

Achievable characteristic mode performance of substructure regions

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Antennas have evolved from large, protruding structures to compact, integrated components, becoming essential in modern technology. While antenna design must meet various performance criteria, it is constrained by fundamental physical limitations. For 75 years, antenna theory has explored these constraints, traditionally focusing on bounding geometries like circumscribing spheres, often beyond designers' control. Increasing integration now demands insights into performance limits within substructure-specific design regions under the designers control.

Characteristic modes, intrinsic electromagnetic behaviors of a structure, are widely used in antenna design and readily available in commercial solvers. Typically presented, though not exclusively, as an eigenvalue problem within the Method of Moment (MoM) framework for loss-less material as, $\mathbf{Z}\mathbf{I}_n = \lambda_n \mathbf{R}\mathbf{I}_n$ where $\mathbf{Z} = \mathbf{R} + j\mathbf{X}$. In this context, $\mathbf{Z}$ represents the electric field integral equation (EFIE) MoM matrix of a structure Ω . Characteristic eigenvalues λ_n and characteristic angles $\alpha_n = \pi - \text{atan}(\lambda_n)$ describe modal behavior, with $\alpha = \pi$ indicating resonance.

The characteristic mode framework can be extended to substructures, analyzing smaller regions $\Omega_c \subseteq \Omega$. Fig. 1 displays the characteristic angles for two substructure geometries over frequency (presented in terms of ka , where $a = \sqrt{5}\ell$), highlighting differences in modal behavior—one with two resonant modes, the other with none, and non of them wide band. This raises a critical question for an antenna designer: What can be achieved within this specific geometry? Is it possible to realize modes with, for instance, wide band characteristics?

In this work we establish a fundamental limit on the frequency derivative of α (or λ) across all frequencies and characteristic values by solving a relaxed QCQP problem. These limits, visualized as arrows in Fig. 1, indicate the maximum slope of the characteristic angles. Further we can observe that resonant modes at low ka values must be capacitive and that wideband solutions are possible no earlier than for $ka > 1.5$.

This analysis reveals substructure potential and helps designers identify regions where performance goals are achievable, acknowledging that while antennas operate using combined modes, each mode remains subject to these fundamental constraints.

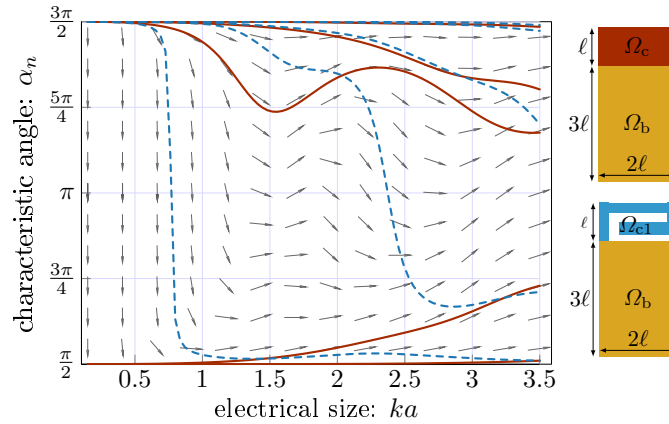


Figure 1: Characteristic angles for two substructure regions, in solid (Ω_c) and dashed (Ω_{c1}), where Ω_b is the uncontrollable background (PEC). The bounds on slope of characteristic angles is displayed as arrows.