensions, mainly arise due to

1. Wind forces
2. Self weight of the antenna
3. Unbalanced weight of the platform and live loads
4. Operational loads due to stowlock mechanism
5. Acceleration torque

These forces and moments are calculated as follows. Table 7.1 gives the values of design variables for a 14 M Ø antenna.

Wind Loads and Moments

On the basis of focal length to diameter ratio, angle of wind attack (ß), solidity ratio and height to diameter ratio of the reflector, the values of coefficients Cd, Cl, Cmm, Cms are found from Figs. 6.5, 6.6 and 6.7. The values of dynamic pressure, wind drag force, lift forces and yaw moments, are calculated using following equations [10].

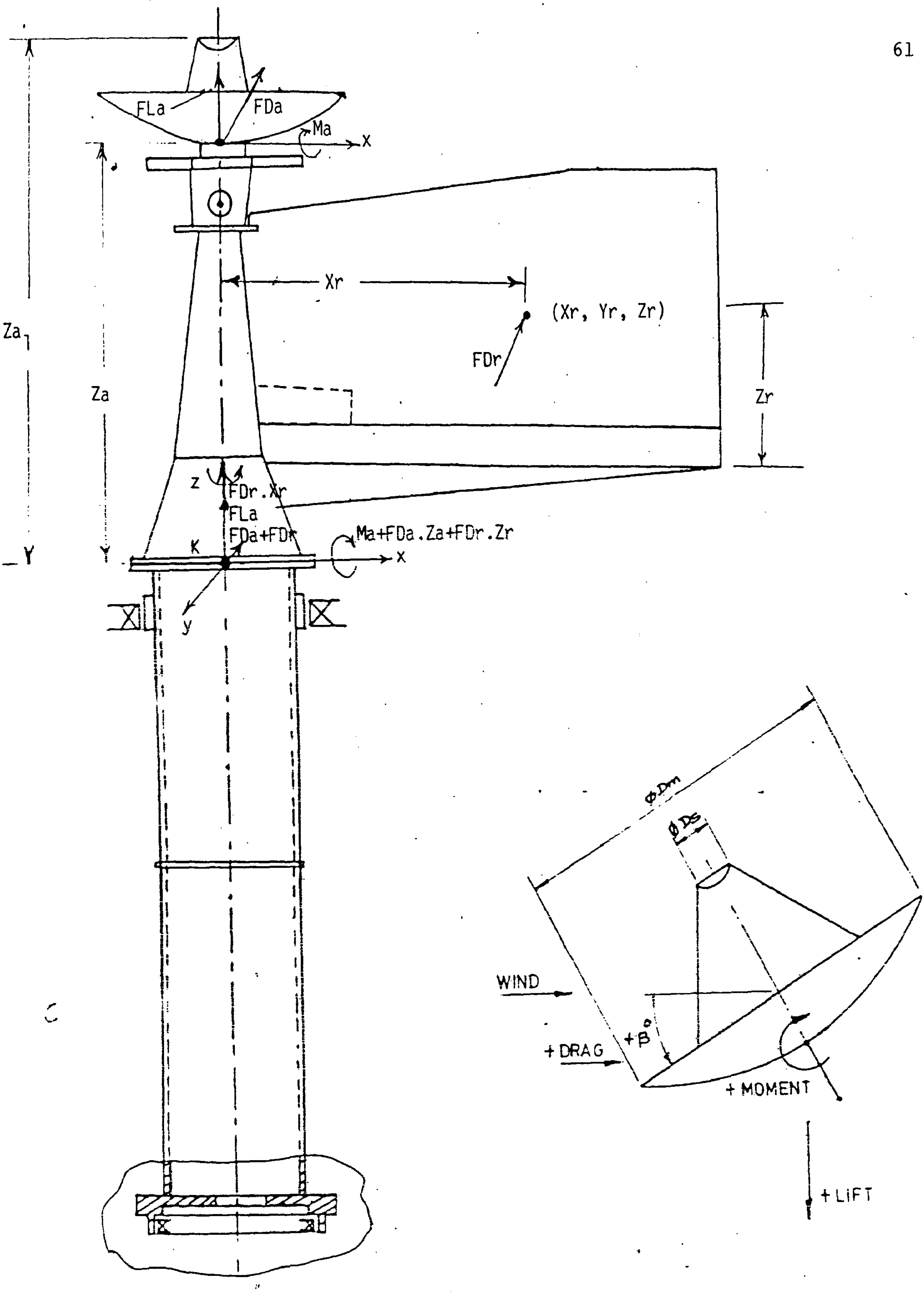


FIG. 6.1 : WIND LOADS AND MOMENTS

The dynamic pressure Pr is given by

$$Pr = \frac{1}{2}.\rho.V^2 \qquad .. \qquad (6.1)$$

The wind drag and lift forces, Fig. 6.1, are given by Eqs. 6.2 and 6.3 respectively.

$$FD_a = \pi/4 \times Dm^2.Cd.Pr \qquad .. \qquad (6.2)$$

$$FL_a = \pi/4.Dm^2.Cl.Pr \qquad .. \qquad (6.3)$$

The yaw moment Ms. due to sub-reflector and yaw moment Mm due to main reflector are respectively given by

$$M_{s1} = \pi/4.Ds^2.Cms.Pr(z_{a1} - z_a).\cos\beta \qquad (6.4)$$

$$Mm = \pi/4.Dm^3.Cmm.Pr \qquad .. \qquad (6.5)$$

Therefore the total yaw moment is

$$Ma = Mm + M_{s1} \qquad .. \qquad (6.6)$$

The moment Ma acts about the vertex of the relector and is transferred directly to point 'K' of King Post. Fig. 6.1.

The lift force FL_a on antenna acts vertically upwards at the vertex and transfers directly at point 'K' Fig. 6.1. The drag force FD_a acts at vertex in 'x' direction and gives a force FD_a and moment $(FD_a.z_a)$ at point 'K' Fig. 6.1.

The wind drag force on room wall FD_r acts at point (Xr, Yr, Zr) on equipment room wall in -y direction and gives a force

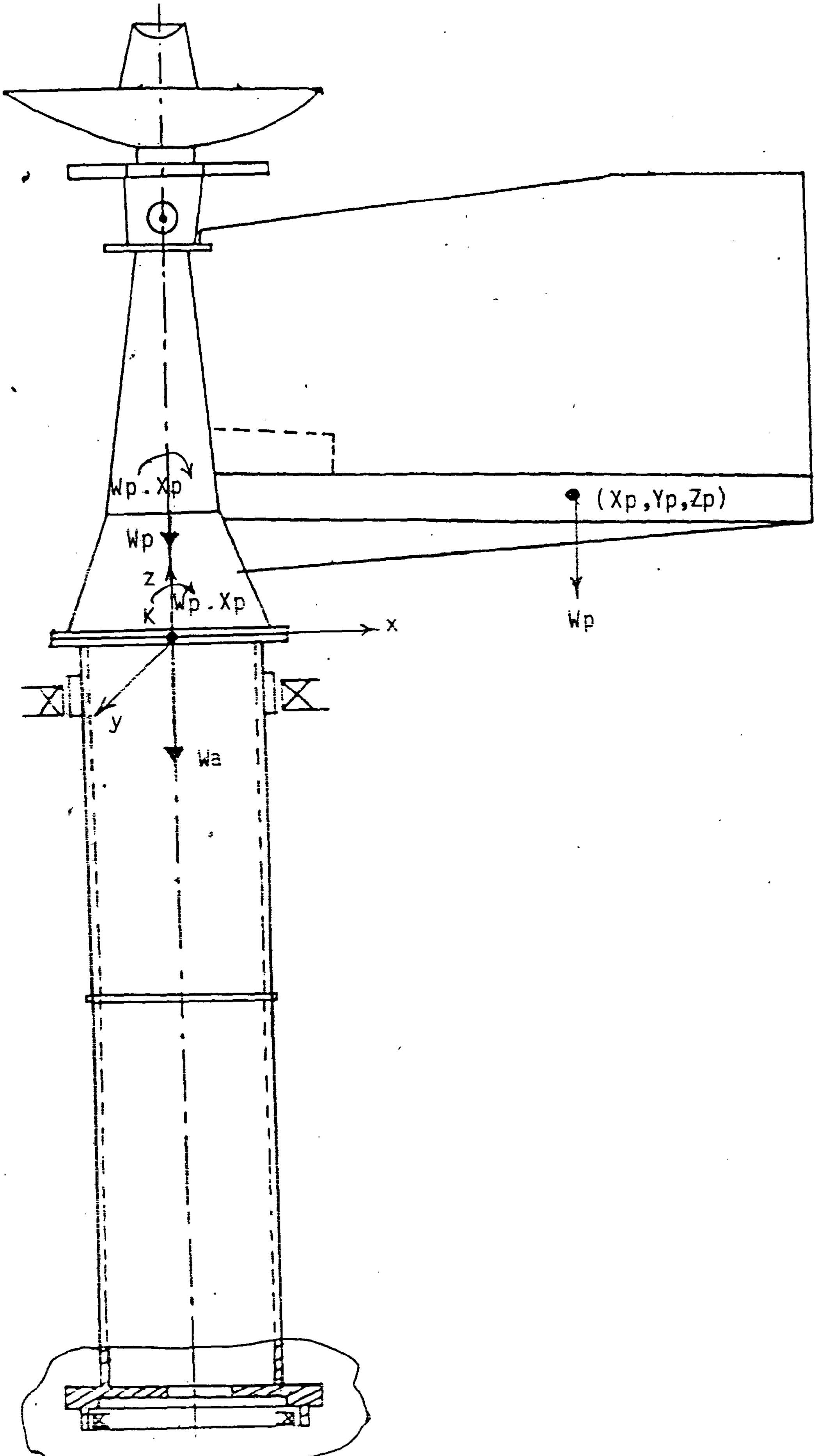


FIG. 6.2 : GRAVITATIONAL LOADS

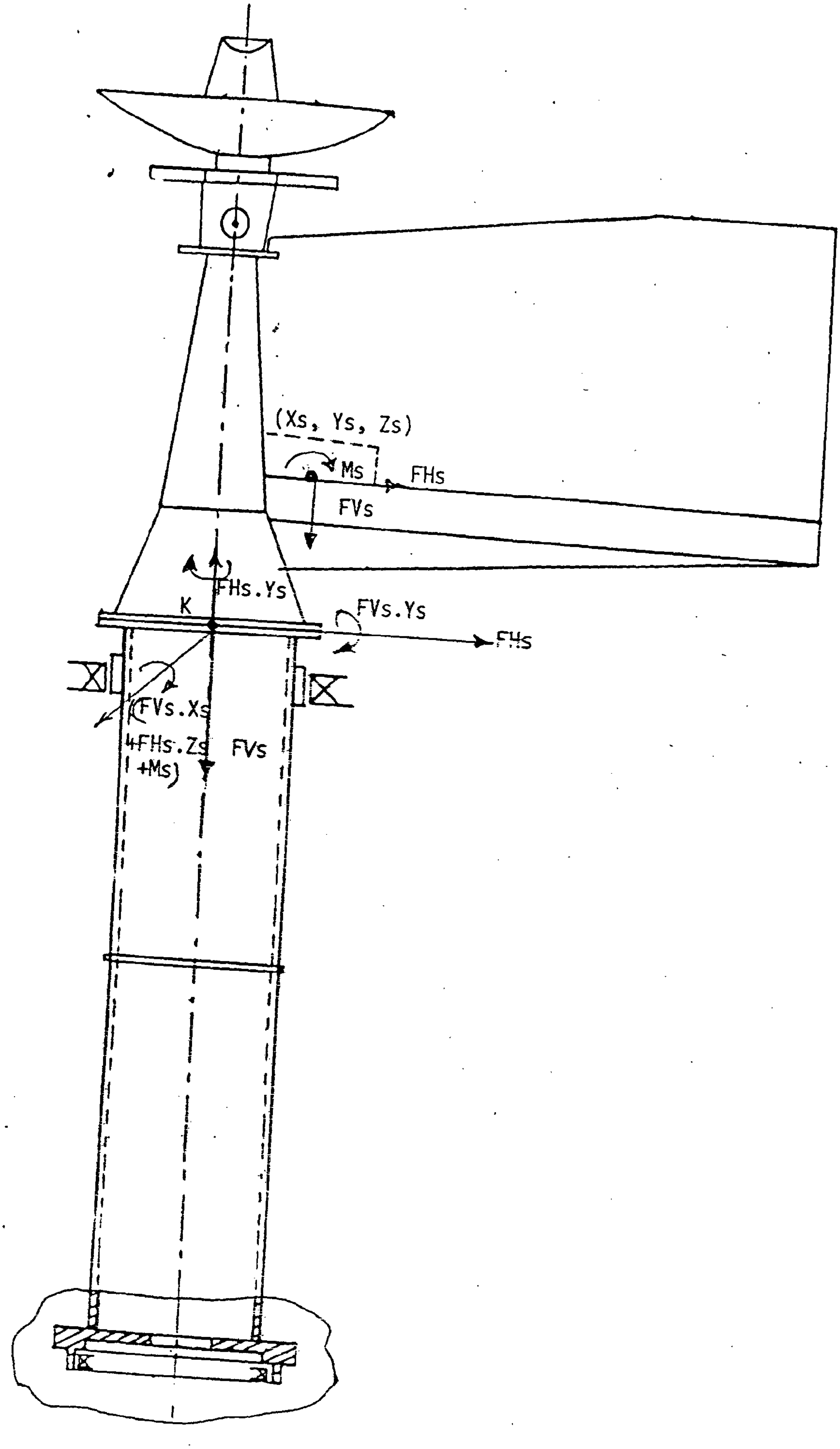


FIG. 6.3 : STOWLOCK REACTIONS

FD_r and moment $FD_r.Zr$ at point 'K' Fig. 6.1. The value of FD_r is calculated from Eq.6.7.

$$FD_r = Ar.Cdr.Pr \quad .. \quad (6.7)$$

Stow Lock Forces

Stow lock mechanism operated at survival wind speed, gives horizontal and vertical forces FH_s and FV_s respectively and moment Ms, at point (Xs, Ys, Zs) Fig. 6.3. These give two forces FH_s and FV_s in x and z directions, a moment ($FH_s.Ys$) about z axis, a moment ($FV_s.Ys$) about X axis and a moment ($FV_s.Xs + FH_sZs$) about y axis, at point 'K' of King Post. Fig. 6.3.

Gravitational Loads

Total weight of antenna parts results in an axial load, Wa in -z direction at point 'K' Fig. 6.2.

Platform Unbalanced Loads

The self weight of platforms (Wp1) and equipment room (Wp2) and live loads (Wp3) causes an unbalance load Wp at point (Xp, Yp, Zp). It gives an axial load Wp and moment Wp.Xp at point 'K' Fig. 6.2.

$$Wp = Wp1 + Wp2 + Wp3 + Wp4 \quad .. \quad (6.8)$$

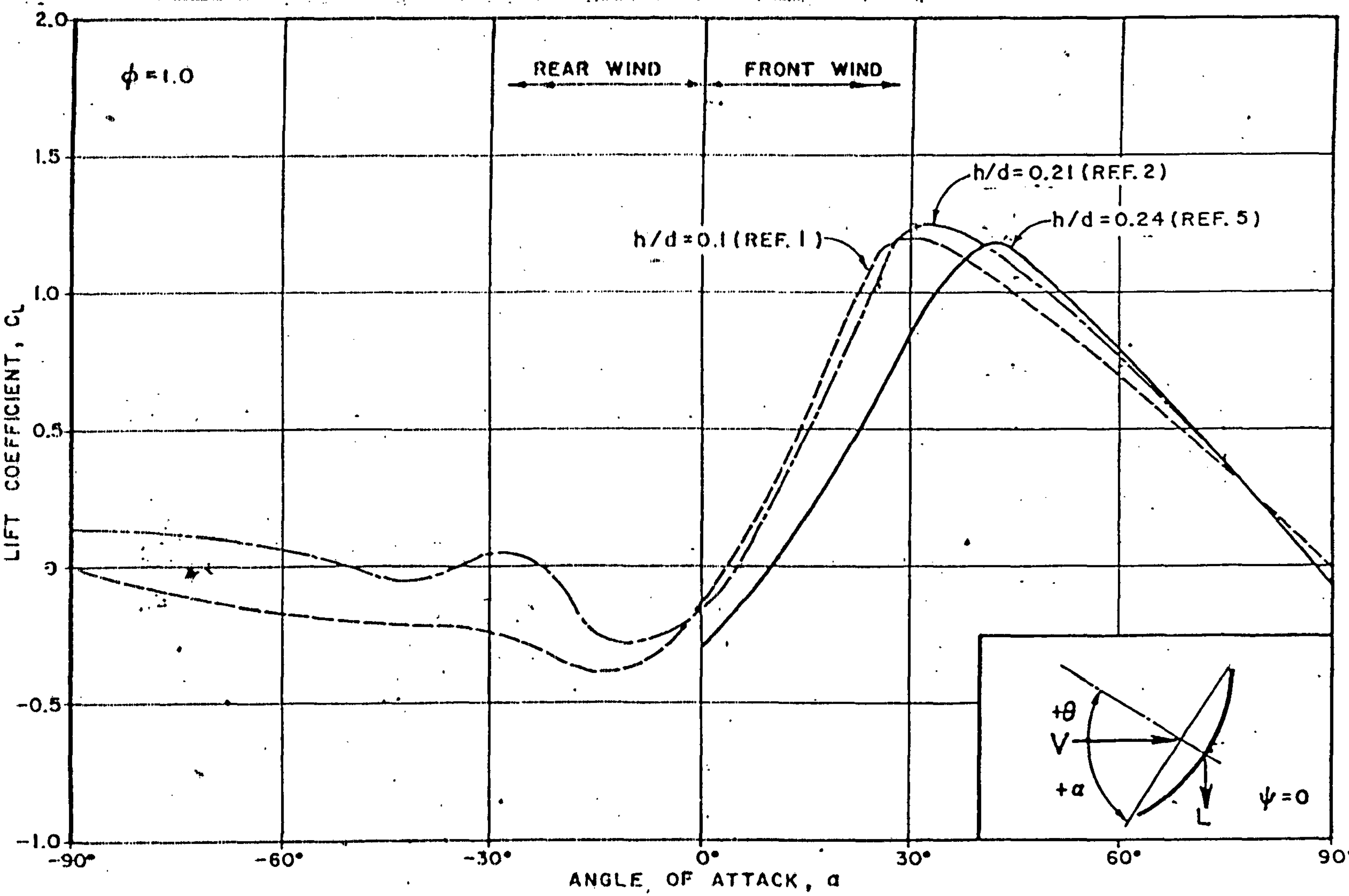


Fig.6.6 Lift coefficients for solid reflectors. [5]

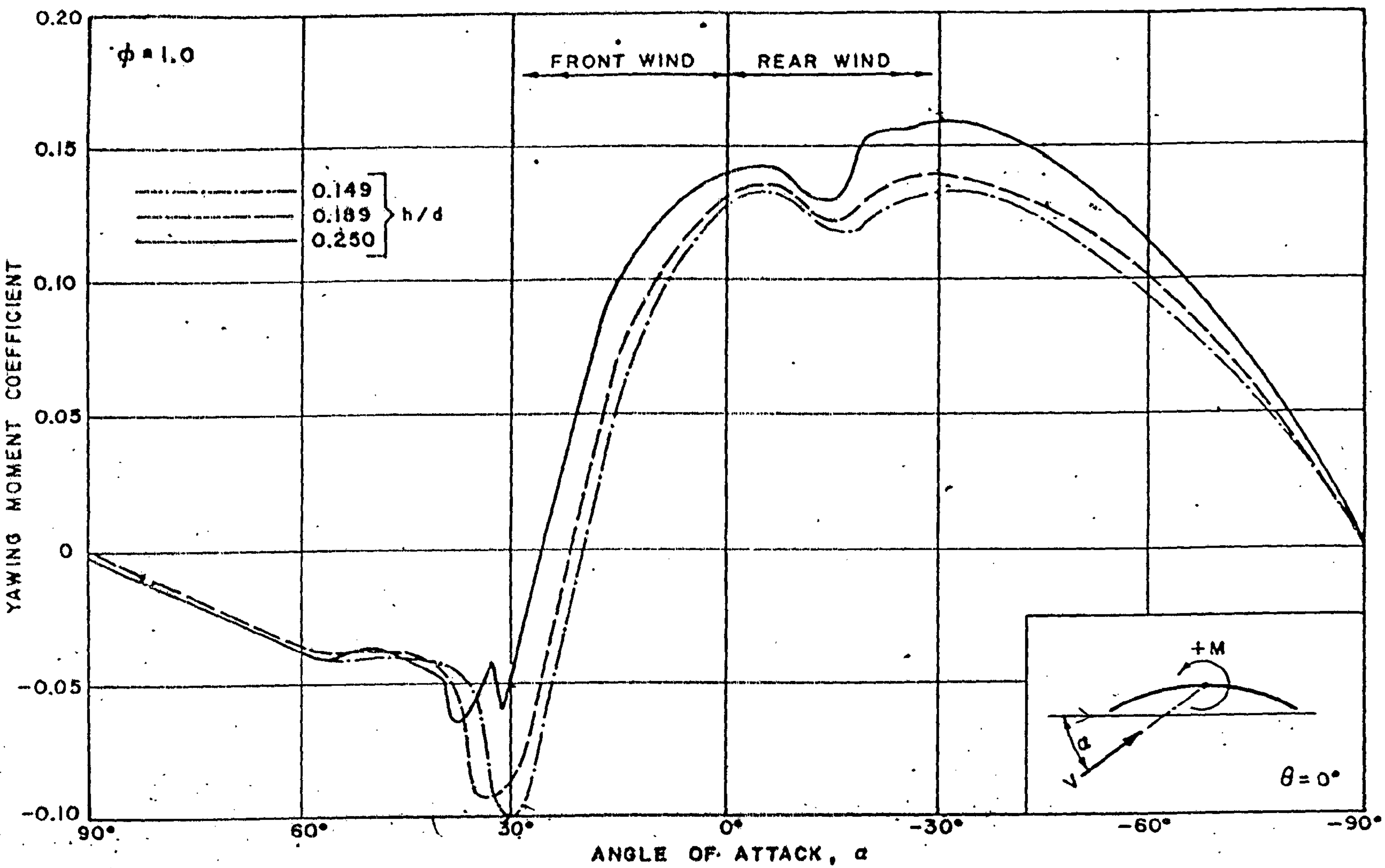


Fig.6.7 Yawing moment coefficients for solid reflectors. [5]

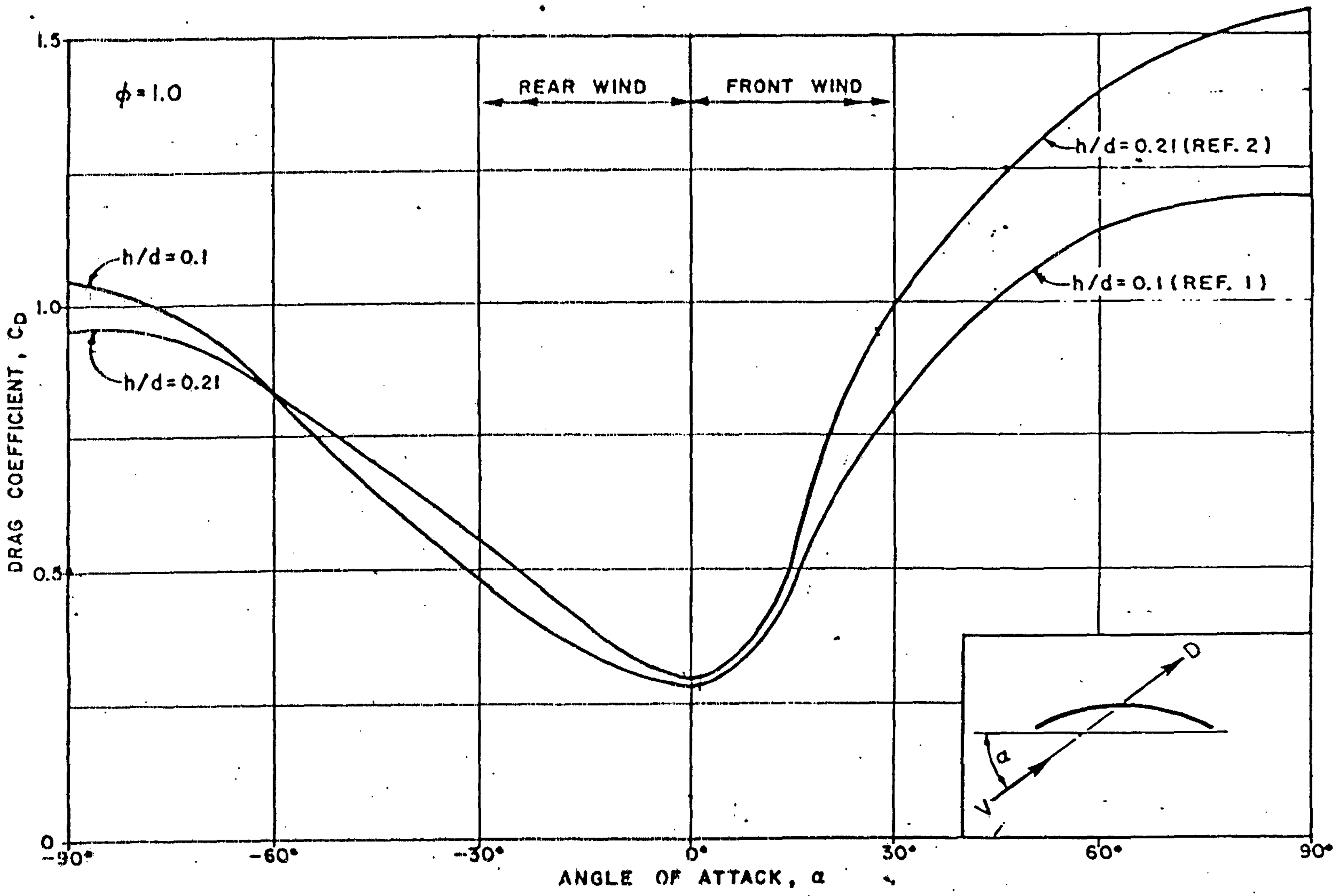


Fig. 6.5 Drag coefficients for solid reflectors. [5]

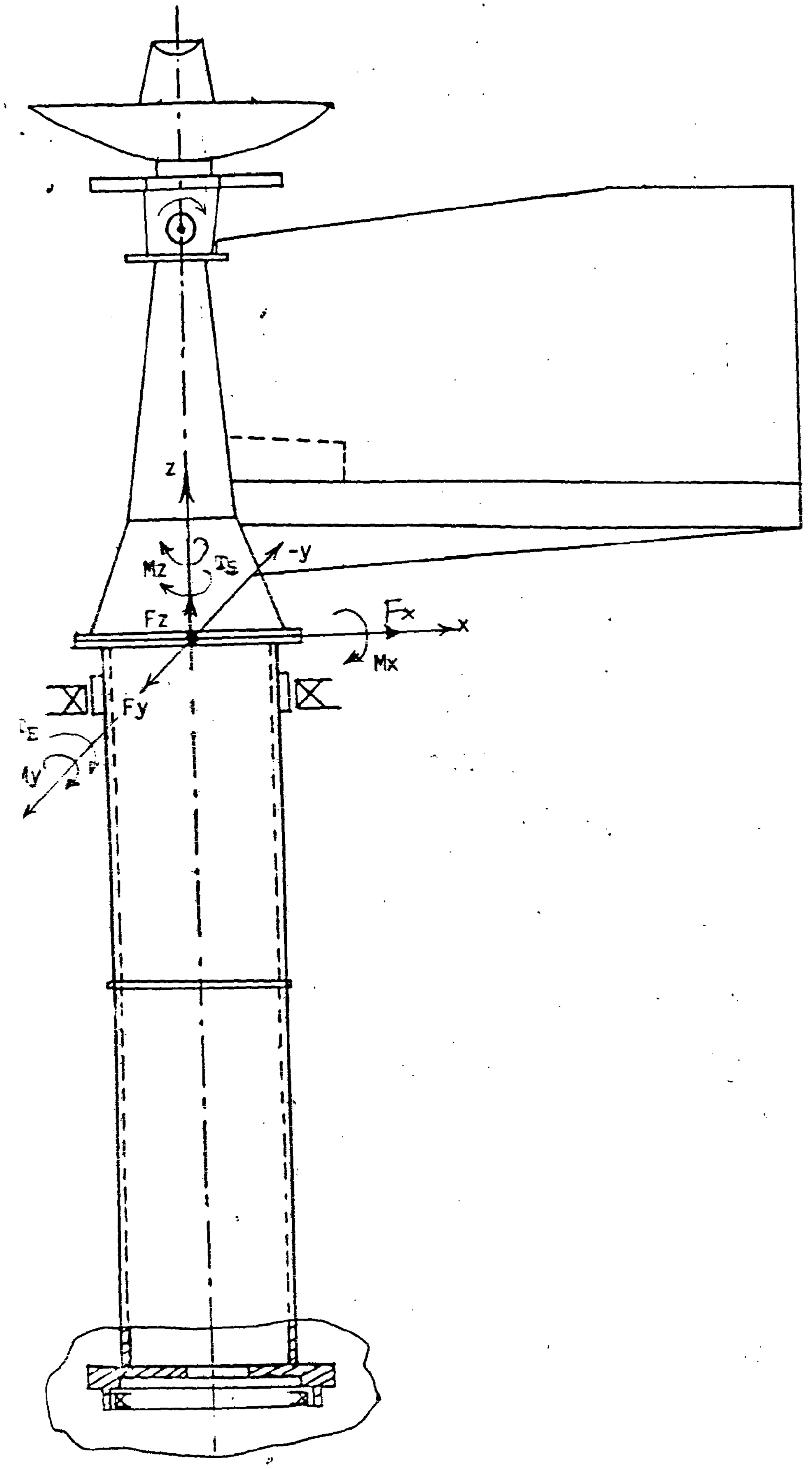


FIG. 6.4 : COMBINED FORCES AND MOMENTS ON KING-POST

Combined Loading

The forces and moments calculated above give three axial forces Fx, Fy, Fz and three moment Mx, My, Mz Fig. 6.4. The moment Mz, acts as torque on the king post. The magnitude of the above forces and moments are calculated from following equations,

$$Fx = FH_s \quad .. \quad (6.9)$$

$$Fy = -FD_r - FD_a \quad .. \quad (6.10)$$

$$Fz = FL_a - FV_s - Wa \quad .. \quad (6.11)$$

$$Mx = FD_r.Zr + FV_s.Ys + Ma \quad .. \quad (6.12)$$

$$My = FD_a.Za + Ms + FV_sXs + FH_s.Zs + Xp.Wp + TE \quad (6.13)$$

$$Mz = FH_s.Ys + FD_r.Xr + TA \quad .. \quad (6.14)$$

Maximum Bending Moment

The king post is subjected to bending moment in xz and yz planes. The value of the total bending moment is calculated at three places using the following equations

Free End (point K)

$$M_{xzk} = My \quad .. \quad (6.15)$$

$$M_{yzk} = Mx \quad .. \quad (6.16)$$

The resultant bending moment at point K is

$$M_k = \sqrt{(M_{xzk})^2 + (M_{yzk})2} \quad .. \quad (6.17)$$

Top Bearing Position (Point 2)

$$M_{xz2} = My + Fx.(L-L_1) \quad .. \quad (6.18)$$

$$M_{yz2} = Mx - Fy\ (L-L_1) \quad .. \quad (6.19)$$

The resultant bending moment at top bearing position is

$$M_2 = \sqrt{(M_{xz2})^2 + (M_{yz2})^2} \quad .. \quad (6.20)$$

Bottom Bearing Position (Point 1)

$$M_{xz1} = my + Fx.L - R_{2x}.L_1 \quad .. \quad (6.21)$$

$$M_{yz1} = Mx - Fy.L - R_{2y}.L_1 \quad .. \quad (6.22)$$

The resultant bending moment is

$$M_1 = \sqrt{(M_{xz1})^2 + (m_{yz1})^2} \quad .. \quad (6.23)$$

Maximum bending moment in the king post M_{max}, comes out at point 2. See the computer programme and the results. So,

$$M_{max} = M_2 \quad .. \quad (6.24)$$

Bearing Reactions

The reactions in x-z plane at the two bearings are:

$$R_{1x} = \frac{My + Fx.L_2}{L_1} \quad .. \quad (6.25)$$

$$R_{2x} = \frac{My + Fx.L}{L_1} \quad .. \quad (6.26)$$

The reactions in y-z plane, at the two bearings are :

$$R_{1y} = \left(\frac{Mx + Fy.L_2}{4} \right)$$

$$R_{2y} = \left(\frac{Mx + Fy.L}{4} \right) \quad .. \quad (6.27)$$

Material

The king post or Azimuth tube is made out of 36 mm thick Mild Steel plate (IS-2062) by rolling and welding. The yield strength and Young Modulus values are,

$$S_y = 24 \text{ kg/mm}^2 = 24{,}000 \text{ T/m}^2$$

$$E = 2x10^7 \text{ T/m}^2$$

King post diameter

The tube is under combined loading, i.e. axial, bending and torsion. The outer diameter, do, of the tube can be found by using following equation [13,25,18]

$$\left(\frac{\pi S_{smax}}{16}\right) do^6 (1 + K^8 - 2K^8) - (Fz/8)^2 \alpha^2 .do^2 (1+K^4+2K^4)$$

$$- \left(\frac{2M_{max}K_bF_z}{8} \right) .\alpha do(1+K^2) - (M_{max}Kb^2+Mz^2.Kt^2) = 0$$

$$.. \quad (6.28)$$

As per the distortion energy theory [12,26]

$$S_{smax} = \frac{0.577 S_y}{N} \quad .. \quad (6.28)$$

The factor of safety is considered as 2.5. The value of do is found by iterative technique assuming α as 1.0 initially. The value of α is calculated by the following relations,

$$\rho_g = \sqrt{I/A} = \sqrt{\left[\frac{(do^4 - di^4).\pi.4}{(do^2 - di^2).\pi.64}\right]} \quad .. \quad (6.29)$$

$$\alpha = \frac{1}{1 - 0.0044.\frac{L}{\rho_g}} \quad .. \quad (6.30)$$

Using this value of α , again do is calculated. The cycle goes on till we get, the constant values of α and do .

Deflection

The king post design is important from deflection point of view at operational wind speeds. The axis of the reflector, mounted on the king post should not deflect from the desirable position by more than 0.02° in order to correctly track the satellite. The deflection at the free end of the king post and at reflector tip is calculated by using castiglano's theorem [24].

Deflection at free end, point K, is given by,

$$\delta_k = \frac{1}{E} \int \frac{M}{Ii} \frac{dMi}{dQ} dx = \frac{1}{E} \sum_{i=1}^{16} \int_{x_{i-1}}^{x_i} \frac{Mi}{Ii} \frac{dMi}{dQ} dx \quad .. \quad (6.31)$$

where Q is a fictitions load at point K and is equal to zero.

$$M_{i=1,4} = My + Qx \quad .. \quad (6.32)$$

$$Mi = 5,\ 15 = (My + R_{2x}.0.430) \frac{x^2}{2} - R_{2x} \frac{x^3}{3} + Q\frac{x^3}{3} \quad .. \quad (6.33)$$

$$M_{i=16,} = My + Q.x - R_{2x} (X-0.430) + R_{1x}(X-6.115) \quad (6.34)$$

$$\delta_{i=1,4} = \frac{My}{E} \frac{1}{Ii} (X_i^2 - X_{i-1}^2) \quad .. \quad (6.35)$$

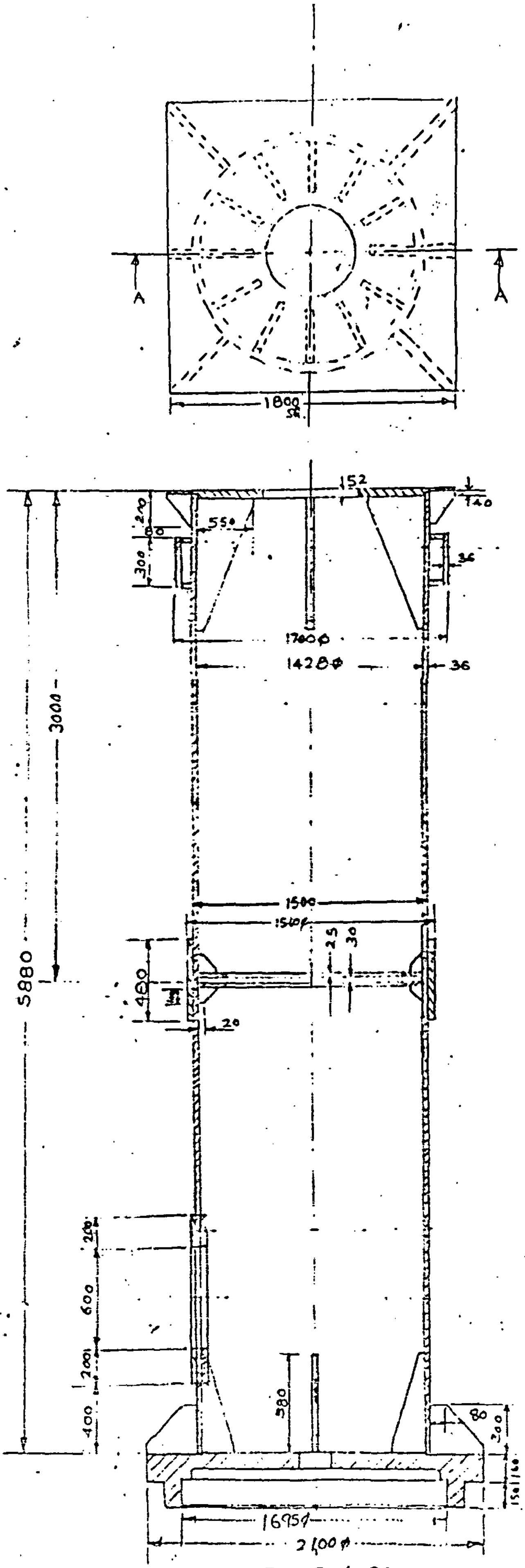
$$\delta_{i=5,16} = 0.5 \frac{1}{EIi} (My+0.435\ R_{2x})(X_i^2 - X_{i-1}^2) \quad (6.36)$$

$$\delta_{i=16} = 0.5 \frac{1}{EIi} (My+R_{2x}.0.435-R_{1x}.6.115)(X_i^2 - X_{i-1}^2)$$

$$+ \frac{1}{3EIi} (R_{1x}-R_{2x})(X_i^3 - X_{i-1}^3) \quad .. \quad (6.37)$$

$$\delta_k = \sum_{i=1}^{16} \delta_i \quad .. \quad (6.38)$$

Angle of deflection, $\theta = \frac{180}{\pi} .\tan^{-1}\left(\frac{\delta k}{0.435} \right)$ degree (6.39)



SCALE 1:20

FIG. 6.8 14 Mφ MCF ANTENNA KING-POST

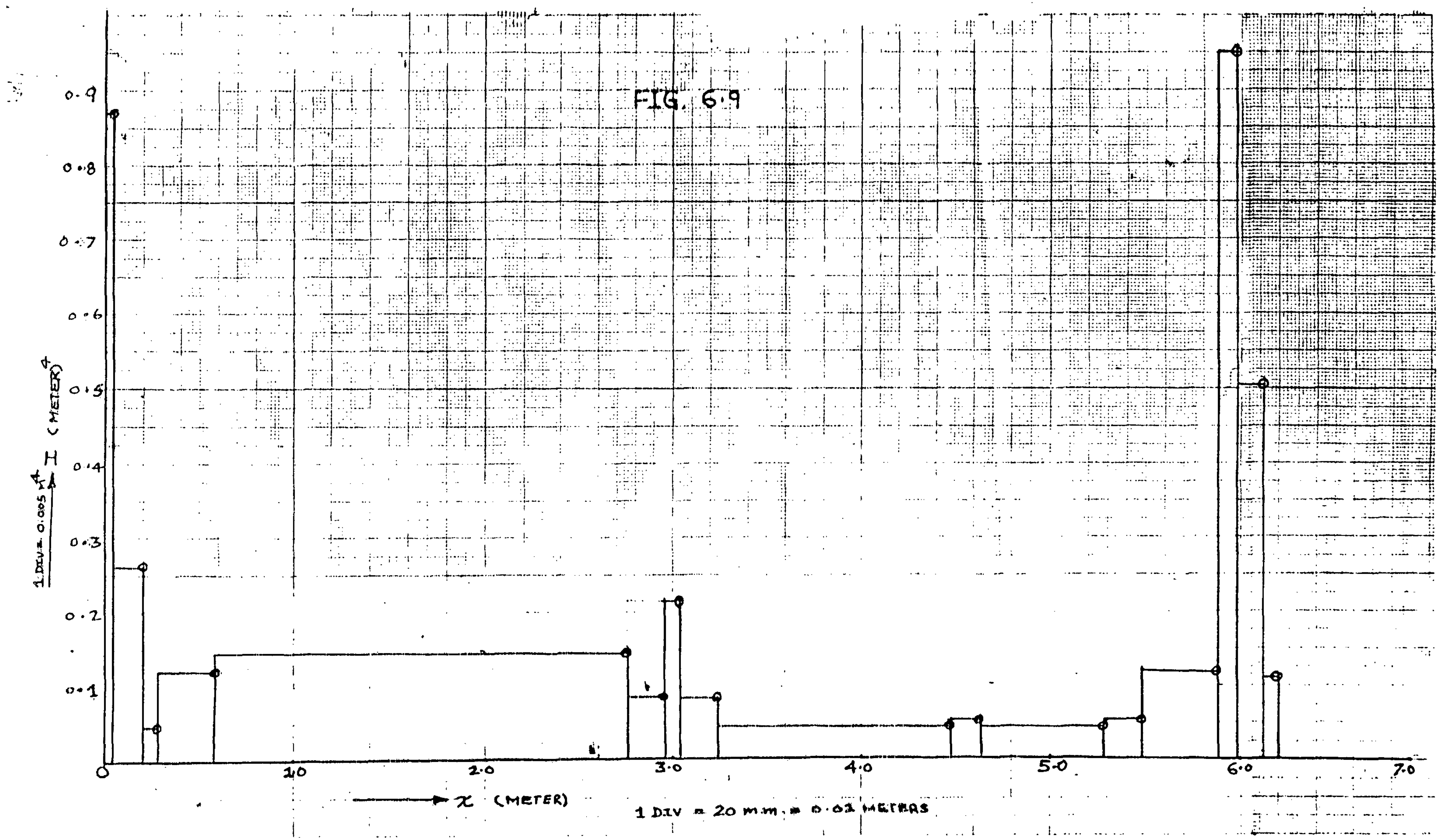


Fig.6.9 Moment of Inertia vs length

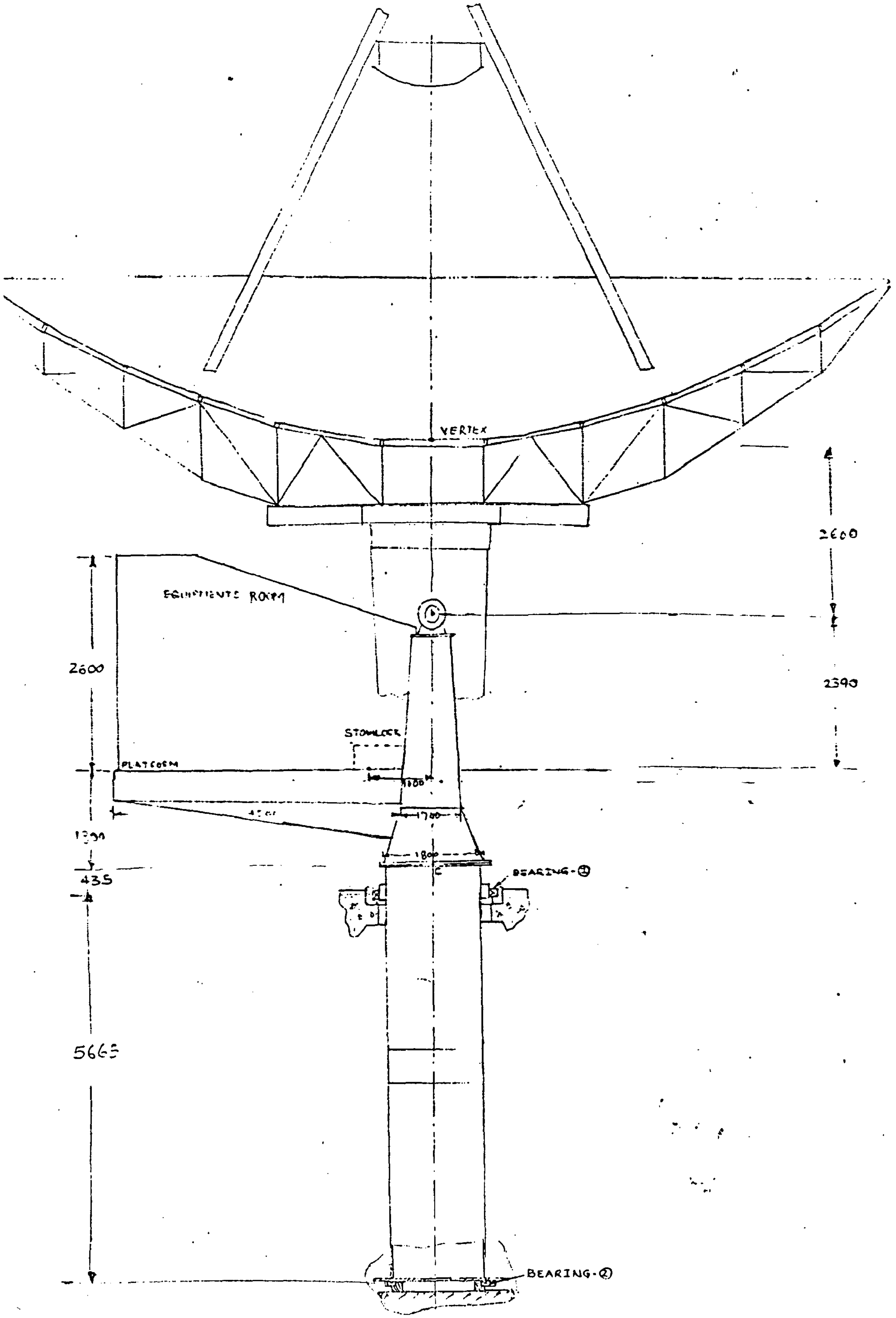


FIG. 6·10 KING-POST ASSEMBLY SCALE 1:50.

The deflection and slope at the free end point K is dependent upon the moment of inertia of the king post which varies along the length of the azimuth tube. The variation of the moment of inertia along the length is shown in Fig. 6.9 and the same has been considered for the calculation of slope and deflection.

6.2 DESIGN OF KING POST BY STATISTICAL APPROACH

The statistics of the design random variables, responsible for finding out the size of king post have already been estimated in chapter 5.0 and are summarized in Table 7.1. On the basis of these variables statistics and Eqs. 5.1 and 5.2 for the mean and standard deviation values the loads and moments, coming on the king post are calculated as follows.

Wind Loads and Moments

The mean and standard deviation (s.d.) values of dynamic pressure (from Eq. 6.1) is

$$\mu Pr = \frac{1}{2} . \mu \sigma . \mu V^2 \quad .. \quad (6.38)$$

$$\sigma Pr = \sqrt{(\mu \sigma 2 \mu V)^2 . \sigma V^2 + (\mu V^2)^2 . \sigma \rho^2} \quad (6.39)$$

Mean and s.d. values of wind drag force and lift force on antenna (from Eqs. 6.2, 6.3) are given as

$$\mu FD_a \quad \frac{\pi}{4} . \mu Dm^2 . \mu Cd . \mu Pr \quad .. \quad (6.40)$$

$$\sigma FD_a = \pi/4 \sqrt{(2 . \mu Dm . Cd . \mu Pr)^2 . \sigma Dm^2 + (\mu Dm^2 . \mu Cd)^2 . \sigma Pr^2 + (\mu Dm^2 . \mu Pr)^2 . \sigma Cd^2} \quad .. \quad (6.41)$$

$$\mu FL_a = \sqrt{4.\mu Dm^2.\mu Cl.\mu Pr} \quad .. \quad (6.42)$$

$$\sigma FL_a = \pi/4.\sqrt{\left[(2\mu Dm.\mu Cl.\mu Pr)^2.\sigma Dm^2 + (\mu Dm^2.\mu Cl)^2.\sigma Pr^2 + (\mu Dm^2.\mu Pr)^2.\sigma Cl^2\right]} \quad .. \quad (6.43)$$

Mean and S.d. values of yaw moment on main and subreflector (using Eqs. 6.4, 6.5) are

$$\mu Mm = \pi/4.\mu Dm^3.\mu Cmm.\mu Pr \quad .. \quad (6.44)$$

$$\sigma Mm = \pi/4\sqrt{\left[(3.\mu Dm^2.\mu Cmm.\mu Pr)^2.\sigma Dm^2 + (\mu Dm^3.\mu Cmm)^2.\sigma Pr^2 + (\mu Dm^3.\mu Pr)^2.\sigma Cmm^2\right]} \quad .. \quad (6.45)$$

$$\mu M_{sl} = \sqrt{4.\mu Ds^2.\mu Cms.\mu Pr.\mu b.Cos(\mu \beta)} \quad .. \quad (6.46)$$

where,

$$\mu b = \mu Z_{al} - \mu Z_a, \quad \sigma_b = \sqrt{(\sigma Za)^2 + (\sigma Zal)^2} \quad (6.47)$$

$$\sigma M_{sl} = \pi/4.\sqrt{\left[(2.\mu Ds.\mu Cms.\mu Pr.Cos^2(\mu\beta)^2.\sigma Ds^2 + (\mu Ds^2.\mu Pr.\mu b.\mu Cos\beta)^2\sigma Cms^2 + (\mu Ds^2.\mu Cms.\mu b.\mu Cos(\mu\beta)^2.\sigma Pr^2 + (\mu Ds^2.\mu Cms.\mu Pr.Cos\mu\beta)^2.\sigma b^2 + (\mu Ds^2.\mu Cms.\mu Pr.\mu b)^2.(\sigma \cos \sigma \beta)^2\right]} \quad (6.48)$$

Total yaw moment Ma on vertex, because of the two reflectors, (using Eqs.6.6) is given by

$$\mu Ma = \mu Mm + \mu M_{s1} \quad .. \quad (6.49)$$

$$\sigma Ma = \sqrt{\sigma Mm^2 + \sigma M_{s1}^2} \quad .. \quad (6.50)$$

Mean and s.d. values of wind drag force on equipment room wall (using Eq. 6.7)

$$\mu FDr = \mu Ar.\mu Cdr.\mu Pr \quad .. \quad (\ .51)$$

$$\sigma FDr = \sqrt{[(\mu Cdr.\mu Pr)^2.\sigma Ar^2 + (\mu Ar.\mu Pr)^2.\sigma Cdr^2 + (\mu Ar.\mu Cdr)^2.\sigma Pr^2]} \quad .. \quad (6.52)$$

Mean and s.d. values of axial forces in x,y and z direction (from Eqs. 6.9, 6.10, 6.11) are

$$\mu Fz = \mu FL_a - \mu FV_s - \mu Wa \quad .. \quad (6.53)$$

$$\sigma Fz = \sqrt{(\sigma FLa^2)^2 + \sigma FV_s^2 + \sigma Wa^2} \quad .. \quad (6.54)$$

$$\mu Fx = \mu FH_s \quad .. \quad (6.55)$$

$$\sigma Fx = \sigma FH_s \quad .. \quad (6.56)$$

$$\mu Fy = -\mu FDr - \mu FDa \quad .. \quad (6.57)$$

$$\sigma Fy = \sqrt{\sigma FDr^2 + \sigma FDa^2} \quad .. \quad (6.58)$$

The mean and s.d. values of total moments coming on king post, around x,y,z axis (using Eqs. 6.12, 6.13, 6.14) are,

$$\mu Mx = \mu FDr.\mu Zr + \mu FVs.\mu FYs + \mu Ma \quad .. \quad (6.59)$$

$$\sigma Mx = \sqrt{\left[\mu FDr^2.\sigma Zr^2 + \mu Zr^2.\sigma FDr^2 + \mu FVs^2.\sigma Ys^2 + \mu Ys^2.\sigma FVs^2 + \sigma Ma^2\right]} \quad .. \quad (6.60)$$

$$\mu My = \mu FDa.\mu Za + \mu Ms + \mu FVs.\mu Xs + \mu FHs.\mu Zs + \mu Wp.\mu Xp + \mu TE \quad . \quad (6.61)$$

$$\sigma My = \sqrt{\left[(\mu FDa^2.\sigma Za^2+\mu Za^2.\sigma FDa^2 + \sigma Ms^2 + \mu FVs^2.\sigma Xs^2 + \mu Xs^2.\sigma FVs^2 + \mu FHs^2.\sigma Zs^2 + \mu Zs^2.\sigma FHs^2 + \mu Wp^2.\sigma Xp^2 + \mu Xp^2.\sigma Wp^2)\right]} \quad .. \quad (6.62)$$

$$\mu Mz = \mu FHs.\mu Ys + \mu FDr.\mu Xr + \mu TA \quad .. \quad (6.63)$$

$$\sigma Mz = \sqrt{\left[\mu FHs^2.\sigma Ys^2 + \mu Ys^2.\sigma FHs^2 + \mu FDr^2.\sigma Xr^2 + \mu Xr^2.\sigma FDr^2\right]} \quad .. \quad (6.64)$$

The mean and s.d. values of the moments coming at the free end of king post (point K) Fig. 6.4 in Xz and Yz planes, and their resultant (using Eqs. 6.15, 6.16, 6.17) are

$$\mu M_{xzk} = \mu My \quad .. \quad (6.65)$$

$$\sigma M_{yzk} = \sigma My \quad .. \quad (6.66)$$

$$\mu M_{yzk} = \mu Mx \quad .. \quad (6.67)$$

$$\sigma M_{yzk} = \sigma Mx \quad .. \quad (6.68)$$

$$\mu Mk = \sqrt{(\mu M_{xzk})^2 + (\mu M_{yzk})^2} \quad .. \quad (6.69)$$

$$\sigma Mk = \sqrt{\left[\frac{\mu Mx^2}{\mu Mx^2 + \mu My^2} . \sigma Mx^2 + \frac{\mu My^2}{\mu Mx^2 + \mu My^2} . \sigma My^2\right]} \quad (6.70)$$

The mean and s.d. values of the moments coming at the top bearing position (point 2) of king post. Fig.6.10 in xz and yz planes and their resultant (using Eqs. 6.18, 6.19 and 6.20), are

$$\mu M_{yz2} = \mu Mx - \mu Fy.\mu L_2 \quad .. \quad (6.71)$$

$$\sigma M_{yz2} = \sqrt{\sigma Mx^2 + (\mu Fy^2.\sigma L_2^2 + \mu L_2^2.\sigma Fy^2} \quad .. \quad (6.72)$$

$$\mu M_{xz2} = \mu My + \mu Fx.\mu L_2 \quad .. \quad (6.73)$$

$$\sigma M_{yz2} = \sqrt{\sigma My^2 + (\mu Fx^2.\sigma L_2^2 + \mu L_2^2.\sigma Fx^2)} \quad (6.74)$$

$$\mu M2 = \sqrt{(\mu M_{xz2})^2 + (\mu M_{yz2})^2} \quad .. \quad (6.75)$$

$$\sigma M2 = \sqrt{\left[\frac{(\mu M_{xz2})^2}{\mu M_{xz2}^2 + \mu M_{yz2}^2}.(\sigma M_{xz2})^2 + \frac{\mu M_{yz2}^2}{\mu M_{xz2}^2 + \mu M_{yz2}^2}.\sigma M_{yz2}^2\right]} \quad .. \quad (6.76)$$

The mean and s.d. values of the moments coming at the bottom bearing position (point 1) of king post, Fig. 6.4 in xz and yz planes and their resultant (using Eqs. 6.21,6.22, 6.23) are

$$\mu M_{xz1} = \mu My + \mu Fx.\mu L - \mu R_{2x}.\mu L_1 \quad .. \quad (6.77)$$

$$\sigma M_{xz1} = \sqrt{(\sigma My^2 + \mu Fx^2.\sigma L^2 + \mu L^2.\sigma Fx^2 + (\mu R_{2x})^2.\sigma L_1^2 + \mu L_1^2.\sigma R_{2x}^2)} \quad .. \quad (6.78)$$

$$\mu M_{xz2} = \mu Mx + \mu Fy.\mu L - \mu R_{2y}.\mu L_1 \quad .. \quad (6.79)$$

$$\sigma M_{yz1} = \sqrt{(\sigma Mx^2 + \mu Fy^2.\sigma L^2 + \mu L^2.\sigma Fy^2 + \mu R_{2y}^2.\sigma L_1^2 + \mu L_1^2.\sigma R_{2y}^2)} \quad .. \quad (6.80)$$

$$\mu M_1 = \sqrt{(\mu M_{xz1})^2 + (\mu M_{yz1})^2} \quad .. \quad (6.81)$$

$$\sigma M_1 = \sqrt{\left[\frac{\mu M_{xz1}^2}{(\mu M_{xz1}^2 + \mu M_{yz1}^2)}.\sigma M_{xz1}^2 + \frac{\mu M_{yz1}^2}{(\mu M_{xz1}^2 + \mu M_{yz1}^2)}.\sigma M_{yz1}^2\right]} \quad .. \quad (6.82)$$

All the above values have been calculated with the help of a FORTRAN programme. It was found that the maximum bending moment (M_{max}) comes at top bearing position. It becomes the most critical section. Therefore,

$$\mu M_{max} = \mu M_2$$

$$\sigma M_{max} = \sigma M_2$$

King Post Diameter

The maximum shear stress in the king post because of combined loading (axial, bending and torsion) is given by following equation.

$$\mu Ss = \frac{16}{\mu do^3(1-K^4)} \sqrt{\left[(\mu M_{max}.\mu Kb) + \frac{\mu\alpha.\mu Fz.\mu do.(1+K^2)}{8}\right. \left. + (\mu Mz.\mu Kt)^2\right]} \quad .. \quad (6.83)$$

Theoretically the factors, K, α , Kt and Kb are random variables, but it is assumed these factors as constants to simplify the standard deviation expression of the maximum shear stress. The general form of the above Equation is,

$$Ss = \frac{16}{\pi.do^3(1-K^4)} \sqrt{\left[(M_{max}.Kb) + \frac{\alpha.Fz.do(1+K^2)}{8}\right. \left. + (Mz.Kt)^2\right]} \quad .. \quad (6.83)$$

or

$$Ss = \sqrt{A + B + C + D}$$

where,

$$A = P.\frac{M_{max}^2 . Kb^2}{do^6} \qquad B = \frac{P.\alpha^2.Fz^2.do^2(1+K^2)^2}{64.do^6}$$

$$C = \frac{P.2M_{max}.kb.\alpha.Fz.do(1+K^2)}{do^6 x8}$$

$$D = \frac{P.Mz^2.Kt^2}{do^6} \qquad P = \frac{256}{\pi^2(1-K^4)^2}$$

The mean and s.d. values (using Eqs. 5.1 and 5.2) are given by

$$\mu Ss = \sqrt{\mu A + \mu B * \mu D} \quad .. \quad (6.84)$$

$$\sigma Ss = \frac{\sqrt{\sigma A^2 + \sigma B^2 + \sigma C^2 + \sigma D^2}}{2.\sqrt{\mu A + \mu B + \mu C + \mu D}} \quad .. \quad (6.85) \quad .. \quad (6.86)$$

where,

$$\sigma A = \sqrt{\left[\left(\frac{6.\sigma do.4.\mu M_{max}^2}{\mu do^7}\right)^2 + \left(\frac{2\mu M_{max}.\sigma M_{max}}{\mu do^6}\right)^2\right]}$$

$$.. \quad (6.87)$$

$$\sigma B = 50.8\sqrt{\left[\left(\frac{2.\mu Fz.\sigma Fz}{\mu do^4}\right)2 + \left(\frac{\mu Fz^2.4.\sigma do^2}{\mu do^5}\right)2\right]}$$

$$.. \quad (6.88)$$

$$\sigma_C = 813.702\sqrt{[(\frac{\mu Mz.o\ M}{\mu do^5})^2 + (\frac{\mu Mmax.\mu do.o\ Fz}{\mu do^5})^2 + (\frac{5.\mu Mmax.\mu Fz.o\ do}{do^6})^2]} \quad .. \quad (6.89)$$

$$\sigma_D = 3252.174\sqrt{[(\frac{2.\mu Mz.o\ Mz}{\mu do^6})^2 \sigma Mz^2 + (\frac{\mu Mz^2.\ \sigma\ do.6}{do^7})^2]} \quad .. \quad (6.90)$$

Coupling Equation [12]

The following equation relates the statistics of material strength, stresses and the Reliability of the system and finds out the unknown dimension do (outer diameter of the king post). This equation is known as COUPLING EQUATION,

$$-\frac{\mu S_{smax} - \mu_{ss}}{\sqrt{\sigma Ss^2 + \sigma ss^2}} = +t \quad .. \quad (6.91)$$

The value of parameter z is found on the basis of system's reliability R using following equation or tables given in Appendix-1 [12]

$$R = \frac{1}{\sigma z.\sqrt{2\pi}} \int_0^{\infty} Exp\ [-\frac{(z-\mu z)^2.dz}{2\ \sigma\ z^2}] \quad .. \quad (6.92)$$

The above equation, using normal area tables [12] can be written as follows,

$$R = \frac{1}{\sqrt{2\pi}} \int_{-\frac{\mu z}{\sigma z}}^{\infty} e^{-t^2/2} . dt \qquad .. \qquad (6.93)$$

where,

R is the component reliability and $t = -\frac{\mu S - \mu s}{\sqrt{\sigma S^2 + \sigma s^2}}$

Reliability

$$R = 1 - P_f \qquad .. \qquad (6.94)$$

The antenna systems are very important and critical from operation point of view and hence needs a high component and system reliability. In the absence of analysis it is difficult to specify suitable value of reliability for king post as it forms one component of the total system. For a test case the king post reliability R is taken as 0.99999

$$P_f = 1/1,00,000 = 0.00001$$

The appendix-1 [12] gives value of 't' nearest to the reliability figure as -4.27, which in turn shows R = 0.99990226.

Now as per coupling equation,

$$\frac{\mu Ss - \mu s}{\sqrt{\sigma Ss^2 + \sigma ss^2}} = 4.27 \qquad .. \qquad (6.95)$$

Deflection of king post

The mean and s.d. values of the deflection (using Eqs. 5.1, 5.2, 6.35, 6.36, 6.37, 6.38) are given by,

$$\mu D = \sum_{i=1,16} \mu Di \quad .. \quad (6.96)$$

$$\sigma D = \sqrt{\sum_{i=1,16} \sigma Di^2} \quad .. \quad (6.97)$$

where,

$$\mu Di_{i=1} = \frac{0.5\ \mu\ My}{E.\mu.Ii} \quad .. \quad (6.98)$$

$$\sigma Di_{i=1} = \frac{0.5}{E}\sqrt{\left[\left(\frac{\mu Xi^2.\sigma My}{\mu Ii}\right)^2 + \left(\frac{\mu Mmax.\mu Xi^2}{\mu Ii}\right)^2 \sigma Ii^2 + \left(\frac{2\mu X1.\ \mu Mmax}{\mu Ii}\right)^2.\sigma Xi^2\right]} \quad .. \quad (6.99)$$

$$\mu Di_{i=2,4} = \frac{\mu MY\ (\mu X_i^2 - \mu X_{i-1}^2)}{2.E.\mu Ii} \quad .. \quad (6.100)$$

$$\sigma Di_{i=2,4} = \frac{1}{2E}\sqrt{\left[\left(\frac{\mu MY(\mu Xi^2 - \mu X_{i-1}^2)}{Ii^2}\right)^2.\sigma Ii^2 + \left(\frac{\mu Xi^2 - \mu X_{i-1}^2}{Ii}\right)^2.\sigma My^2 + \left(\frac{\mu My.2.\mu Xi}{Ii}\right)^2(\sigma Xi)^2 + \left(\frac{\mu My.2.\mu X_{i-1}}{\mu Ii}\right)^2\right]} \quad .. \quad (6.101)$$

$$\underset{i=5,15}{\mu Di} = \frac{1}{2E\mu Ii}(\mu My+0.435.\mu R_{2x})(\mu Xi^2-\mu X_{i-1}^2)$$

$$- \frac{1}{3.E.\mu Ii}(\mu R_{2x})(\mu X_i^3 - \mu X^3_{i-1}) \quad .. \quad (6.102)$$

$$\underset{i=5,15}{\sigma Di} = \sqrt{\Big[\Big(\frac{1}{2.E.\mu Ii}(\mu My+.435.\mu R_{2x})(\mu Xi^2-\mu X_{i-1}^2)\Big)^2.\sigma Ii^2}$$

$$+ \Big(\frac{(\mu Xi^2 - \mu X^2{}_{i-1})}{2.E.\mu Ii}\Big)^2.\sigma M^2_{max}$$

$$+ \Big(\frac{.435.(\mu Xi^2 - \mu X_{i-1}^2)}{2.E.\mu.Ii} - \frac{(Xi^3 - X_{i-1}^3)}{3.E.\mu Ii}\Big)^2.\sigma R_{2x}^2$$

$$+ \Big(\frac{\mu Xi(\mu My+.435.\mu R_{2x})}{2.E.\mu Ii} - \frac{\mu Xi^3.\mu R_{2x}}{E.\mu Ii}\Big)^2(\sigma Xi)^2$$

$$+ \Big(-\frac{\mu X_{i-1}(\mu My+.435.\mu R_{2x}}{E.\mu.Ii} + \frac{\mu X_{i-1}^2.\mu R_{2y}}{E.\mu.Ii}\Big)^2.\sigma X_{i-1}^2\Big]$$

$$.. \quad (6.103)$$

$$\underset{i=16}{\mu Di} = \frac{1}{2.E.\mu Ii}(\mu My + \mu R_{2x} \times .435 - \mu R_{1x}.6.115)$$

$$+ (\mu Xi^2-\mu X_{i-1}^2) + (\mu R_{1x}-\mu R_{2x})(\mu Xi^3-\mu X_{i-1}^3)\frac{1}{3.E.\mu Ii}$$

$$.. \quad (6.104)$$

$$SD_{i=16} = \sqrt{\Big[} \left(\frac{1}{\mu.Ii} .\mu Di \right)^2 .\sigma Ii^2 + \left(\frac{\mu Xi^2 - \mu X_{i-1}^2}{2.E.\mu Ii} \right)^2 .\sigma My^2$$

$$+ \left(\frac{.435(\mu Xi^2 - \mu X_{i-1}^2)}{2.E.\mu.Ii} - \frac{(\mu Xi^3 - \mu X_{i-1}^3)}{3.E.\mu.Ii} \right)^2 .\sigma R_{2x}^2$$

$$+ \left(- \frac{6.115(\mu Xi^2 - \mu X_{i-1}^2)}{2.E.\mu.Ii} + \frac{(\mu Xi^3 - \mu X_{i-1}^3)}{3.E.\mu.Ii} \right)^2 .\sigma R_{1x}^2$$

$$+ \left(\frac{\mu Xi}{E.\mu.Ii} (\mu My + \mu R_{2x} \times .435 - \mu R_{1x} \times 6.115) \right.$$

$$+ \frac{\mu Xi^2}{E.\mu.Ii} (\mu R_{1x} - \mu R_{2x})^2 .\sigma Xi^2$$

$$+ \left(- \frac{\mu X_{i-1}}{E.\mu.Ii} (\mu My + \mu R_{2x} \times .435 - \mu R_{1x} \times 6.115) \right.$$

$$- \frac{\mu X_{i-1}^2}{E.\mu.Ii} (\mu R_{1x} - \mu R_{2x})^2 .\sigma X_{i-1}^2 \Big] \quad .. \quad (6.105)$$

CHAPTER - 7

RESULTS AND DISCUSSIONS

Estimate of design wind speed is based on the most severe wind conditions which the antenna structure will encounter during its anticipated life time of 15 years. This involves prediction far into the future, hence the probability considerations based on statistical analysis of previous observations of wind speed are employed.

The risk values of the design wind speed are found out for two different projected life of antenna structure (15 years and 50 year) using a 50 years return period for wind predictions.

In the present problem about 33 design variables (there are random in nature) like Geometrical parameters, loading, strength, stress etc. have been considered and their statistics has been found or estimated. A number of assumptions have been made due to insufficient data.

The diameter of the king post has been found by two approach viz. deterministic and probabilistic. Table 7.1 shows the values of design variables considered in the two approaches.

Table 7.2 shows the results i.e. the values of wind forces, yaw moments, the axial forces and moments acting on the king post, diameter and deflection of king post, etc.

Considering loads and moments at survival wind speed i.e. 200 KMPH and the deflections are calculated at operational wind speed i.e. 60 KMPH, Appendix-1. The diameter do, is found, with the help of a computer programme, (Appendix-2) equal to 1.6036 metres and deflection is found with the help of a computer programme (Appendix-3) as 0.068°, the deflections are also found at 80, 100 and 200 KMPH, and are shown in Table 7.2. These values of deflection found to be with in acceptable limits upto wind speeds of 100 KMPH.

In probabilistic approach the diameter and deflection are found. Considering loads and moments at mean wind speed value i.e. 72.4 KMPH with s.d. as 42.2 KMPH (Appendix-4). The mean diameter μdo found with the help of computer programme (Appendix5) is equal to 1.279 meters and deflection found with the help of computer programme (Appendix-6) is

Check for significant root

The mean value of diameter μdo, is used to recalculate the values of μs, σ s and t. The value of 't' comes out to be 4.4622 This value of t gives the reliability R, value as 0.964948 which shows that the value of μdo is associated with the required reliability.

Table 7.1 DESIGN VARIABLES VALUES

S.No.	Design variables	Deterministic approach: Survival condition (for stresses)	Deterministic approach: Operational condition (for deflection)	Statistical approach: Mean value	Statistical approach: Standard deviation
1.	Dm, Ds (m)	14.0,1.612	14.0,1.612	13.94,1.612	0.02, 0.0007
2.	L, Ll	6.10,5.665	6.10,5.665	6.10,5.665	0.00166
3.	t	0.036	0.036	0.036	0.00166
4.	Za,Zal	5.29,11.29	5.29,11.29	5.29,11.29	0.00166
5.	Ar (m^2)	11.35	11.35	11.35	0.181
6.	Xs,Ys,Zs(m)	1.0,0.7,1.3	1.0,0.7,1.3	1.0,0.7,1.3	0.00166
7.	Xr,Zr,Xp Xp	2.35,2.55, 3.05	2.35,2.55, 3.05	2.35,2.55, 3.05	0.00166
8.	Cmm, Cms, Cd,Cdr, Cl	0.13,0.12 0.3, 1.0, 0.15	0.135,0.12 0.6, 1.0, 0.0	0.135,0.12 0.6, 1.0, 0.0	0.0033
9.	FHs, FVs (T)	47.0,20.0	0.0,0.0	47.0,20.0	1.566,0.666
10.	Ms (T-M)	20.5	0,0	20.5	0.342
11.	ρ (T/M^3)	0.0000097	0.0000097	0.0000097	0.00077
12.	Wa,Wp (T)	140.0,33.85	140.0,33.85	140.0,33.85	4.666,3.825
13.	ß (degree)	0	-35	-35	0.666
14.	E (T/M^2)	20000000.0	20000000.0	20000000.0	23000.0
15.	Kt,Kb	2.0,2.0	2.0,2.0	1.5,1.5	0.166

Table 7.2 RESULTS

S.No.	Parameters & variables		Deterministic approach: Survival condition		Deterministic approach: Operational condition		Statistical approach (Operational & survival): Mean value	Statistical approach (Operational & survival): Standard deviation
1.	V,	KMPH	200	100	80	60	72.4	42.2
2.	Pr	T/M^2	0.144	0.485	0.0310	0.174	0.0254	0.0297
3.	FLa	T	-4.439	0.0	0.0	0.0	-0.582	0.6801
4.	FDa	T	8.95	4.47	2.866	1.61	1.164	1.360
5.	FDr	T	2.201	0.550	0.352	0.198	0.288	0.337
6.	Mm	T-M	54.35	14.11	9.03	5.07	7.03	8.21
7.	Ms	T-M	2.375	0.54	-0.35	-0.197	0.373	0.526
8.	Ma	T-M	56.72	13.50	8.679	4.88	7.404	8.234
9.	Fz	T	-164.47	-140.0	-140.0	-140.0	-160.562	4.762
10.	Fy	T	-11.16	-5.03	-3.219	-1.81	-1.452	1.401
11.	Fx	T	47.0	0.0	0.0	0.0	47.0	1.50
12.	Mx	T-M	76.34	-14.96	9.57	5.387	22.14	8.292
13.	My	T-M	261.195	132.472	122.32	114.83	212.53	13.67
14.	Mz	T-M	38.074	2.67	2.20	1.84	34.960	1.355
15.	R2	T	96.715	23.38	21.59	20.20	88.12	2.974
16.	M_{max}	T-M	293.11	133.578	122.82	114.60	234.085	13.852
17.	do	M	1.6036	-	-	-	1.279	0.00056
18.	θ	deg.	-0.1877	0.0791	0.0731	0.068	0.2236467	0.0157579

Sensitivity of 'R' to Tolerance on 'do'

The value of R is sensitive to the level of geometric variability if bilateral tolerances are used. This sensitivity can be avoided by using unilateral tolerances. Considering the lower limit of diameter, the do becomes

$$do - 0.001689 = 1.2783$$

The value of 't' comes out to be 4.435, which is less than the value of t(=4.415) founded earlier for 'do'. This shows the reliability of system reduces with negative tolerance, hence the negative tolerances or bilateral tolerances in a system should be avoided to get high reliability.

The diameter found by using statistical approach is about 25% less than the diameter found by deterministic approach and is based on high reliability. This reduces the size of the king post, thus resulting in weight reduction of 3.7 tons and significant cost reduction.

The value of the standard deviation in diameter on the basis of experience is given by

$$\sigma_{do} = 0.00044.\mu_{do} = 0.00056276 \text{ m} = 0.56276 \text{ mm}$$

therefore,

$3\sigma do = 1.688$ mm

This value of $3\sigma do$ which is the tolerance limits on the king post diameter was taken as 1.83084 mm in Chapter-5. So the diameter of the king post can be specified as

$$do = 1279.999 \pm 1.688 \text{ mm}$$

$$1280 \pm 1.688 \text{ mm}$$

Sensitivity of reliability 'R' to tolerance on a diameter 'do'.

In the present dissertation, only one component of a large size antenna system was designed and analyzed based on some reliability. The results show the reduction in size and weight of the king post. The design approach can be used for designing other components of the antenna system like Bullgear, pinion, yoke, elevation drive shafts, octagon, reflector etc. This will result into a more reliable and optimized design of the system. The system weight and size will be reduced.

The complete analysis of present 14 meter diameter antennas installed at MCF, HASSAN for INSAT satellite control earth station, can be done by this approach.

Not only the forthcoming antennas system design but the other mechanical systems can also be designed by this approach for getting more reliable design.

More and more statistical data should be collected for various design variables by testing and inspection at manufacturing stage itself. The amount of large data thus collecteed will help in designing the system.

The statistical design approach may be extended in making reliability predictions for the existing antenna systems.

For a better design, reliability analysis of the complete antenna system, its subsystems and components will be necessary. This analysis will help in employing suitable reliability values for individual components.

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APPENDIX – A

```
IND POST LOADING
OPEN(UNIT=1,FILE='C:\ACM7.DAT')
OPEN(UNIT=2,FILE='C:\ACM7.OUT')
READ(1,*)V,BETA,Cd,Cmm,Cms,Cl,FHs,FVs,AMs,TA,TE
READ(1,*)Cdr,Dm,Ds,RHO,Ar,Wp,Wa,Zr
READ(1,*)Xr,Xs,Ys,Zs,Za,Za1,Xp,RL,RL1,RPI
BETA =180.0*BETA/RPI
    DPr=0.5*RHO*V**2
WRITE(2,*)DPr
FDa=RPI*Dm**2*Cd*DPr/4.0
WRITE(2,*)FDa
FLa=RPI*Dm**2*Cl*DPr/4.0
WRITE(2,*)FLa
FDr=Ar*Cdr*DPr
WRITE(2,*)FDr
AMm=Cmm*RPI*Dm**3*DPr/4.0
WRITE(2,*)AMm
AMs1=Cms*RPI*Ds**2*DPr*(Za1-Za)*COS(BETA)/4.0
WRITE(2,*)AMs1
AMa=AMm+AMs1
WRITE(2,*)AMa
Fz=FLa-FVs-Wa
WRITE(2,*)Fz
Fx=FHs
WRITE(2,*)Fx
Fy=FDr-FDa
WRITE(2,*)Fy
AMx=FDr*Zr+FVs*Ys+AMa
WRITE(2,*)AMx
AMy=FDa*Za+AMs+FVs*Xs+FHs*Zs+Wp*Xp+TE
WRITE(2,*)AMy
AMz=FHs*Ys+FDr*Xr+TA
WRITE(2,*)AMz
AMxzk=AMy
WRITE(2,*)AMxzk
AMyzk=AMx
WRITE(2,*)AMyzk
AMk=SQRT(AMyzk**2+AMxzk**2)
WRITE(2,*)AMk
R2x=(AMy+Fx*6.1)/5.665
WRITE(2,*)R2x
R1x=(AMy+Fx*0.435)/5.665
WRITE(2,*)R1x
AMyz2=AMx-Fy*(RL-RL1)
WRITE(2,*)AMyz2
AMxz2=AMy+Fx*(RL-RL1)
WRITE(2,*)AMxz2
AM2=SQRT(AMxz2**2+AMyz2**2)
WRITE(2,*)AM2
AMxz1=AMy+Fx*RL-R2x*RL1
WRITE(2,*)AMxz1
R2y=(AMx+Fy*6.1)/5.665
AMyz1=AMx+(Fy*RL)-R2y*RL1
WRITE(2,*)AMyz1
AM1=SQRT(AMxz1**2+AMyz1**2)
WRITE(2,*)AM1
AMmax=AM2
WRITE(2,*)AMmax
WRITE(2,*)V,AMmax,AMk,AM1,AM2
WRITE(2,*)Fz,AMz,AMy,R1x,R2x
STOP
```

```
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31358
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96899
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[illegible]

APPENDIX - B

```
      KING POST DIAMETER
      OPEN(UNIT=1,FILE='ACM16.DAT')
      OPEN(UNIT=2,FILE='ACM16.OUT')
       READ (1,*) Sy,AKb,AKt,AN
       READ (1,*) AMz,AMmax,Fz
       API=3.1415927
      ALPH=1.0
      AL4=0.0
          AL3=0.0
          AL2=0.2
          AL1=0.0
          DO 20 J=1,100
      DO 10  I=1,200
       D0=0.45 +(I-1)*.01
       AK=1-0.072/D0
        Ssmax=0.5*Sy/AN
        C1=(API*Ssmax/16.)**2
        C2=(Fz/8 )**2
        C3=2.*AMmax*AKb*Fz/8.
        C4=AMmax**2*AKb**2+2.*AMz*AKt**2
        X=C1*D0**6*(1+AK**4-2*AK**4)
       X=X (ALPH**2*C2*D0**2*(1+AK**4+2*AK*AK))
       X=X-(C3*ALPH*D0*(1+AK*AK)+C4)
       D01=D02
       D02=D0
       F01=F02
       F02=ABS(X)
       IF (X.GE.0.0) GOTO 30
       D0=(F01*D02+F02*D01)/(F02+F01)
       WRITE(2,*)'ALPHAD=  ',ALPH,' D0=  ',D0
       AL4=AL3
                AL3=AL2
                AL2=AL1
                AL1=ALPH
                IF (AL1.EQ.AL2.AND.AL2.EQ.AL3.AND AL3.EQ.AL4) GOTO 99
                DI=D0-0.072
       AREA=3.14/4.0*(D0*D0-DI*DI)
       AINERT=3.14*(D0**4-DI**4)/64.0
       RHO=SQRT(AINERT/AREA)
       ALPH=1/(1.0-0.0044*5.665/RHO)
       STOP
       END
```

```
21200,2.0,2.0,2.5
7.744,293,112,164,479
```

```
 ALPHAD=        1.00000000 D0=         1.59999967
 ALPHAD=        1.04719245 D0=         1.60369623
 ALPHAD=        1.04707509 D0=         1.60369705
 ALPHAD=        1.04707623 D0=         1.60368705
 ALPHAD=        1.04707623 D0=         1.60368705
 ALPHAD=        1.04707623 D0=         1.60368705
 ALPHAD=        1.04707623 D0=         1.60368705
```

APPENDIX - C

```
C      CALCULATION OF KING POST DEFLECTION
C      WIND VELOCITY:200 MPH
C      FILE NAME:ATM2.FOR
       DIMENSION X(30),S(30),D(30)
       OPEN(UNIT=1,FILE='C:\ACM[illegible].DAT')
       OPEN(UNIT=2,FILE='C:\[illegible]M2.OUT')
       READ(1,*)(S(I),I=1,16)
       READ(1,*)(X(I),I=1,16)
       READ(1,*)V,CY,R1X,R2X
       READ(1,*)E
       SUMD=0.0
       DO 10 I=1,16
       IF(I.GT.[illegible])GO TO 5
       D(I)[illegible]
       WRITE(2,*)D(I)
       PRINT*,D(I)
       GO TO 40
  5    IF(I.GT.[illegible])GO TO 20
       D(I)=(0.5*CY/E)*(1./S(I))*(X(I)**2-X(I-1)**2)
       WRITE(2,*)D(I)
       PRINT*,D(I)
       GO TO 40
 20    IF(I.GT.15)GO TO 30
       D(I)=(0.5/E)*(1./S(I))*(CY+0.435*R2Y)*(X(I)**2-X(I-1)**2)
     *-(1/3.)*(1/E)*(R2X/S(I))*(X(I)**3-X(I-1)**3)
       WRITE(2,*)D(I)
       PRINT*,D(I)
       GO TO 40
 30    D(I)=(0.5/E)*(1/S(I))*(CY+R2X*0.435-R1X*6.115)*(X(I)**2-X(I-1)**2)
     *+(R1X-R2X)*(X(I)**3-X(I-1)**3)/(3.*E*S(I))
       WRITE(2,*)D(I)
       PRINT*,D(I)
 40    SUMD=SUMD+D(I)
 10    CONTINUE
       PRINT*,SUMD
       THETA=(180./3.1416)*ATAN(SUMD/0.435)
       PRINT*,THETA
       WRITE(2,*)V,SUMD,THETA
       PRINT*,V,SUMD,THETA
       STOP
       END
```

```
 0.868,0.261,0.045,0.104,0.143,0.087,0.211,0.087,0.045,0.055,0.047,0.054,0.126
?.955,0.595,0.110
 0.04,0.2,0.28,0.58,2.76,2.96,3.04,3.24,4.48,4.68,5.28,5.48,5.88,5.96,6.115,6.?
?
 290.0,261.19577026,49.71593475,96.715
 ?0093000
```

```
 [illegible] 03
 [illegible] 07
 [illegible]
 [illegible]
 [illegible] 04
 [illegible] 04
 7.[illegible] 07
 1.[illegible] 07
 [illegible] 04
 1.[illegible] 04
 5.60[illegible]E-04
-?.[illegible] 04
 ?.?20[illegible] 04
-6.[illegible] 06
-2.6006[illegible]E-05
-6.0807[illegible] 05
 [illegible]   -1.4[illegible]590E-07     -0.13776387
```

[illegible].069,0.261,0.045,0.104,0.145,0.087,0.211,0.087,0.0[illegible],0.055,0.047,0.054,[illegible]
[illegible],0.505,0.110
[illegible].04,0.2,0.28,0.58,2.76,2.96,3.04,3.24,4.48,4.68,5.29,5.49,5.88,5.96,6.[illegible]...
9

80,122.32854462,21.5937423,21.593
20000000

[illegible].[illegible]E-07
[illegible]E-07
[illegible]-06
[illegible]-06
[illegible]-04
2.[illegible]E-05
[illegible]E-06
2.[illegible]E-05
[illegible].[illegible]E-04
2.77[illegible]74E-05
[illegible]E-05
1.[illegible]E-05
9.[illegible]E-06
[illegible]E-08
[illegible].[illegible]E-07
-6.704[illegible]E-08
80.00000000 5.551840[illegible]E-04 7.31255412E-02

```
0.068,0.261,0.045,0.104,0.145,0.087,0.211,0.027,0.045,0.055,0.047,0.054,0 [illegible]
0.955,0.505,0.110
0.04,0.2,0.28,0.59,2.76,2.96,3.04,3.24,4.48,4.68,5.28,5.48,5.88,5.96,6.115,[illegible]

100.0,132.47213745,23.38431358,23.384
20000000
```

```
[illegible]-09
[illegible]-07
[illegible]-06
9.[illegible]3E-06
1.[illegible]70E-04
2.40[illegible]-05
4.122[illegible]212E-06
2.477[illegible]057E-05
2.74[illegible]47E-04
2.956[illegible]078E-05
8.[illegible]E-05
1.[illegible]725E-05
3.336[illegible]11E-06
1.0475[illegible]038E-07
1.[illegible]E-07
[illegible]E-08
   [illegible]2.0[illegible]000000    6.01195206E-04    7.91850509E-02
```

```
0.868,0.261,0.045,0.104,0.143,0.087,0.211,0.087,0.045,0.055,0.047,0.054,0.126
?.955,0.505,0.110
0.04,0.2,0.28,0.58,2.76,2.96,3.04,3.24,4.48,4.68,5.28,5.48,5.88,5.96,6.115,6.1
7
?00.0,?61.19577026,49.71593475,96.715
?0000000
```

```
[illegible]E-08
[illegible]E-07
[illegible]E-06
[illegible]E-05
1.[illegible]E-04
[illegible]E-06
7.452[illegible]E-07
-1.8807?938E-07
-?.89672100E-04
-1.16309354E-04
-5.60857691E-04
-?.16??6?1E-04
-2.2204??99E-04
-6.577?9060E-06
-2.60064?44E-05
-6.0807?243E-05
[illegible]0   -1.4255159 0E-0?   -0.19776?87
```

APPENDIX – D

```
      DESIGN OF KING POST
      LOADING ON KINGPOST
      STATISTICAL APPROACH
      FILE NAME ACM19.FOR
      GEOMETRICAL DIMENSIONS IN METRES
      FORCES ARE IN TONNES
      WIND VELOCITY IN KMPH
       OPEN(UNIT=1,FILE='C:\ACM19.DAT')
       OPEN(UNIT=2,FILE='C:\ACM19.OUT')
       READ(1,*) UV,SV,URHO,SRHO,UCd,SCd, UCmm,SCmm,UCms,SCms
       READ(1,*) UBTA,SBTA,UC1,SC1,UFHs,SFHs,UFVs,SFVs,UMs,SMs
       READ(1,*) UCdr,SCdr,UDm,SDm,UDs,SDs,UAr,SAr,UWp,SWp
       READ(1,*) UWa,SWa,UZr,SZr,UXr,SXr,UXs,SXs,UYs,SYs
       READ(1,*) UZs,SZs,UZa,SZa,UZa1,SZa1,UXp,SXp,UL,SL,Ut,St
           READ(1,*) UL2,SL2,API,UL1,SL1
       READ(1,*) UTA,STA,UTE,STE
           UBTA=180.0*UBTA/3.14159
           SBTA=180.0*SBTA/3.14159
       UPr=0.5*URHO*(UV**2)
           SPr=0.5*SQRT((URHO*2.0*UV*SV)**2 + (UV**4)*SRHO**2)
       UFDa=(API/4.0)*(UDm**2)*UCd*UPr
       C1=2.*UDm*UCd*UPr*SDm
       C2=UCd*UDm*UDm*SPr
       C3=UPr*UDm*UDm*SCd
       SFDa= (API/4.)*SQRT(C1**2+C2**2+C3**2)
       UFLa= (API/4.0)*(UDm**2)*UC1*UPr
       C4=2.*UDm*UC1*UPr*SDm
       C5=(UDm**2)*UC1*SPr
       C6=(UDm**2)*UPr*SC1
       SFLa=(API/4.)*SQRT(C4**2+C5**2+C6**2)
       UFDr=UAr*UCdr*UPr
P=(UAR*UCdr*SPr)**2
           SFDr=SQRT((UCdr*UPr*SAr)**2+(UAr*UPr*SCdr)**2+P)
       UMm=(API/4.0)*(UDm**3)*UCmm*UPr
       C7=3.*(UDm**2)*UCmm*UPr*SDm
       C8=(UDm**3)*UCmm*SPr
       C9=(UDm**3)*UPr*SCmm
       SMm=(API/4.0)*SQRT(C7**2+C8**2+C9**2)
UMs1=(API/4.0)*UDs*UDs*UCms*UPr*(UZa1-UZa)*COS(UBTA)
U5=UZa1-UZa
       S5=SQRT(SZa**2+SZa1**2)
           D1=UDs*UDs*UPr*U5*COS(UBTA)*SCms
       D2=2.0*UDs*UCms*UPr*U5*COS(UBTA)*SDs
       D3=(UDs**2)*UCms*U5*COS(UBTA)*SPr
       D4=(UDs**2)*UCms*UPr*COS(UBTA)*S5
       D5=(UDs**2)*UCms*UPr*COS(SBTA)*U5
       SMs1=(API/4.0)*SQRT(D1**2+D2**2+D3**2+D4**2+D5**2)
```

```
      [illegible] UMs1
      [illegible](SMa**2+SMs1**2)
      UFz=UFLa+UFVs+UWa
      SFz=SQRT(SFLa**2+SFVs**2+SWa**2)
      UFx=UFHs
      SFx=SFHs
      UFy=UFDr+UFDa
      SFy=SQRT(SFDr**2+SFDa**2)
      UMx=UFDr*LZr+UFVs*UYs+UMa
      F1=(UYs*SFVs)**2+SMa**2
SMx=SQRT((UFDr*SZr)**2+(UZr*SFDr)**2+(UFVs*SYs)**2+F1)
UMy=UFDa*UZa+UMs+UFVs*UXs+UFHs*UZs+UWp*UXp+UTE
E1=(UFDr*SZr)**2
      E2=(UZa*SFDa)**2
      E3=(UFVs*SYs)**2
      E4=(UYs*SFVs)**2
      E5=(UFHs*SZs)**2
      E6=(UZs*SFHs)**2
      E7=(UWp*SXp)**2
      E8=(UXp*SWp)**2
      SMy=SQRT(E1+E2+SMs**2+E3+E4+E5+E6+E7+E8+STE**2)
      UMz=[illegible]UFDr*UXr+UTA
G=[illegible]
      SMz=SQRT((UFHs*SYs)**2+(UYs*SFHs)**2+(UFDr*SXr)**2+G+STA**2)
      UR2x=(UMy+UFx*UL)/UL1
E9=(UFx*SL/UL1)**2
         E10=(UL*SFx/UL1)**2
SR2x=SQRT(((UMy+UFx*UL)*SL1/(UL1**2))**2+(SMy/UL1)**2+E9+E10)
      UR1x=[illegible]UFx*UL2)/UL1
         E11=[illegible]UFx*UL2)/((UL1)**2))**2
         E12=(UFx*SL2/UL1)**2
         SR1x=SQRT(E11+(SMy/UL1)**2+E12+(UL2*SFx/UL1)**2)
         UMyz2=UMz-UFy*UL2
      SMyz2=SQRT(SMz*SMz+(UFy*SL2)**2+(UL2*SFy)**2)
      UMxz2=UMy+UFx*UL2
      SMxz2=SQRT(SMy**2+(UFx*SL2)**2+(UL2*SFx)**2)
      UM2=SQRT(UMxz2**2+UMyz2**2)
      F=(UMyz2*SMyz2)**2/(UMxz2**2+UMyz2**2)
      SM2=SQRT(((UMxz2*SMxz2)**2/(UMxz2**2+UMyz2**2))+F)
      UMmax=UM2
      SMmax=SM2
      WRITE(2,*)UPr,SPr,UFDa,SFDa,UFLa,SFLa
WRITE(2,*)UFDr,SFDr,UMm,SMm,UMs1,SMs1
      WRITE(2,*)UMa,SMa,UFz,SFz,UFx,SFx,UFy,SFy
      WRITE(2,*)UMx,SMx,UMy,SMy,UMyz2,SMyz2,UMxz2,SMxz2
         WRITE(2,*)UV,SV,UMmax,SMmax,UMz,SMz,E9,E10,E11,E12
      WRITE(2,*)UR2x,SR2x,UR1x,SR1x
      WRITE(2,*)C1,C2,C3,C4,C5,C6,C7,C8,C9
         WRITE(2,*)D1,D2,D3,D4,D5,UBTA,SBTA
         STOP
      END
```

APPENDIX-E

```
        [illegible] DIAMETER
        STAT[illegible]AL APPROACH
        Ud0 IN  METRES (M)
        FORCES IN TONNES(T)
        MOMENTS IN T-M
        OPEN(UNIT=1,FILE='C:\ACM23.DAT')
                 OPEN(UNIT=2,FILE='C:\ACM23.OUT')
        READ(1,*) AKb,AKt,ALPHA,API,AK
                 READ(1,*) US,SS,UFz,SFz,UMmax,SMmax
                 READ(1,*) UMz,SMz
                 DO 10 I=1,200
                 Ud0=0.45+(I-1)*0.01
                 Sd0=0.00044*Ud0
                 UP=256.0/((API* (1-AK**4))**2)
                 A=UP*((UMmax*AKb)**2)/(Ud0**6)
                 B= UP*((ALPHA*UFz*Ud0*(1+AK**2))**2)/(64.0*(Ud0**6))
                 C=(UP*2.0*UMmax*AKb*ALPHA*UFz*Ud0*(1+AK*AK))/(8.0*(Ud0**6))
                 D=(UP*((UMz*AKt)**2))/(Ud0**6)
                 TUs=SQRT(A+B+C+D)
        A1=((  [illegible]*UMmax*UMmax[illegible].00044)**2)/(Ud0**12)
                 A2=((2.0*UMmax*SMmax)**2)/(Ud0**12)
                 SA=UP*(AKb**2)*SQRT(A1+A2)
                 B1=((2.0*UFz*SFz)**2)/(Ud0**8)
                 B2=((4.0*UFz*UFz*0.00044)**2)/(Ud0**8)
                 SB=((UP*(ALPHA*(1+AK*AK))**2)*SQRT(B1+B2))/64.0
                 C1=((UFz*SMmax)**2)/(Ud0**10)
                 C2=((UMmax*SFz)**2)/(Ud0**10)
                 C3=((UMmax*UFz*5.0*0.00044)**2)/(Ud0**10)
                 SC=((UP*2.0*AKb*ALPHA*(1+AK*AK))/8.0)*SQRT(C1+C2+C3)
                 D1=((2.0*UMz*SMz)**2)/(Ud0**12)
                 D2=((UMz*UMz*6.0*0.00044)**2)/(Ud0**12)
                 SD=UP*AKt*AKt*SQRT(D1+D2)
                 TSs=(0.5*SQRT(SA**2+SB**2+SC**2+SD**2))/ TUs
                 Z=(US-TUs)/SQRT(SS**2+TSs**2)
12      IF (Z.GE.4.27) GOTO 30
30      WRITE(2,*) Ud0,US,TUs,SS,TSs,UP,Z
90       STOP
                  END
```

```
2.[illegible],2.0,1.[illegible],3.14159,0.952
[illegible]0[illegible]3.0,[illegible]5[illegible],1[illegible] [illegible]3[illegible]0,4.76211,2[illegible]4.[illegible]0543,1[illegible].[illegible]5[illegible]27
[illegible].94008,1.[illegible]
```

```
   [illegible]   12000.30000000    7120.49771404    1050.00000000    339.
[illegible]    [illegible]    4.41516701
```

```
!.0,2.0,1.05,3.14159,0.952


:          KING POST DIAMETER
:          STATISTICAL APPROACH
:          UdO IN  METRES (M)
:          FORCES IN TONNES(T)
:          MOMENTS IN T-M
           OPEN(UNIT=1,FILE='C:\ACM22.DAT')
                 OPEN(UNIT=2,FILE='C:\ACM22.OUT')
           READ(1,*) AKb,AKt,ALPHA,API,AK
                 READ(1,*) US,SS,UFz,SFz,UMmax,SMmax
                 READ(1,*) UMz,SMz
                 UdO=1.387
                 SdO=0.00044*UdO
                 UP=256.0/((API* (1-AK**4))**2)
                 A=UP*((UMmax*AKb)**2)/(UdO**6)
           WRITE(2,*) A
                 B= UP*((ALPHA*UFz*UdO*(1+AK**2))**2)/(64.0*(UdO**6))
                 WRITE(2,*) B
                 C=(UP*2.0*UMmax*AKb*ALPHA*UFz*UdO*(1+AK*AK))/(8.0*(UdO**6))
                 WRITE(2,*) C
                 D=(UP*((UMz*AKt)**2))/(UdO**6)
                 WRITE(2,*) D
                 TUs=SQRT(A+B+C+D)
           A1=((6.0*UMmax*UMmax  *.00044)**2)/(UdO**12)
                 A2=((2.0*UMmax*SMmax)**2)/(UdO**12)
                 SA=UP*(AKb**2)*SQRT(A1+A2)
                 B1=((2.0*UFz*SFz)**2)/(UdO**8)
                 B2=((4.0*UFz*UFz*0.00044)**2)/(UdO**8)
                 SB=((UP*(ALPHA*(1+AK*AK))**2)*SQRT(B1+B2))/64.0
                 C1=((UFz*SMmax)**2)/(UdO**10)
                 C2=((UMmax*SFz)**2)/(UdO**10)
                 C3=((UMmax*UFz*5.0*0.00044)**2)/(UdO**10)
                 SC=((UP*2.0*AKb*ALPHA*(1+AK*AK))/8.0)*SQRT(C1+C2+C3)
                 D1=((2.0*UMz*SMz)**2)/(UdO**12)
                 D2=((UMz*UMz*6.0*0.00044)**2)/(UdO**12)
                 SD=UP*AKt*AKt*SQRT(D1+D2)
                 TSs=(0.5*SQRT(SA**2+SB**2+SC**2+SD**2))/ TUs
                 Z=(US-TUs)/SQRT(SS**2+TSs**2)
              WRITE(2,*) UdO,US,TUs,SS,TSs,UP,Z
                 WRITE(2,*) SA,SB,SC,SD,C1,C2,C3
90          STOP
                  END
```

```
1.0,2.0,1.05,3.14159,0.952
2000.0,1050,159.11799,4.76211,232.56271,13.85169
3.57808,1.3548,1.27999997
```

```
   3.99940400E+07
  480061.12500000
   8.76346600E+06
  833732.62500000
        1.27999997   12000.00000000     7076.10791016     1050.00000000       339.283
53882       813.04553223          4.46224928
   4.76534750E+06    28747.12109375   584468.62500000    67314.46875000   411476.031
25000   103891.36718750       561.38983154
```

```
2.0,2.0,1.05,3.14159,0.952
12000.0,1050,159.11799,4.76211,232.56271,13.85169
33.57808,1.3548,1.2783
```

```
   4.03142160E+07
  482619.84375000
   8.82189100E+06
  840407.12500000
        1.27830005   12000.00000000     7103.45947266     1050.00000000       340.676
14746       813.04553223          4.43573761
   4.80349700E+06    28900.34179687   588365.25000000    67853.35937500   416980.84
75000   105281.24218750       568.90020752
```

APPENDIX-F

```
C        1234567 KIGS POST   ...
C        D(I) DEFLECTION IN ...
C        P(I)STANDARD DEVIATION
C        S(I) MOMENT OF INERTIA
C        CY MEAN VALUE OF MY
C        PSY  STANDARD DEV OF MY
C        DIMESION X(50) ,D(50)

                PARAMETER          MAX = 16
         DIMENSION          P(MAX)
         DIMENSION          SI(MAX)  , PX(MAX)
         DIMENSION          S(MAX)   , PS(MAX)
         DIMENSION          X(MAX)   , D(MAX)

         DATA               PS /MAX*0.000594027/
         DATA               PX /MAX*0.00166/

            OPEN(UNIT=1 ,FILE ='  C.DAT',status='old')
                      OPEN(UNIT=2 ,FILE ='ABC.OUT',STATUS='NEW')

            READ(1,*)( S(I) ,      I = 1 , MAX )
            READ(1,*)( X(I) ,      I = 1 , MAX )
                      READ(1,*) V , SV , CY , PCY ,
                      READ(1,*) PR1X , PR2X , R1X , R2X

         WRITE(2,100)
 100     FORMAT('  INPUT DATA ')
         WRITE(2,101)
 101     FORMAT('  SIXTEEN VALUES OF S ')
         WRITE(2,*)(S(I),I=1,16)
         WRITE(2,102)
 102     FORMAT('  SIXTEEN VALUES OF X ')
         WRITE(2,*)(X(I),I=1,16)
         WRITE(2,103)
 103     FORMAT('  V , SV , CY , PCY ,     ')
         WRITE(2,*) V,SV,CY,PCY,
         WRITE(2,104)
 104     FORMAT(' PR1X , PR2X , R1X , R2X  ')
         WRITE(2,*) PR1X,PR2X,R1X,R2X


         PD=0.0
         SUM = 0.0
**************************
         DO I = 1 , 16

                  IF ( I.  .1 )THEN

         XSQ = X(I) * X(I)

                      D(I) =  (0.5 * CY /   ) * ( 1. / S(I) ) * XSQ

                      R1 =  XS   * PCY / S(I)
                           R1 = R1 * R1
                      R2 - CY * XSQ * PS(I) / ( S(I) * S(I) )
                           R2 = R2 * R2
                      R3 = 2.  * X(I) * CY * PX(I) / S(I)
                           R3 = R3 * R3
                      P(I) = 0.5 /   * SQRT( R1 + R2 + R3 )
                  ENDIF
```

```
IF ( I.EQ.2 .OR. I.EQ. ) THEN

XSQ     = X(I)   * X(I)
XSQM1   = X(I-1) * X(I-1)
XSQF    = XSQ - XSQM1

SSQ     = S(I)   * S(I)

                  D1 =   0.5 * CY / [illegible]
                  D2 =   1. / S(I)
                  D3 =   XSQF

          D(I) = D1 * D2 + D3

             R4 = CY + XSQF * PS(I) / SSQ
                       R4 = R4 * R4
             R5 = PCY * XSQF / S(I)
                       R5 = R5 * R5
             R6 = CY * 2. * X(I) * PX(I) / S(I)
                       R6 = R6 * R6
             R7 = CY *2. * X(I-1) * PX(I-1) / S(I)
                       R7 = R7 * R7
             P(I) = 0.5 / [illegible] * SQRT ( R4 + R5 + R6 + R7 )
ENDIF

IF ( I.GE.4 .AND. I.LE.15 ) THEN

XSQ     = X(I)   * X(I)
XSQM1   = X(I-1) * X(I-1)
XSQF    = XSQ - XSQM1
XCUF    = XSQ * X(I) - XSQM1 * X(I-1)
SSQ     = S(I)   * S(I)
E2      = 2. * E
ES      = E * S(I)
E2S     = E2 * S(I)
E3S     = 3. * E * S(I)

             D1 = XSQF / E2S
             D2 = CY + 0.435 * R2X
             D3 = 1/3 * 1/E * R2X / S(I) * XCUF
          D(I) = D1 * D2 - D3

     A = ( CY + .435 * R2X ) * XSQF + P(I) /
1                      ( E2 * SSQ )
          A = A * A
     B =  XSQF * PCY / E2S
          B = B * B
     C1=  .435 * XSQF * PR2X / E2S
     C2=  XCUF * PR2X / E3S
          C=C1-C2
          C = C * C
     D1= ( X(I) * ( CY + .435 * R2X ) * PX(I) ) / ES
     D2= XSQ * R2X * PX(I) / ES
          D = D1 - D2
          D = D * D
     E1= X(I-1) * (CY + .435 * R2X ) * PX(I-1) / ES
     E2= XSQM1 * R2X * PX(I-1) / ES
          EE = -E1 + E2
          EE = EE * EE
```

```
    R(I) = SQRT ( A +    + C + DD + EE )
      ENDIF

      IF ( I.EQ.15 )THEN

      XSQ     = X(I)   * X(I)
      XSQM1   = X(I-1) * X(I-1)
      XSQF    = XSQ - XSQM1
      XCUF    = XSQ * X(I) - XSQM1 * X(I-1)
      SSQ     = S(I)   * S(I)
      E2      = 2. * E
      ES      = E * S(I)
      E2S     = E2 * S(I)
      E3S     = 3. * E * S(I)


      D(I) = 1 /  E2S * ( CY + R2X * .435 - R1X * 6.115 )*
     1        XSQF + ( R1X - R2X ) * XCUF / E3S

            Q1 =  XSQF / E2S * PCY
            Q2 =   .435 * XSQF / E2S
            QQ =  ( Q2 - XCUF / E3S ) * PX(I)
            Q3 =  -6.115 * XSQF / E2S
            Q3 =  ( Q3 + XCUF / E3S ) * PR1X
            Q4 =  ( CY + R2X * .435 - R1X * 6.115 ) / ES
            Q5 =  ( R1X - R2X ) / ES
            Q6 =  ( X(I) * Q4 + X(I) * X(I) * Q5 ) * PX(I)
            Q7 =  ( -X(I-1) * Q4 - XSQM1 * Q5) * PX(I-1)
      P(I) = SQRT( ( D(I) * P(I) / S(I) )**2 + Q1**2 +
     1               Q2**2 + Q6**2 + Q7**2 + Q3**2 )

      ENDIF

      PP     =  PP      +   P(I)**2
      SUMD   = SUMD     +   D(I)


      ENDDO

0     TYPE *, D
              PP = SQRT(PP)

      THETA  = ( 180.0 / 3.1416 ) * ATAN( SUMD / .435 )
      PTHETA = ( 180.0 / 3.1416 ) * ATAN( PP / 0.435 )

      WRITE(2,105)
105   FORMAT(//'0  OUTPUT DATA '//
     1       ' V , SV , SUMD , THETA , PP , PTHETA'// )

              WRITE (2,*) V , SV , SUMD , THETA , PP , PTHETA
              STOP
              END
```

```
INPUT DATA
SIXTEEN VALUES OF S
0.3000000      0.2810000      4.5000002E-02  0.1040000      0.1450000
6.6999997E-02  0.2110000      [illegible].6999997E-02  4.5000002E-02  5.5000000E-02
4.6999998E-02  5.4000001E-02  0.1260000      0.4550000      0.5050000
0.1100000
SIXTEEN VALUES OF X
3.9999999E-02  0.2000000      1.2[illegible]      0.5100000      2.750000
 2.960000      3.040000       3.240000       4.480000       4.660000
 5.250000      5.450000       5.[illegible]       5.960000       6.115000
 5.175000
V / SV / CY / FCY / E
 72.40000      42.20000       117.4200       15.4[illegible]       2.0000000E+07
PR1X / PR2X / R1X / R2X
 4.699000      5.270000       2[illegible]        20.64000


 OUTPUT DATA

V / SV / SUMS / THETA / PP / PTHETA

 72.40000      42.20000       1.[illegible]E-03  0.2236457      1.1963715E-04
1.5757900E-02
```