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Analytical Studies of Earth Station Antenna/DTH Using Cohen's Empirical Formulas in Matlab

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Abstract: ***Satellite communication is buzzword of today's shift changing competitive world. Earth station antenna are the ground segment infrastructure which interacts with satellite's antenna for transmit & receive purpose of the signals. DTH is the miniature version of the Earth station antenna which works on the same principle that of Earth station antenna, So DTH antenna of specific size has been picked up and detailed calculation have been carried out to predict C_l , C_d , C_p & C_m from Cohen's empirical curves. From the comparative studies of these coefficients, values of maximum Lift (L), Drag (D), Moment (M) & Pressure distribution for specific azimuth & Elevation angles have been calculated. Earth station antenna/DTH are subjected to wind gamut of forces viz. wind loads, gravity loads, acceleration loads, temperature loads & earthquake loads but the calculation of wind load have been emphasized in present work as it is the major & governing contributing factor in the design. These calculations of above parameters have been performed in MATLAB (version R2011b) by developing the original code by digitizing the co-ordinates and coding the formulae using the Edward Cohen's paper. Graphical & Pictorial representation of the standard curves for the L, D, M along with the resultant pressure co-efficient Cp have been carried out & calculations have been done for different Wind speed both for ESA & DTH antenna in order to capture the holistic behavior the structural analysis has been carried out by using multi-physics ANSYS for Reflector, Mount as well as the complete antenna system. The results have been tabulated for wide gamut of iterations of analysis in the domain of stress, strain & displacement, Structural analysis is carried out on the whole system for critical values of lift, drag and moment.***

Keywords: Parabolic Reflector, Structural Analysis, Cohen's Empirical Formula, Lift, Drag, Moment, Techno-commercial

1. Introduction

DTH: DTH stands for Direct To Home television. DTH technology refers to the satellite television broadcasting process which is actually intended for home reception. DTH refers to reception of the satellite signals on a TV with a personal dish. The satellite that are used for this purpose are geo-stationary satellites.

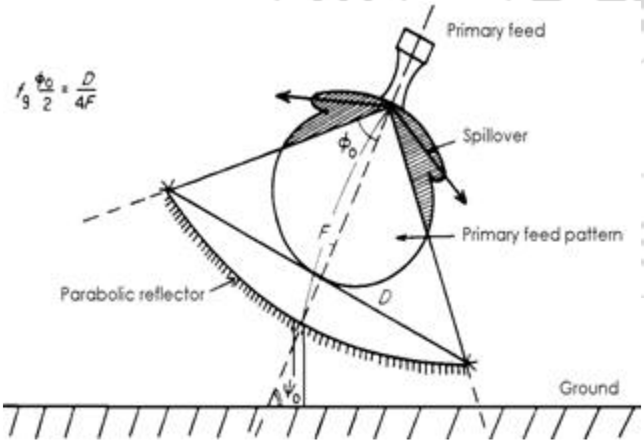

Figure 1: Principle of parabolic reflector

2. Offset or Off-axis feed

The performance of an Asymmetric configuration is affected by the blockage of the aperture by the feed and the sub reflector assembly. The result is a reduction in the antenna efficiency and an increase in the side lobe levels. The asymmetric configuration can remove this limitation.

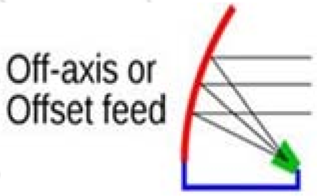

Figure 2: Off axis feed antenna

2.1 Wind Load Calculations

Wind forces undoubtedly play a significant role in the design and operations of large steerable antennas, and the need for satisfactory estimates of these forces is becoming increasingly evident. A resolution of the problem of predicting wind forces on antennas depends upon improved knowledge of the variation of pressures and local velocities on the reflector & it is supporting framework, integrated loadings, and ground effect for both solid and porous conditions. The following is the general theory involved in wind load calculations as presented by ***Edward Cohen***.

By application of Bernoulli's principle and the theories of dimensional analysis, the resultant wind force and torque on a body immersed in an air stream can be expressed in the form

$$F = \frac{1}{2}(\rho v^2) \quad A \quad C_R$$
$$T = \frac{1}{2}(\rho v^2) \quad A \quad d \quad C_m \dots\dots\dots\dots\dots\dots (1).$$

where, ρ = mass density of the air stream
V = wind velocity
A = typical area of the body
d = typical dimension of the body
C_R & C_M = dimensionless force and moment coefficients

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This depends upon the geometrical properties of the body and on the Reynolds number.

The term $\frac{1}{2}(\rho v^2)$ is the dynamic pressure of the undisturbed flow, and is designated "q". Employing conventional aerodynamics terminology, the force F may be divided into three orthogonal forces; drag, lift and side force, with coefficients designated C_D, C_L, and C_S, respectively. Similarly the torque may be divided into orthogonal roll, pitch and yaw moments, with corresponding coefficients, C_W, C_X, and C_Y.

In equation form:

Drag = C_D q A
Lift = C_L q A
Side force = C_s q A
Rolling moment = C_W d q A …………….. (2)
Pitching moment = C_X d q A
Yawing moment = C_Y d q A

These forces and induced moments acting on a typical steerable antenna; these are referenced to axis system assumed positive for the following discussion. Angles designating astronomical positions in altitude (elevation), θ, and azimuth, ψ, are adopted. The wind is assumed to flow only in the horizontal direction; hence the angle, alpha(α), which the wind makes with the plane of the reflector rim (the angle of attack) is a function of the altitude and azimuth angles relative to the wind stream, expressed by:

$$\alpha = \sin^{-1}(\cos\theta \cos\psi) \quad …………….\ (3)$$

The coordinates defining the positive direction of the forces are fixed relative to the wind, drag being in the horizontal direction parallel to the wind, lift in the vertical direction normal to the wind and side force in the horizontal direction normal to the wind.

The aerodynamic characteristics of parabolic reflectors with sharp leading edges are greatly affected by such parameters as reflector depth to diameter ratio (h/d), surface solidity ratio (ϕ), and surface geometry. For the case of reflectors, force coefficients are referenced to the plan form area ($\pi d^2/4$), and the torque coefficients to the product of the plan form area and diameter ($\pi d^3/4$).

Edward Cohen .conducted tests on paraboloids using small models, with flow being in turbulent region, and considered the effects of differences in Reynolds number between wind tunnel and full-scale conditions to be negligible.

The general airfoil equations for a flat plate and a circular arc airfoil of
$\lambda = \infty$ are, respectively:

$$\frac{w}{V} = \cos\alpha \qquad \alpha\sqrt{\left(\frac{d-x}{x}\right)}\ , 0 \le x \le d\ …………….\ (4)$$

$$\frac{w}{V} \qquad \left(\frac{8h}{d}\right)\sqrt{\left\{\frac{x}{d}\left(1-\frac{x}{d}\right)\right\}}, 0 \le x \le d\ \alpha = 0°\ ..(5)$$

Where w/V is the ratio of the local to the free-stream velocity, d is the length of chord section, h/d is the camber ratio of the circular arc, and x is a position along the chord measured from the leading edge. In these equations the plus (+) sign applies to the convex surface, and the minus (–) sign applies to the concave face.

The lift resulting from equation 4 for the flat plate is given by

$$C_L = 2\pi\alpha \quad …………………..(6)$$

Where α is measured in radians. That resulting from equation 5 for the circular arc at α = 0° varies with h/d and is termed the ideal lift "C_{IL}" because at this incidence the flow enters the leading edge smoothly and leaves the trailing edge smoothly resulting in zero pressure at both the edges. At all angels other than α = 0°, theoretically infinite velocity, and this infinite pressure, occurs in the vicinity of the sharp leading edge. This is evident from equation 4.

For a given low angle of attack (α), the potential flow pressure distribution on a circular arc airfoil may be obtained by adding the flat plate distribution at this angle to the pressure distribution occurring at a angle of zero lift, α_{ZL}. The distribution for zero lift is obtained by subtracting the pressure distribution on the plate for $\alpha = \frac{C_{IL}}{2\pi}$ from the distribution on the arc for zero incidence.

For the case of circular-arc airfoil, the angle of attack for zero lift is very nearly:

$$\alpha_{ZL} = \frac{(-2h)}{d} \quad ………………(7)$$

Hence the equation of lift becomes,

$$C_L = 2\pi \left(\alpha + \frac{2h}{d}\right) \quad …………….(8)$$

The above equation is form circular arc airfoil having infinite aspect ratio. For the case of solid parabolic reflector having circular plan form and aspect ratio 4/π, the lifting surface theory gives

$$C_L = 1.75\left(\alpha + \frac{2h}{d}\right) + 1.5\left(\alpha + \frac{2h}{d}\right)^2 \quad ……………….(9)$$

For the case of porous reflector, the above potential flow theory was applied to obtain first approximation of the chord wise pressure profiles by assuming that the theoretical lift curves are directly proportional to the reflector solidity ratio. This assumption at first may appear arbitrary but *Cohen* was able to produce reasonable results. Hence the equations are modified as follows:

$$C_L = \emptyset \quad 2\pi \quad \left(\alpha + \frac{2h}{d}\right) \quad …………….(10)$$

$$C_L = \emptyset \quad \left[1.75\left(\alpha + \frac{2h}{d}\right) + 1.5\left(\alpha + \frac{2h}{d}\right)^2\right] \ ……..(11)$$

As per *Cohen* et al., the pressure isobars for some angle of attacks as per the SAIL (Software for Antenna wind and Alignment) software developed in-house at SAC are produced as follows:

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2.2 Pressure distribution on antenna

Distribution of pressure on a body immersed in a moving fluid depends largely upon the variation of fluid velocity around the body, in accordance with Bernoulli's general pressure-velocity relationship law for an ideal fluid:

$$\frac{\Delta p}{\frac{1}{2}(\rho v^2)} = 1 - \left(\frac{w}{V}\right)^2 \qquad \dots\dots\dots\dots.(12)$$

Where ΔP is the local static pressure on the body, w is the local velocity corresponding to local ΔP, and $(\frac{1}{2}\rho v^2)$ and V are free stream, "q" pressure and velocity respectively. This equation is independent of dynamic system employed, then numerical value of each ratio being the significant factor regardless of the actual magnitude of each individual quantity. Thus, it is convenient to introduce a dimensionless pressure coefficient;

$$C_P = \frac{\Delta P}{\frac{1}{2}(\rho v^2)} \qquad \dots\dots\dots\dots\dots\dots(13)$$

Where:

$$C_P = 1 - \left(\frac{w}{V}\right)^2 \qquad \dots\dots\dots\dots\dots\dots(14)$$

Making use of above two equations, Cohen computed C_P values for solid and porous reflectors. The procedure employed was similar to that for calculating C_L, C_D, and C_M. But these potential solutions were useful only for low angle of attack. For high angle of attack problems actual boundary layer flow has to be incorporated, and the effect of leading edge separation and particularly the effect of leakage through an open reflector etc. have to be taken into consideration. Equations 13 and 14 are valid only for solid reflectors, for porous reflectors a correction similar to the one used for C_L and C_D calculations should be used. For the case of porous reflectors the expression for C_P is modified as follows:

$$C_P = \emptyset\left[1 - \left(\frac{w}{V}\right)^2\right] \text{ ------------------- } (15)$$

Where, ϕ = solidity ratio.

2.3 Design Specifications of Antenna

a) Mechanical (Structural Specifications):

- Antenna Diameter **: 0.6 m**
- Type of Mount **:** Elevation Over Azimuth Manual /Step Track Along With Servo

b) Environmental Specification

Wind Speed

- OPERATIONAL **: 50 m/s**
- OCCASIONAL GUSTING **: 60 m/s**
- DRIVE TO STOW **: 100 m/s**
- SURVIVAL IN STOW **: 200 m/s**

Temperature: 295 k

2.4 Static Structural Analysis

A static analysis calculates the effects of steady loading conditions on a structure, while ignoring inertia and damping effects, such as caused by time varying loads. A static analysis however includes steady inertia loads (such as gravity and rotational loads velocity), and time varying loads that can be approximated as static equivalent loads.

Static analysis determines the displacements, stresses, strains and forces in structures or components caused by loads that do not induce significant inertia and damping effects. Steady loading and response conditions are assumed that is the loads and the structure's response are assumed to vary slowly with respect to time.

These types of loading that can be applied in static analysis include:

1) Externally applied forces and pressures.
2) Steady state inertial force (such as gravity or rotational velocity).
3) Imposed (non-zero) displacements.
4) Temperatures (for thermal strains).

Engineering Materials

ANSYS workbench has structural steel as its default material for solid modelling. But, the antenna that we are designing needs to be of light weight and as strong as steel.

This is achieved by introducing alloy of aluminum as a material for our antenna. We had added aluminum 3003 as material. But, it didn't decrease weight substantially. So finally we went for E-Glass which is light in weight and also has higher strength to weight ratio.

Mesh Generation

With use of ANSYS 15.0. Mesh was generated on dish, mount and assembly of dish and mount. For dish, coarse type of mesh was used and smoothing was kept medium. Finite element method was used. The same parameters were used for mount (alone), dish & mount.

Analysis of Model

Detailed analysis of Assembled model was carried out in Static structural module of ANSYS 15.0. The Critical loads of namely Lift, Drag & Moment were applied on model and its total deformation was recorded. The critical value of lift was obtained at +40 degrees while Drag & Moment were observed at +90 & -10 Degrees respectively.

FOR WIND SPEED 50 KMPH

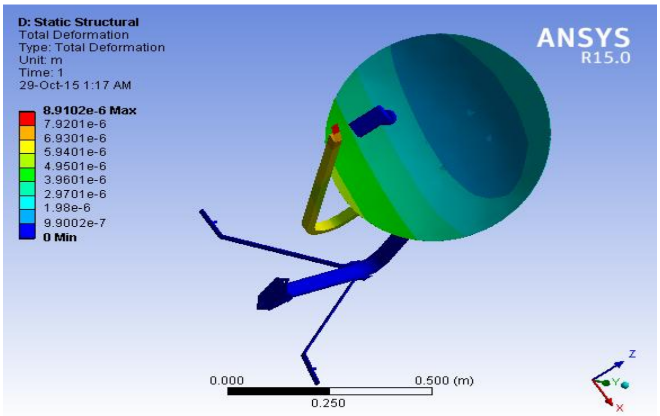

Figure 5.3: Deformation at Critical lift 46N

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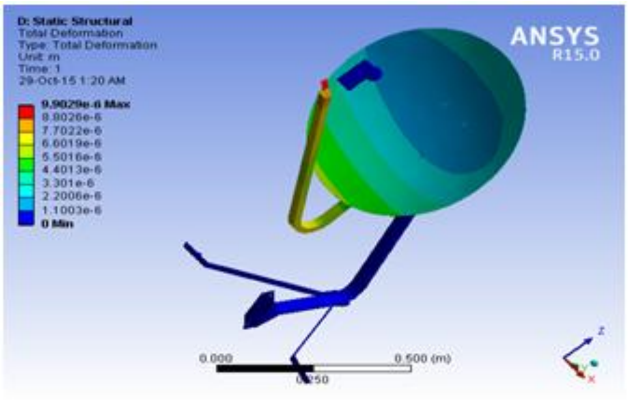

Figure 5.4: Deformation at Critical Drag 51.125N

FOR WIND SPEED 60 KMPH:

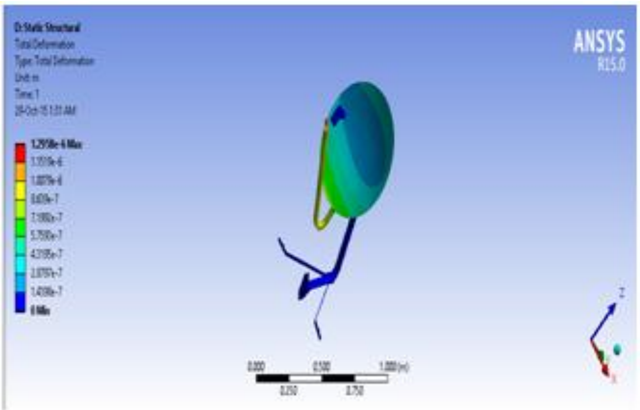

Figure 5.5: Deformation for Lift of 55.8N

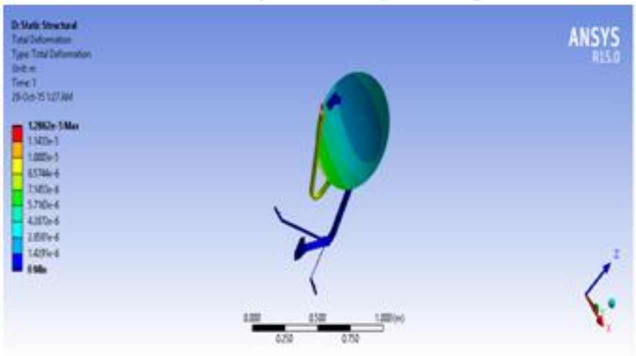

Figure 5.6: Deformation of Model for 73.65 N Drag force

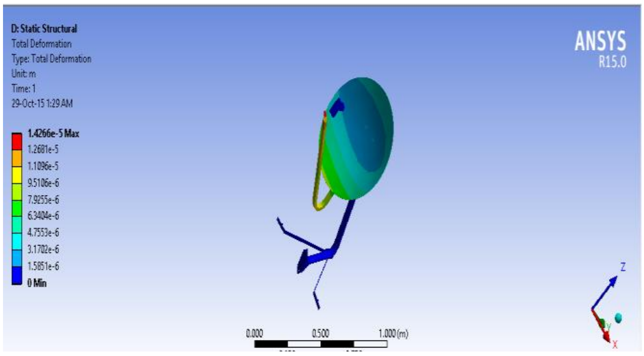

Figure 5.7: Total deformation for moment force of 6.69N.

Pointing Error

The satellites send the signals to dish present on earth. Dish receives and demodulates it. In DTH antenna The orientation angle is very much important. Even a slight disturbance can cause feed camera to move which results in loss of signal. Pointing error is error that is present in between transmission and reception of Signals. Pointing error is responsible for loss of signals. We have calculated pointing error for antenna with help of formula

$PE = \tan^{-1}(\delta / F)$

F= focal length of antenna

δ= deformation of antenna

3. Conclusion

The analysis of the model brought us to various conclusions:

1) The value of Critical lift, Drag, Moment are at 40, 90 & -10 degrees respectively which decides the design criteria of DTH.
2) These various forces of Lift, Drag & Moment helps us to decide the type of mount and loading of mount.

An Average DTH antenna dish made up of aluminum alloy cost about 1500-1800 Indian rupees. But the design that we have provided weights almost 7.4Kg and made up of E-glass. Market price of E-glass is $1500-$2500 per Ton .we have considered price of $2500 per Ton. On mathematical calculation, the designed DTH costs about 1200 Indian rupees. So, we have substantially reduced the price of DTH antenna without altering its dimensions and without compromising with quality of required material of DTH antenna.

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