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Paraboloidal antennas: wind loading.
Part 1: mean forces and moments

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PARABOLOIDAL ANTENNAS: WIND LOADING. Part 1: mean forces and moments

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APPENDIX B **23**

B1. PARABOLA GEOMETRY **23**

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PARABOLOIDAL ANTENNAS: WIND LOADING. Part 1: Mean Forces and Moments

1. NOTATION AND UNITS

		SI unit
A	reference area*, $\pi d^2/4$	m^2
a	depth of paraboloid, see Sketch 1.1	m
C_D	drag coefficient, component along wind direction 0*u*, see Appendix A2	
C_L	lift or cross-flow force coefficient, component normal to wind direction (along 0*v*), see Appendix A2	
C_M	moment coefficient, see Section 3	
C_{Mp}, C_{Mq}, C_{Mr}	moment coefficients in steering-axis system, about 0*p*, 0*q*, 0*r* respectively, see Appendix A3	
C_{Mu}, C_{Mv}, C_{Mw}	rolling, pitching, yawing moment coefficients respectively, about 0*u*, 0*v*, 0*w* axes in wind-axis system, see Appendix A2	
C_{Mx}, C_{My}, C_{Mz}	moment coefficients in body-axis system, about 0*x*, 0*y*, 0*z* respectively, see Section 3	
C_P, C_Q, C_R	force coefficient components in steering-axis system, along 0*p*, 0*q*, 0*r* respectively, see Appendix A3	
C_S	side-force coefficient, component normal to wind direction (along 0*w*), see Appendix A2	
C_T	transverse force coefficient, component normal to paraboloid axis, in plane of axis and wind velocity vector, see Section 3	
C_X	normal force coefficient, component along 0*x* direction, see Section 3	
C_Y, C_Z	lateral force coefficients, components along 0*y* and 0*z* directions, see Section 3	
D	drag force, force component along wind direction, $\frac{1}{2}\rho V^2 A C_D$	N
d	diameter of paraboloid rim, see Sketch 1.1	m
F	force component, see Appendix A1	N
f	focal length of paraboloid	m
I_u	intensity of *u*-component of turbulence, σ_u/V, see Section 3.3	

For footnotes see end of Notation Section

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L	lift force, force component along 0*w* normal to wind direction, $\frac{1}{2}\rho V^2 A C_L$	N
M	moment, $\frac{1}{2}\rho V^2 A d C_M$	Nm
M_x, M_y, M_z	moments about 0*x*, 0*y*, 0*z* axes, $\frac{1}{2}\rho V^2 A d C_{Mx}$, $\frac{1}{2}\rho V^2 A d C_{My}$, $\frac{1}{2}\rho V^2 A d C_{Mz}$ respectively	Nm
Re_d	Reynolds number based on dimension *d*, Vd/ν	
S	force component along 0*v* direction, $\frac{1}{2}\rho V^2 A \ C_S$	N
T	transverse force component, $\frac{1}{2}\rho V^2 A C_T$, see Section 3	N
V	time-averaged wind velocity at antenna vertex height	m/s
$0p, 0q, 0r$	steering axes, set of right-handed Cartesian coordinate axes with origin at paraboloid vertex having 0*q* along elevation axis and 0*r* along azimuth axis, see Appendix A3	
$0u, 0v, 0w$	flow axes, set of right-handed Cartesian coordinate axes fixed with respect to wind, having origin at paraboloid vertex and 0*u* along the mean wind direction, see Appendix A2	
X, Y, Z	body-axis force components, $\frac{1}{2}\rho V^2 A C_X$, $\frac{1}{2}\rho V^2 A C_Y$ and $\frac{1}{2}\rho V^2 A C_Z$	N
$0x, 0y, 0z$	body axes, set of right-handed Cartesian coordinate axes fixed with respect to paraboloid, having origin at paraboloid vertex and 0*x* along the negative paraboloid axis, see Section 1.1	
x_{cp}	location of moment centre along paraboloid axis	m
α	incidence angle, angle between the 0*x* axis and the wind velocity vector, see Equation (3.2)	degree
θ, ψ	elevation and azimuth angles of reflector axis relative to datum position† defined in Section 1.1	degree
λ_x, λ_y, λ_z	translational displacement between axis systems, see Appendix A1	m
ν	kinematic viscosity of fluid (typical value for air = 1.45×10^{-5} m^2/s)	m^2/s
$[\Phi_x], [\Phi_y], [\Phi_z]$	transformation matrices for rotation of axis systems, see Appendix A1	
ϕ_x, ϕ_y, ϕ_z	rotational displacements between axis systems, see Appendix A1	degree
ρ	density of fluid (typical value for air = 1.23 kg/m^3)	kg/m^3

* Note that *A* is independent of the inclination of the antenna to the flow.

† For other purposes elevation and azimuth angles may be measured from other datum positions, *e.g.* from horizontal for elevation and from North for azimuth. Care should be exercised to ensure that correct values are derived for use in this Data Item.

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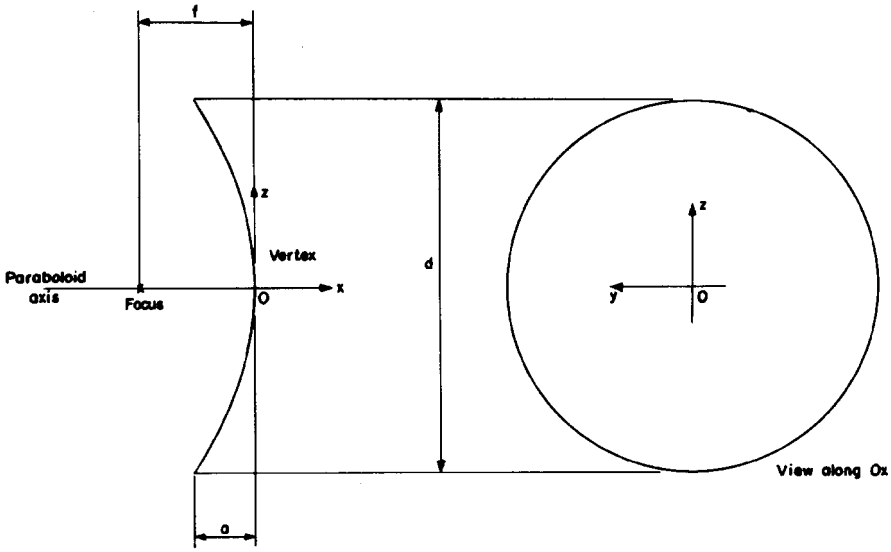
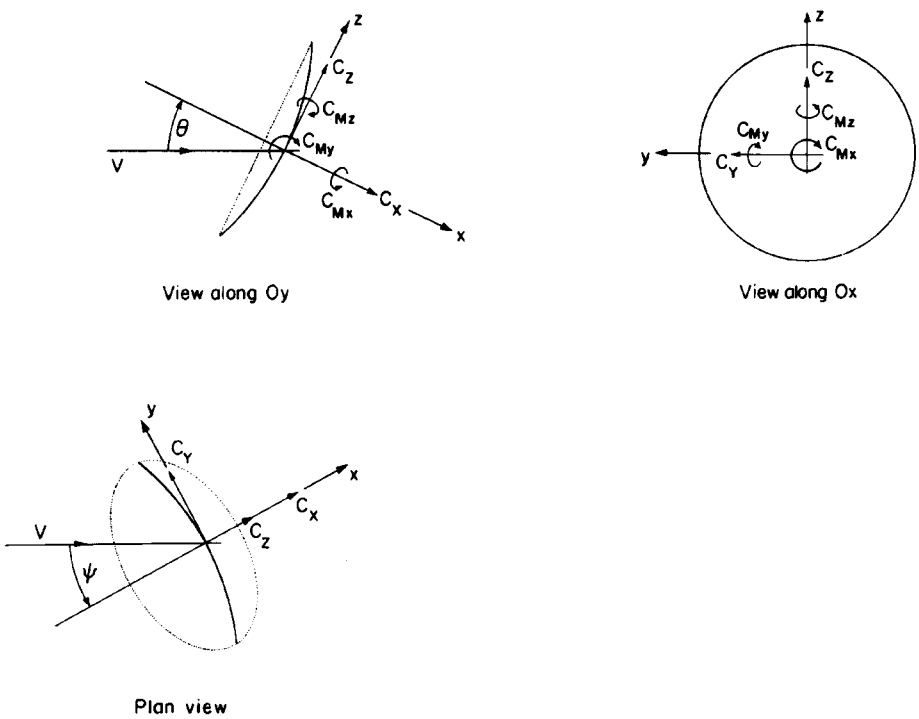


Sketch 1.1

1.1 Axis Systems and Force Coefficients

Information on wind loading on paraboloidal antennas may be required in one of the number of axis systems depending on its application. In this Data Item the data are presented in terms of a system of body axes fixed with respect to the antenna, with its origin at the paraboloid vertex and with the 0*x* axis along the negative axis of the parabola (*i.e.* away from the convex surface). The system is defined in Sketch 1.2. The datum position* is defined as $\theta = 0° = \psi$ when 0*x* is along wind.



Sketch 1.2 Force and moment coefficient components in a body-axis system for an antenna at azimuth angle ψ and elevation angle θ

* For other purposes elevation and azimuth angles may be measured from other datum positions, *e.g.* from horizontal for elevation and from North for azimuth. Care should be exercised to ensure that correct values are derived for use in this Data Item.

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Appendix A sets out the procedure for converting to other axis systems and provides the transformation equations required to convert the data from this Data Item to a wind axis system and to a system of 'steering' or 'stability' axes. It is assumed that the systems coincide for zero elevation and azimuth angles.

2. PURPOSE, SCOPE AND USE OF THIS DATA ITEM

2.1 Purpose and Scope

This Data Item provides force and moment coefficients for use primarily in estimating mean wind loading on stationary or slow moving paraboloidal reflectors such as are used for microwave communications antennas, radio telescopes and solar energy concentrators.

2.2 Applicability, Limitations and Uncertainty

The basic application is to structures in the natural wind. The data may be used to derive the mean component of wind loading (using the mean-hourly wind speed), and the fluctuating components arising from turbulence buffeting, in a spectral and correlational approach* to the total wind loading.

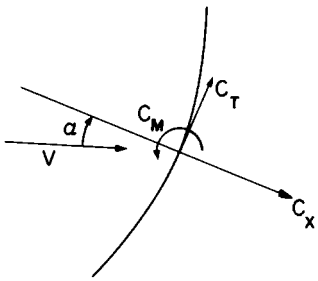
The information in this Data Item may also be used in a quasi-static, discrete-gust loading approach† in which the total wind loading is assumed to be produced by a discrete gust.

The Data Item may also be used to estimate the mean loading induced by other gas or liquid flows over paraboloidal shapes. For gas flows the Mach number should be less than about 0.4, whilst for liquid flows, the possibility of significant forces arising from free-surface effects or from cavitation should be considered separately.

Specific limitations on the application of the data and estimates of the uncertainty, based on the spread of experimental data, are given as comments in the text or on the Figures. The ranges of the experimental data on which the information is based are given in Table 7.1. A Calculation Sheet, providing a step-by-step procedure for calculating the basic forces and moments on an antenna, is given in Table 7.2.

3. FORCE AND MOMENT COEFFICIENTS FOR ISOLATED PARABOLOIDAL ANTENNAS

Because of the symmetry of a thin, isolated paraboloid the overall wind loading on it may be expressed in terms of only two forces and a moment: an axial force *X* and a transverse force *T* (normal to the paraboloid axis and in the plane of the axis and the wind velocity vector) and a moment *M* about the paraboloid vertex in the same plane as the force *T*.



Sketch 3.1

* This approach is explained in Reference 1.
† This approach is used in the current UK Code of Practice[2].

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Figures 1 and 2 give the force coefficients, C_X and C_T, for thin, isolated paraboloidal antennas in smooth, uniform flow as functions of the paraboloid focal length/diameter ratio, f/d, and the wind incidence angle, α. The correlations are based on data from Derivations 5, 7, 13, 15, 18, 19 and 20. For zero elevation angle $(\alpha = \psi)$ the experimental data for C_X are generally within the larger of ± 0.1 or ± 15 per cent of the values given by Figure 1 and experimental data for C_T within ± 0.07 of the values given by Figure 2.

Experimental data for moments are subject to larger uncertainties than those for forces because of a greater sensitivity of interference from mountings and nearby surfaces and structures. The moment coefficient C_M for a thin, isolated, antenna is given approximately by*

$$C_M = C_T x_{cp}/d = -C_T(2f/d + a/d)\,. \tag{3.1}$$

Values of x_{cp}/d [$= -(2f/d + a/d)$] are given as a function of f/d or a/d in Figure 3. Experimental data for C_M at zero elevation angle $(\alpha = \psi)$ and in smooth uniform flow are generally within ± 0.05 of values given by Equation (3.1). The data suggest also that Equation (3.1) may underestimate C_M for $\alpha < 90°$ but is more likely to overestimate for $\alpha > 100°$.

The incidence angle α can be expressed in terms of the elevation and azimuth angles, θ and ψ, (assuming that for $\theta = 0° = \psi$ the wind is along the $0x$ direction) by

$$\alpha = \cos^{-1}(\cos\theta\ \cos\psi)\ . \tag{3.2}$$

The transverse force coefficient C_T and the moment coefficient C_M can then be resolved to give the body axis components as:

$$\left.\begin{aligned} C_Y &= -C_T \sin\psi/\sin\alpha\,, \\ C_Z &= C_T \sin\theta\cos\psi/\sin\alpha\,, \\ C_{Mz} &= -C_M \sin\psi/\sin\alpha = -C_Y\,(2f/d + a/d)\,, \\ \text{and}\quad C_{My} &= C_M \sin\theta\ \cos\psi/\sin\alpha = -C_Z\,(2f/d + a/d)\,. \end{aligned}\right\} \tag{3.3}$$

The third body-axis coefficient, C_{Mx}, is zero for the case considered here because of the rotational symmetry of the paraboloid about $0x$.

Force coefficient data (Derivation 19) for non-zero elevation angles show a similar scatter to those for zero elevation angle except for negative values of C_X which show a larger scatter of about ± 0.2. Moment coefficient data (Derivations 7 and 19) for non-zero elevation angles also show similar scatter to those for zero elevation angle except for C_{My} from Derivation 19 where the scatter is biased towards + 0.09, – 0.01.

The force and moment coefficients for other axis systems may be obtained by use of the equations in Appendix A. For the cases considered here the maximum drag coefficient, C_D, occurs for zero incidence at which condition it is equal to C_X.

* Equation 3.1 is derived as follows. A normal to the paraboloid surface at $[-x, y]$ (in the present axis system x is negative on the paraboloid surface) intersects the axis at a distance $-(2f + x)$ from the vertex and since $-a < -x < 0$ the limits on the intersection are $-2f$ and $-(2f + a)$. The resultant force on the paraboloid is the sum of normal pressure forces on the surface and must therefore act through a point between $-2f$ and $-(2f + a)$ from the vertex. The maximum value has been assumed, leading to Equation 3.1.

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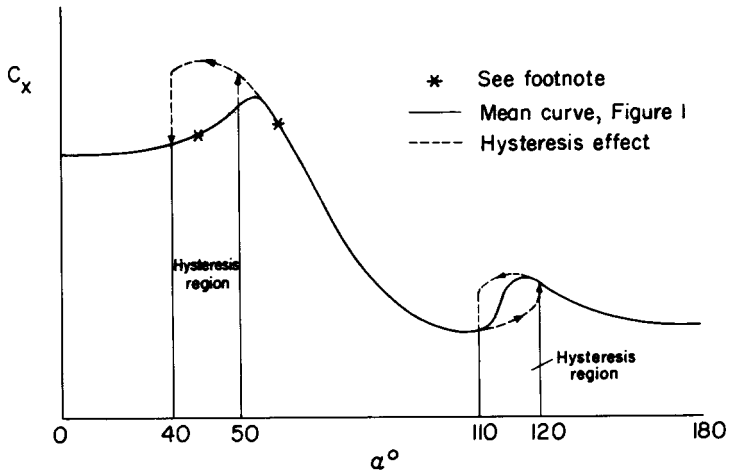
3.1 Hysteresis Effects

In common with most sharp-edged bodies, a thin paraboloid may be expected to experience hysteresis effects on the wind-induced forces over ranges of incidence where the separation patterns are changing. For paraboloid shapes the effects will be mitigated by the low aspect ratio of the body and consequently highly three-dimensional flow. Data from Derivations 13 and 15 suggest that hysteresis effects, if present, will be experienced in the region of $\alpha = 40°$ to 60° and 100° to 120°, usually over a range of about 8 to 10 degrees, the exact angle depending on the rim angle of the reflector. Sketch 3.2 shows a possible example. However, with the exception of data from Derivations 13 and 15, no positive evidence* of hysteresis effects is available and the curves in Figures 1 and 2 are drawn as continuous curves.



Sketch 3.2

3.2 Perforated Surfaces

Perforated surfaces of various types are sometimes used for antenna surfaces†. The principal effect of the openings is to allow flow through the surface into the separated wake regions, reducing the magnitude of the (negative) base pressure in those regions. Over much of the incidence range the forces and moments on the antenna are reduced but increases and sign changes also occur. The available data (Derivations 5, 7, 11 and 19) do not allow precise calibration of the effects of perforation of the antenna surface but some general trends can be established.

Figure 4 indicates the effect of perforation‡ on values of C_X over certain ranges of incidence. Within these ranges the correction factor varies over a range of up to ± 0.1 with a tendency to reduce the relative magnitude of the peak values of C_X at around 60° incidence.

* It is possible that this is a result of experimental techniques. Forces may be measured with α changing in only one direction. If forces are measured at fairly wide incidence spacings (10° or more) they may span the hysteresis region and lead only to small distortions from a smooth curve, as, for example, the points marked by an asterisk in Sketch 3.2. In order to positively establish hysteresis, closely-spaced force measurements must be taken with α varying in both directions and with the wind tunnel operating continuously since hysteresis is a function of persistance of an established flow pattern beyond a normal change-over point.

† The effects of icing on the porosity of such surfaces should not be overlooked. In addition to increasing the solidity of the surface, icing will also tend to increase the length/diameter ratio of the openings which, for ratios greater than about 0.5 further reduces their effective porosity.

‡ The solidity ratio is calculated as if the antenna surface were a flat sheet, *i.e.* no allowance is made for inclination of the holes to the flow direction.

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