EXPERIMENTAL AEROELASTICITY AGENDA

- **Session 1- Background on aeroelasticity and wind tunnels**

- **Session 2 - Wind tunnel facilities**

- **Session 3 - Model design and fabrication**

- **Session 4 - Wind tunnel testing and case studies**
  - Flutter and divergence
    - Flutter test case study
    - Supersonic divergence case study
  - Dynamic response case study

- **Session 5- Active control and smart structure tests**

FLUTTER

$$\begin{pmatrix} m & mr \\ mr & I \end{pmatrix}\begin{pmatrix} y \\ \alpha \end{pmatrix}+\begin{pmatrix} K_y & 0 \\ 0 & K_\alpha \end{pmatrix}\begin{pmatrix} y \\ \alpha \end{pmatrix}=\begin{pmatrix} -L \\ M \end{pmatrix}$$

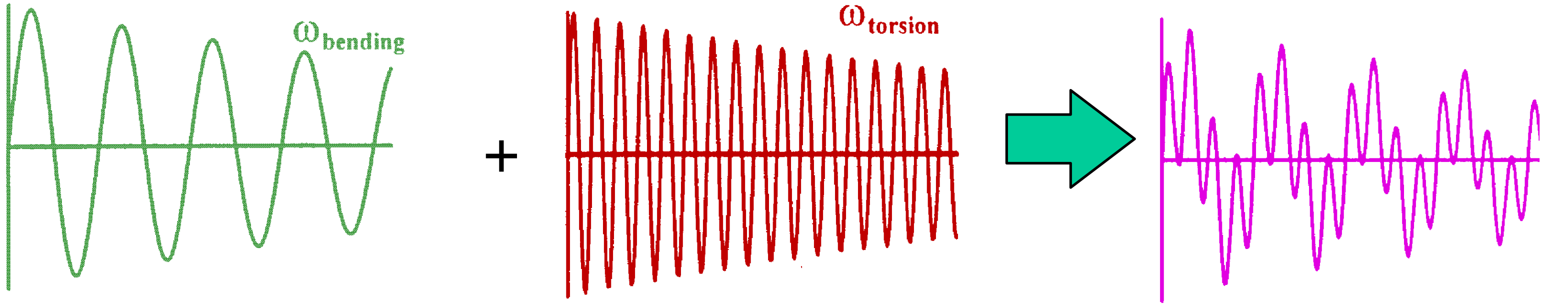
"INERTIALLY COUPLED WHICH SUGGESTS "MASS BALANCING"

"UNSTEADY" AERODYNAMICS WHERE

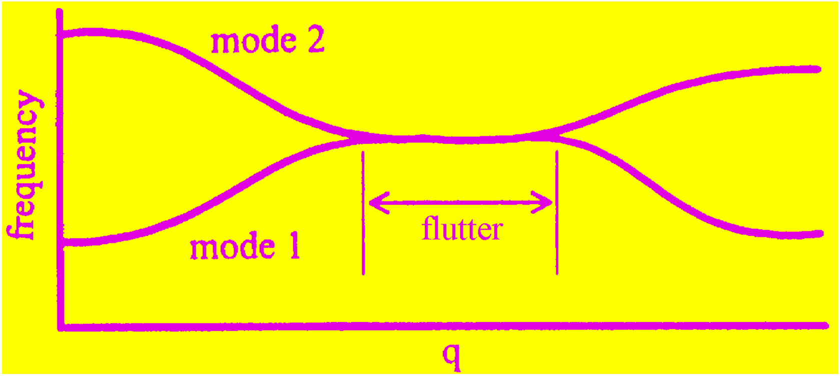
$$L = L(y, \dot{y}, \alpha, \dot{\alpha}, \rho, t)$$

$$M = M(y, \dot{y}, \alpha, \dot{\alpha}, \rho, t)$$

Time domain solutions: the response to a disturbance (initial condition) is examined



Frequency domain solutions: "roots" directly lead to frequency and damping trends



SIMILARITY PARAMETERS

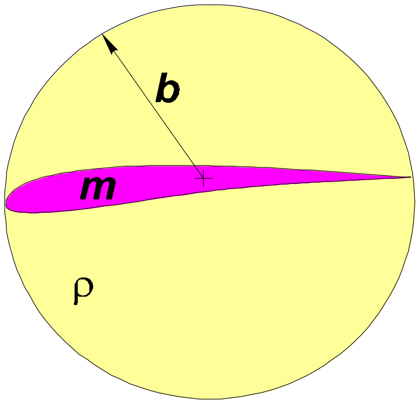
- **Reduce the level of effort for analysis and tests**
- **Ensure ‘dynamic scaling’ for comparisons**

- **In aerodynamic studies the Mach number and Reynolds number are used**
  - Mach number $M \equiv \frac{U_\infty}{a_\infty}$
  - Reynolds number $R_e \equiv \frac{r_\infty U_\infty c}{m_\infty}$
    - **where :**

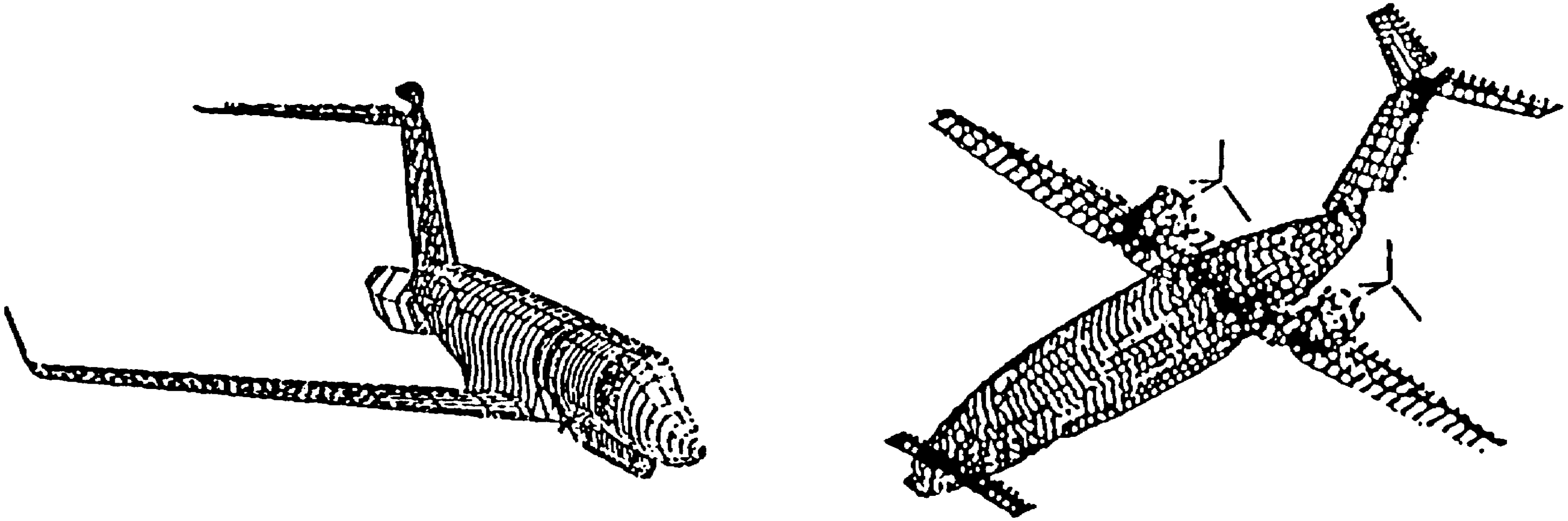
$U_\infty \equiv$ *flow velocity*
$\mu_\infty \equiv$ *viscosity*
$a_\infty \equiv$ *speed of sound*
$c =$ *reference length*
$\rho_\infty \equiv$ *density*

- **In Aeroelasticity we define:**
  - MASS RATIO $\mu \equiv \frac{m}{\pi b^2 \rho s}$
  - REDUCED FREQUENCY $k \equiv \frac{b\omega}{U_\infty}$
  - FLUTTER SPEED INDEX $FSI \equiv \left(V \text{ or } F\right) \equiv \frac{U_\infty}{b\omega\sqrt{\mu}}$
    - **where :**

$U_\infty \equiv$ *flow velocity*
$m \equiv$ *mass of wing*
$s \equiv$ *span*
$\rho \equiv$ *fluid density*
$\omega \equiv$ *frequency*
$b =$ *reference length*



AEROELASTIC MODELS

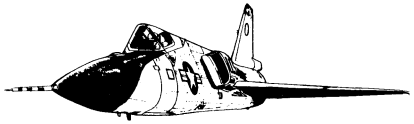


- **A model of the aeroelastic system is constructed to simplify the analysis.**
- **This aeroelastic model has three components . . .**
  - A model of the structure (e.g., finite element model) that permits analysis of the structural dynamics.
  - An appropriate model of the unsteady aerodynamic loads.
  - An aeroelastic solver to predict frequency and damping behavior for different flight conditions.

THE AEROELASTIC MODEL

- 1st Principles are used to construct a discrete model of the structure and the aerodynamics.

$$\boxed{M\ddot{q} + C\dot{q} + Kq = F}$$



Where [M], [C], and [K] describe the mass, damping, and stiffness of the structure; {q} refers to the 'generalized' coordinates which represent motion of the structure; and {F} represents the external loads on the structure.

- In aeroelastic systems, {F} will include the unsteady aerodynamic loads which are dependent upon the motion, {q}, of the structure. Thus,

$$\boxed{F = M_A\ddot{q} + C_A\dot{q} + K_Aq}$$

where $[M_a]$, $[C_a]$, and $[K_a]$ represent aerodynamic "mass", aerodynamic "damping", and aerodynamic "stiffness" contributions. These terms depend upon freestream conditions such as velocity, density, and Mach number.

- The combined equations may be solved as an "eigenvalue" problem

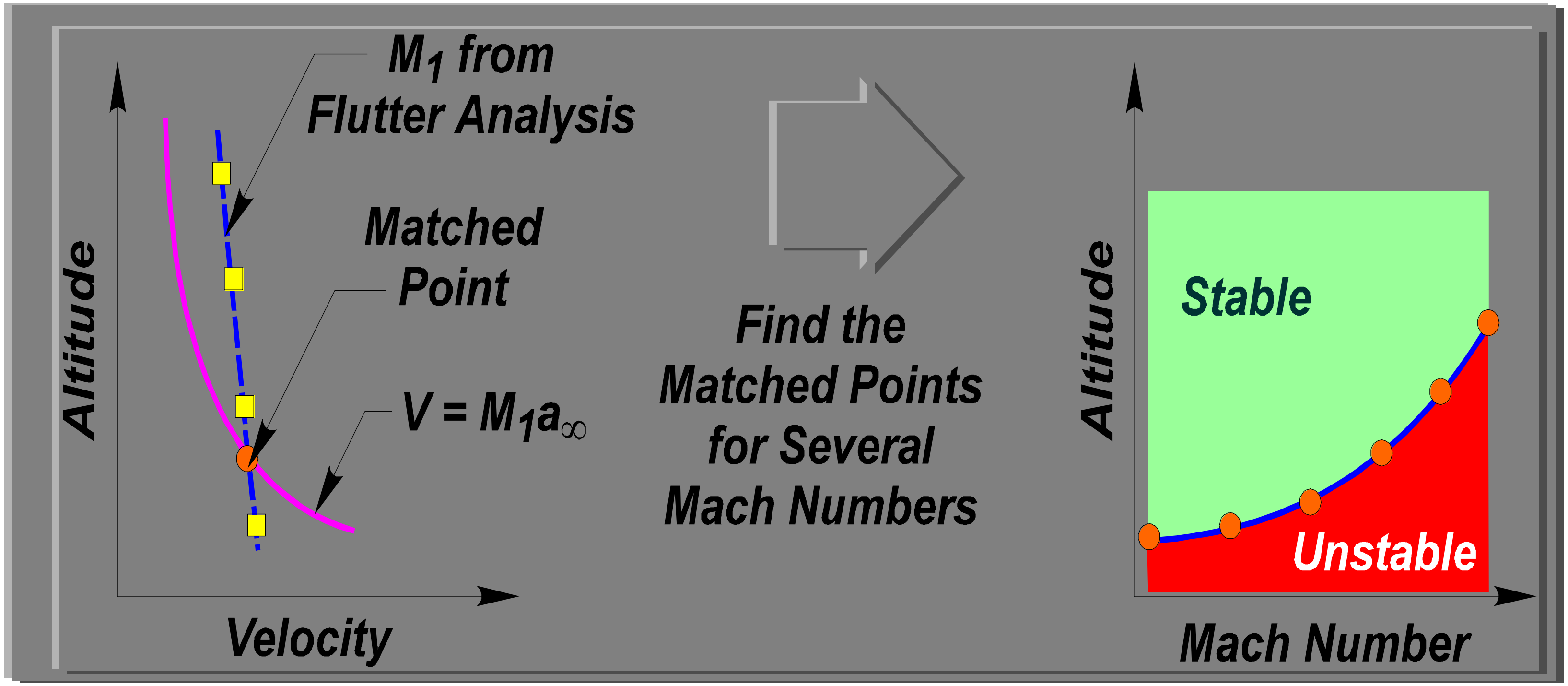
$$\boxed{(M - M_A)\ddot{q} + (C - C_A)\dot{q} + (K - K_A)q = 0}$$

AEROELASTIC ANALYSIS

- **Fidelity of the structural model is key to aeroelastic analysis . . .**
  - A finite element model (FEM) is most desirable.
  - A "dynamically similar" model could be used.
  - Measured modes may be a source for a structural model.
- **Many numerical models for aeroelastic analysis exist, and include : (MSC-NASTRAN, CAP-TSD, ASTROS, or the "home grown" variety)**
- **Aeroelastic stability analysis is performed for**
  - All altitudes of interest
  - Mach numbers within the flight envelope
  - Symmetric and antisymmetric modes
- **The analyst's concern must include**
  - The transonic regime
(difficult unsteady aerodynamics, flow discontinuities and uncertainties)
  - Examination of all participating modes of vibration.

THE “ MATCHED - POINT ” CONCEPT

1. In the atmosphere, an altitude - velocity profile is set for a specified $M_{¥}$.
2. From analysis, an altitude - flutter velocity profile is predicted for the same specified $M_{¥}$.
3. The intersection of these two profiles establishes altitude, velocity, and $M_{¥}$ conditions from which flutter boundaries are built .



SOLUTION METHODS FOR THE AEROELASTIC EQUATIONS

- **In general, the equations of motion for the aero(servo)elastic system are :**

$$[M]\{\ddot{q}\} + [C]\{\dot{q}\} + [K]\{q\} = [A(M_\infty, \rho, k)] + [B(q)]$$

- **Many methods are used, we will consider a few …**
  - Velocity “root - locus” plots
  - Theodorsen’s method
  - the “V-g” method (a.k.a. American method)
  - the “p-k” method (a.k.a. British method)

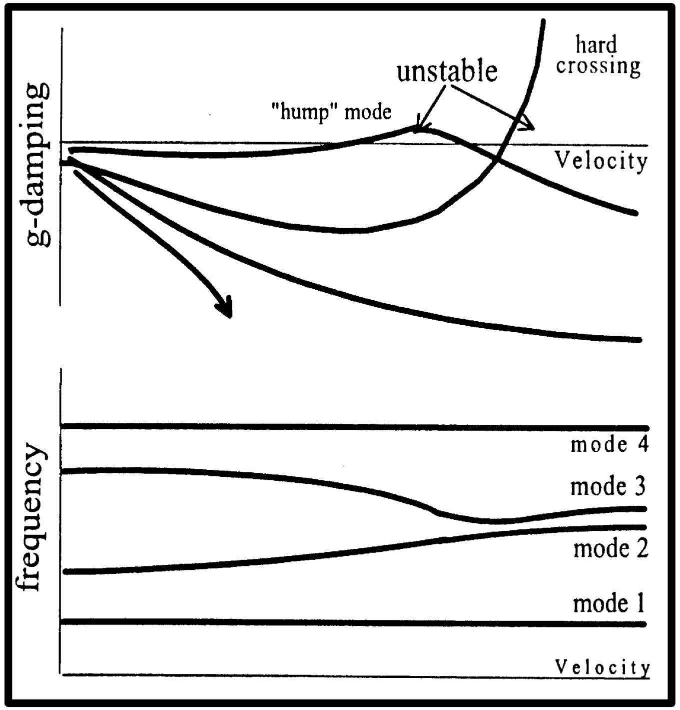
- **We solve the “general” aeroelastic set of equations; however, we must consider**
  - relationship between “circular” frequency and reduced frequency
  - harmonic motion is assumed
  - relationship between Mach number, velocity, altitude, flow conditions
  - eigenvalues are complex -- frequency and damping are found
    for “separated” equations, the solution must agree
  - the presence and form of damping

THE “V-G” METHOD

- **The eigenvalue formulation leads to two polynomials …**
  - one associated with the real terms
  - one with the imaginary terms

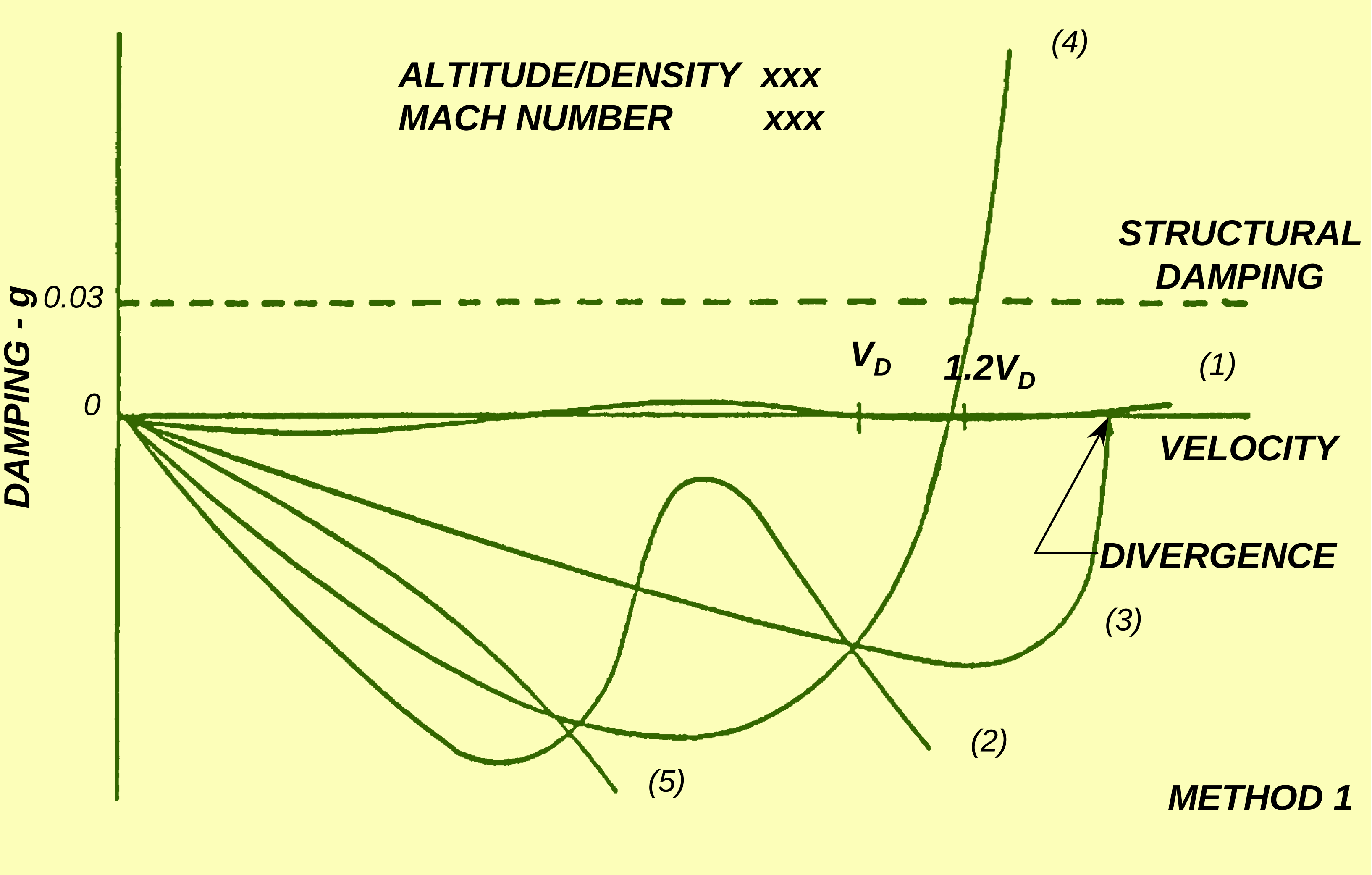
$$\Delta = \begin{vmatrix} A_R + iA_I & B_R + iB_I \\ D_R + iD_I & E_R + iE_I \end{vmatrix} = 0$$

- **Steps …**
  - 0. establish structural, physical properties
  - 1. assume M & altitude
  - 2. assume k, determine the aerodynamics
  - 3. solve for Z : $Z_R = (\omega_\alpha / \omega)^2$; $Z_I = g\, Z_R$
  - 4. plot V vs. g (V is known from k)
  - 5. plot V vs. ω (ω is known from Z_R)
  - 6. Repeat steps 2 through 5 for crossing
  - 7. Repeat steps 1 - 6 for “matched point”



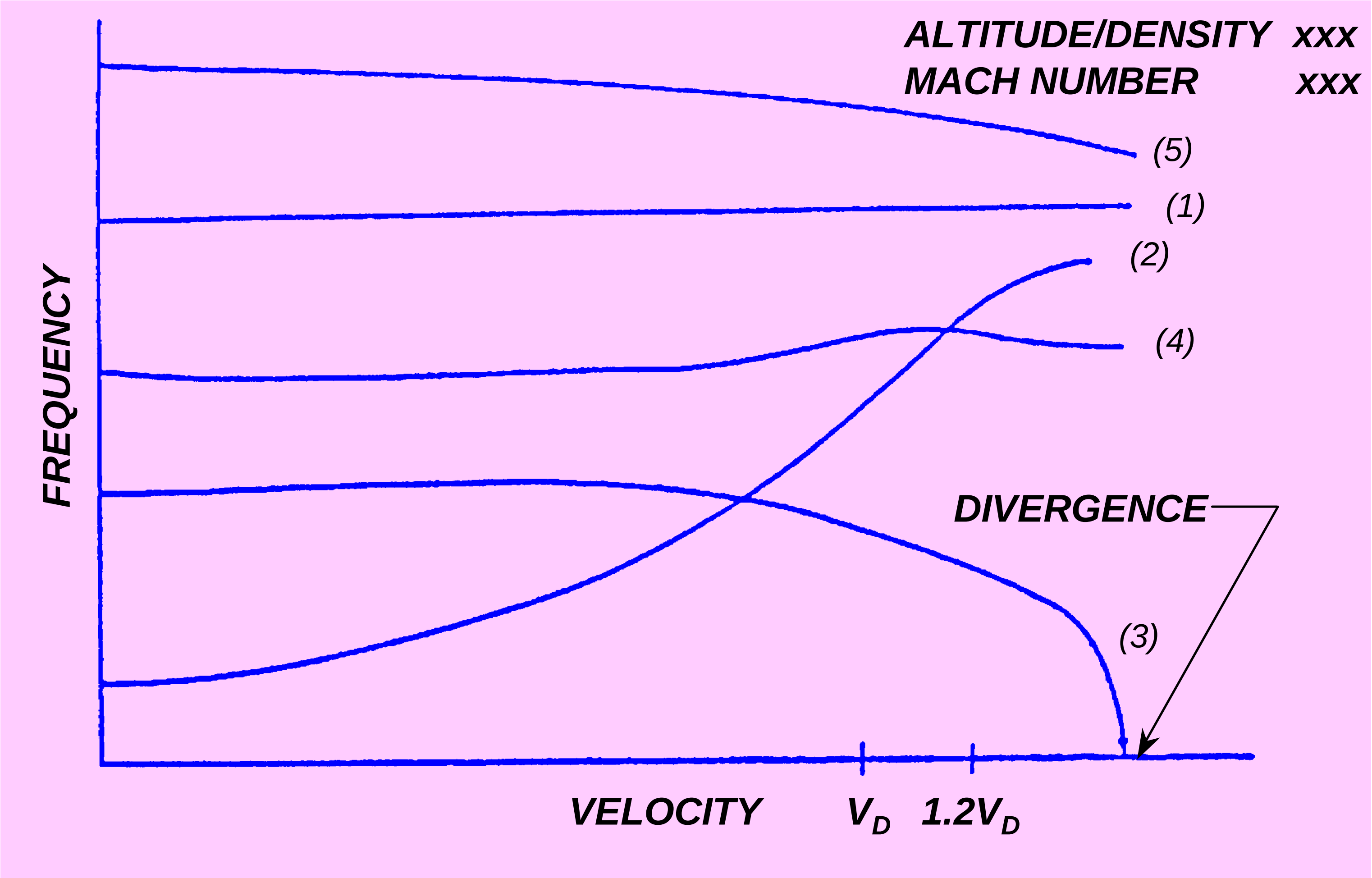
AEROELASTIC ANALYSIS

- **Velocity - Damping (V-g) diagrams are found in the regulations. Method 1 permits the assumption of .03 (3%) damping**



AEROELASTIC ANALYSIS

- **Velocity - Frequency diagrams are also found in the regulations (AC 25.629.1)**



THE “p-k” METHOD

H. Hassig (1971) described it in detail. From,

$$[M]\{\ddot{q}\} + [C]\{\dot{q}\} + [K]\{q\} = [A(M_\infty, \rho, k)] + [B(q)]$$

or,

$$\boxed{\left[\frac{1}{g_o}\frac{V^2}{b^2}[M]p^2 + [D]\frac{V}{b}p + (1+ig)[K] - \frac{\rho V^2}{2}c_o\,[A(k)] - H_A\left(\frac{V}{b}p\right)[D_A]\right]\{q\} = 0}$$

(0) Define system constants.

(1) Assume k , determine aerodynamic components [A(ik)].

(2) Solve for $p = \gamma k + ik$

(3) Does assumed value of k agree with predicted k (imaginary term) ?

(4) No ? return to step (1)

(5) Yes ? converged k provides V, g, and frequency (1 point on diagram)

(6) choose new M_∞ and ρ , return to (1)

(7) plot the converged roots vs. V

(8) flutter found at zero damping (analogous to the V-g (k) method)

CHOOSING NATURAL VIBRATION MODES

- **Choosing the modes for flutter analysis may be “tailored”, based upon experience and available resources.**
  - For example, consider the primary structural modes for a transport aircraft (AR = 8; Λ = 30°)

1.	1st Wing Bending	2.1 Hz
2.	2nd Wing Bending	6.5 Hz
3.	1st Wing Torsion	10 Hz
4.	3rd Wing Bending	14 Hz
5.	Outboard Aileron	17 Hz
6.	Inboard Aileron	19 Hz
7.	2nd Wing Torsion	22 Hz
8.	4th Wing Bending	25 Hz
9.	3rd Wing Torsion	30 Hz
10.	5th Wing Bending	35 Hz

  - Predicted flutter speeds depend on choice of modes

MODES USED	FLUTTER SPEED (fps)	FLUTTER FREQUENCY (Hz)
1 & 3	2630	6.7
2 & 3	4920	8.0
1 - 3	2520	6.3
1 - 4	2550	6.3
1 - 5	2610	6.6
1 - 6	2640	6.7
1 - 7	2600	6.7
1 - 8	2600	6.7
1 - 9	2600	6.7
1 - 10	2600	6.7

FLUTTER ALLEVIATION

- **How may we eliminate aeroelastic instabilities, or suppress the critical velocity and Mach number to acceptable levels?**
  - Eliminate sources of elastic, inertial, and/or aerodynamic coupling
  - How?
    - **"Mass balance" -- add or redistribute mass to move the c.g. forward**
    - **Modify the vibration characteristics**
      - tailor the natural frequencies
      - increase structural damping
    - **Eliminate sources of aerodynamic "forcing" such as vortex shedding or turbulence from leading components.**
    - **Active suppression via the flight control system.**

TEST PROCESS

- **Communications**
  - Include facility personnel in the process starting with model design
  - Have periodic meeting / frequent contact
  - Ensure tunnel operators are informed about test plans / objectives
- **Test planning**
  - Address test procedures
  - Prioritize
- **Test conduct**
  - Typical test procedures
  - Predictive techniques
  - Attitude

    “Please remove loose change when exiting the test section”;

    Always check; check behind yourself; check always

    - Surface appearance / integrity
    - Loose screws, bolts, nuts

TEST PROCEDURES

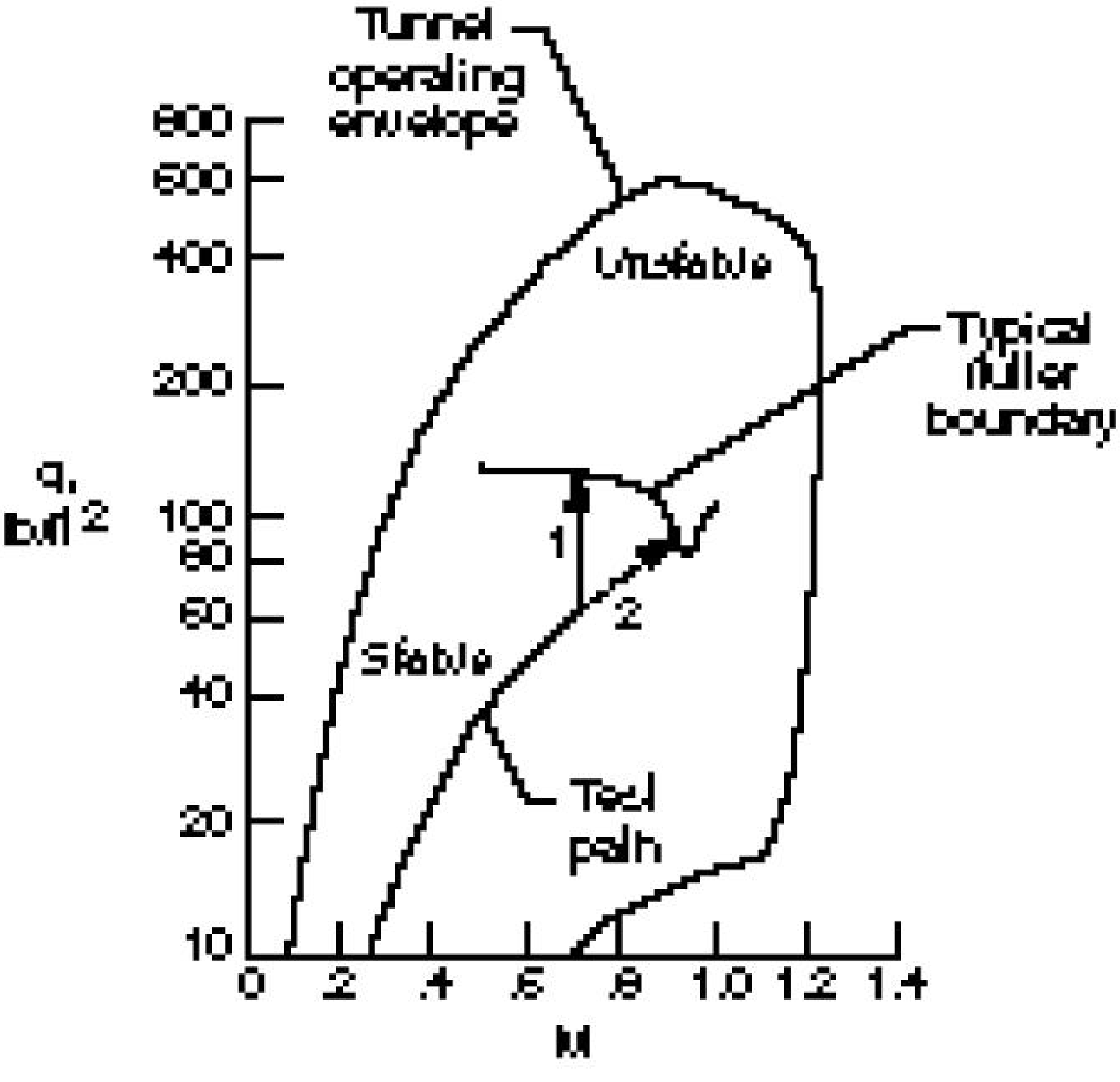
- **Insist on clear, concise communications**

- **Proceed cautiously - change test conditions slowly**

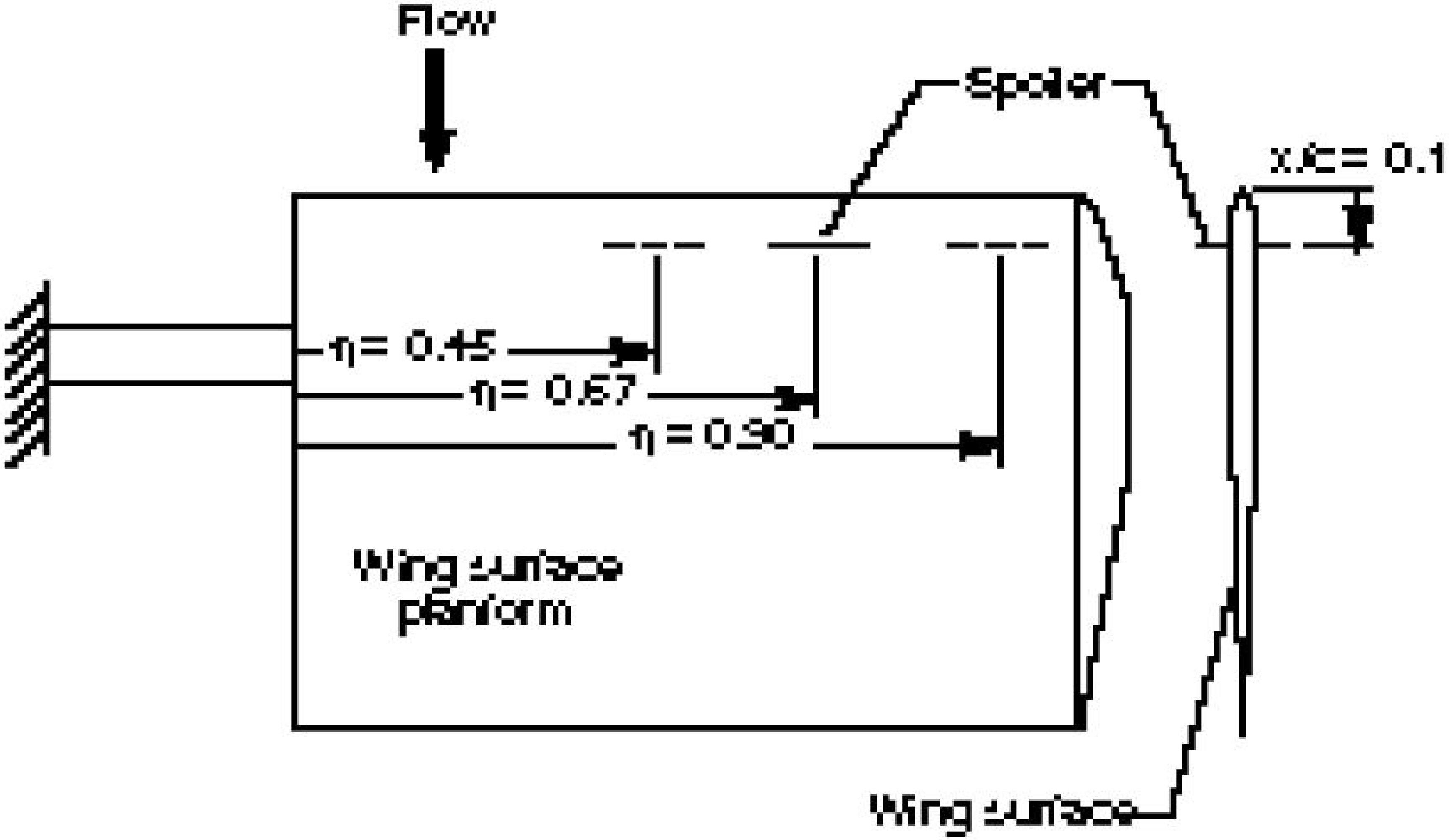
- **Begin at safe conditions**
  - Low Mach number
  - Low dynamic pressure
  - Low tunnel start pressure

- **Consider objectives in charting test “path”**

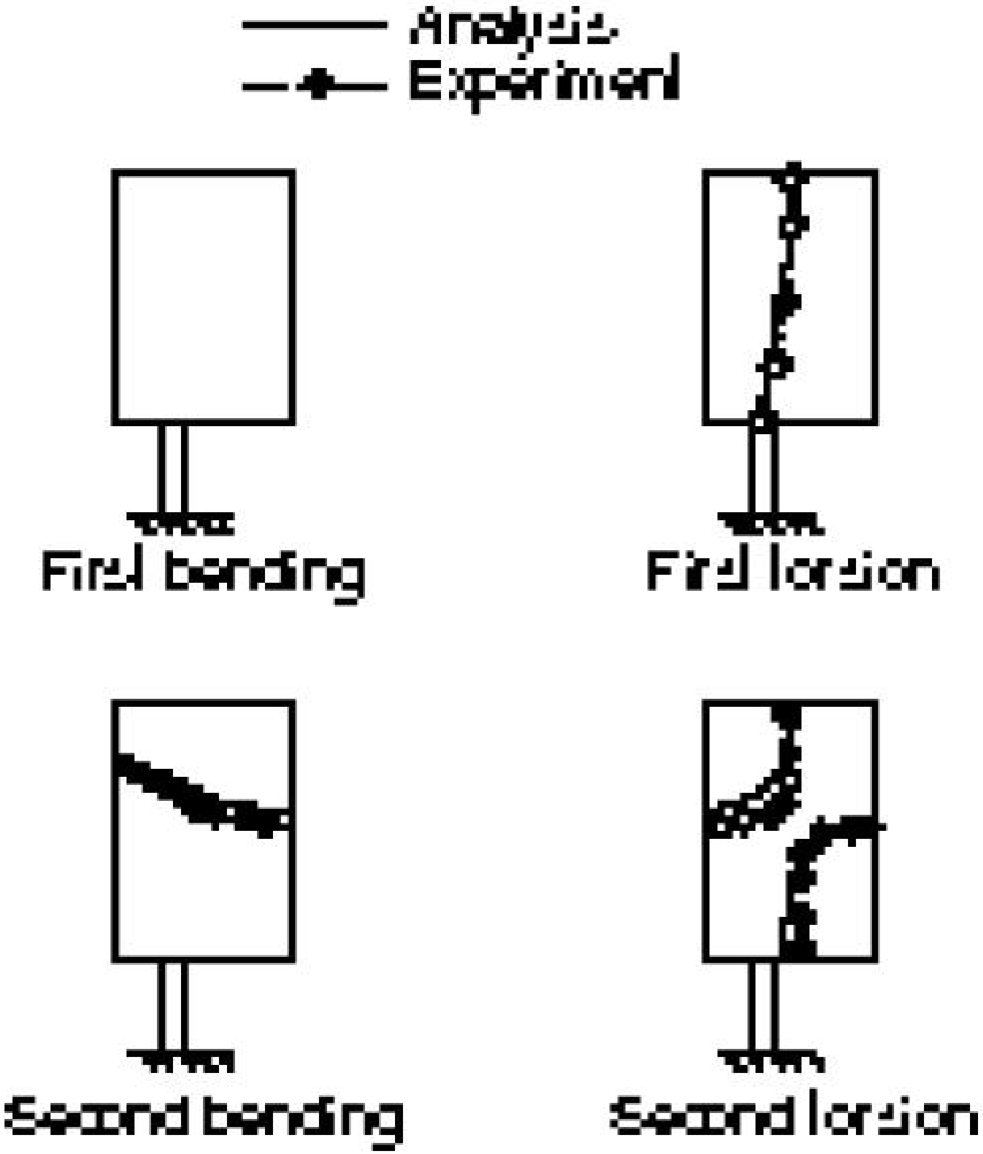
FLUTTER TESTING



SPOILER MOUNTING POSITIONS



NODE LINES



First bending

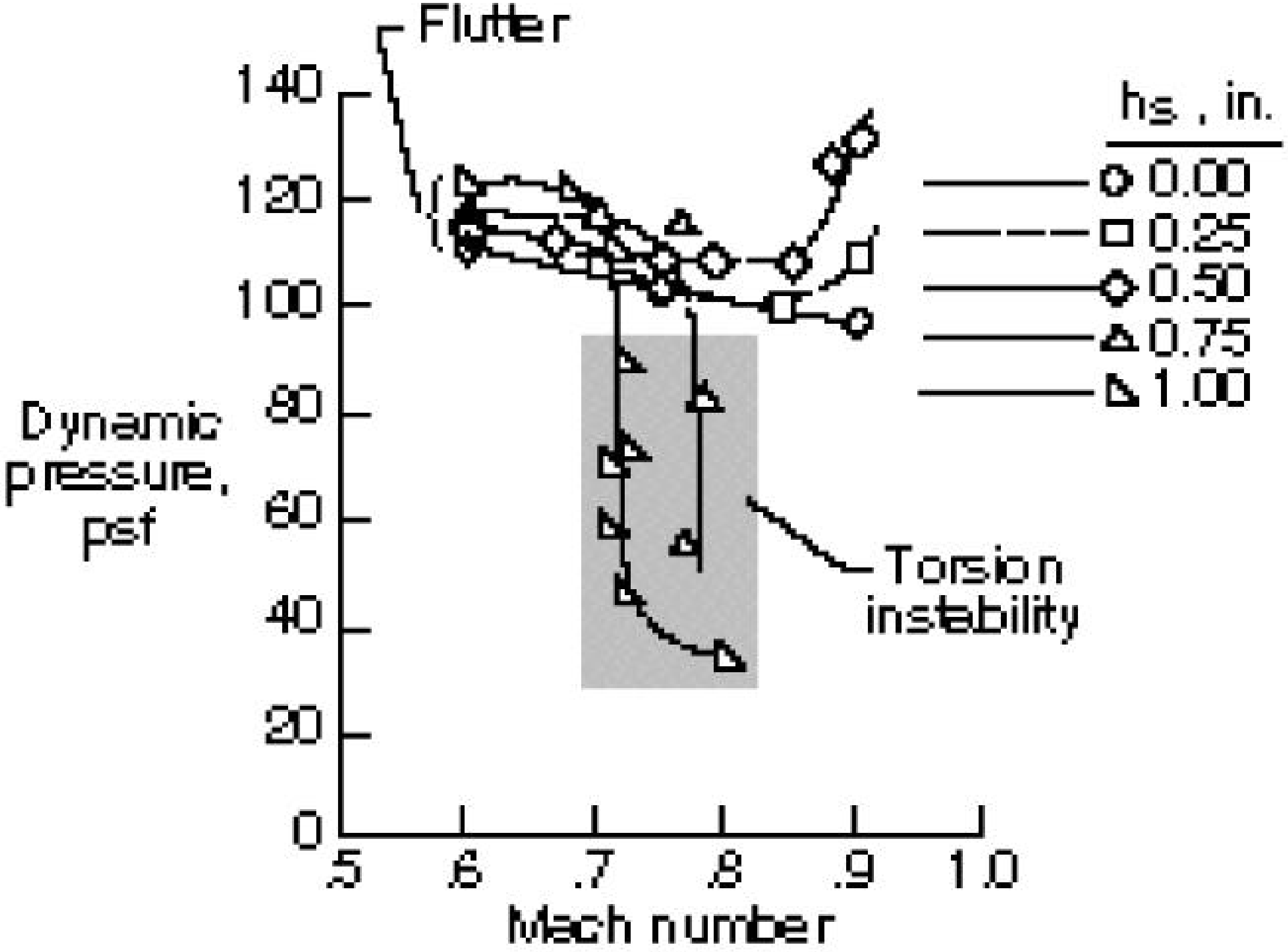
First torsion

Second bending

Second torsion

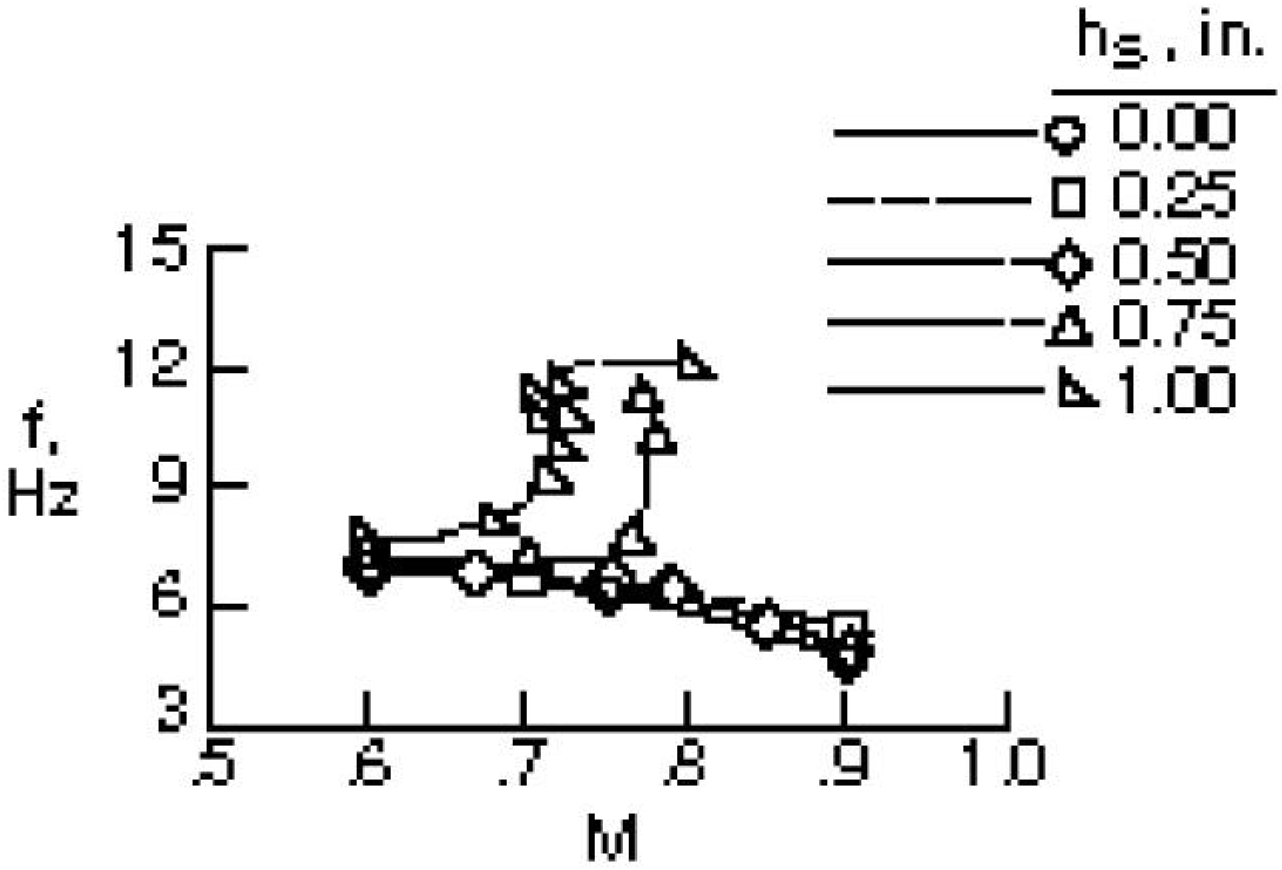
Spoiler height effects

(w=3.0”)



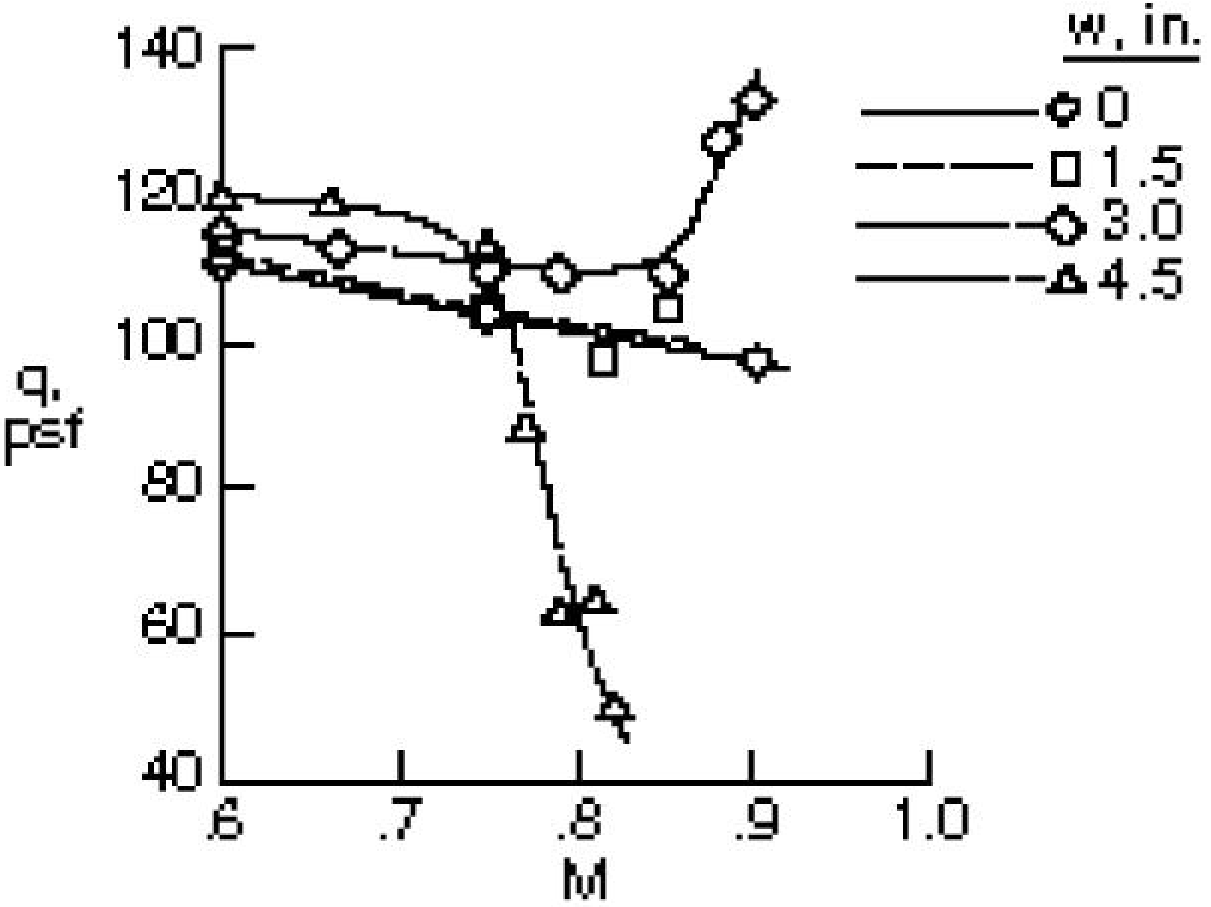
SPOILER HEIGHT EFFECTS

(w=3.0”)



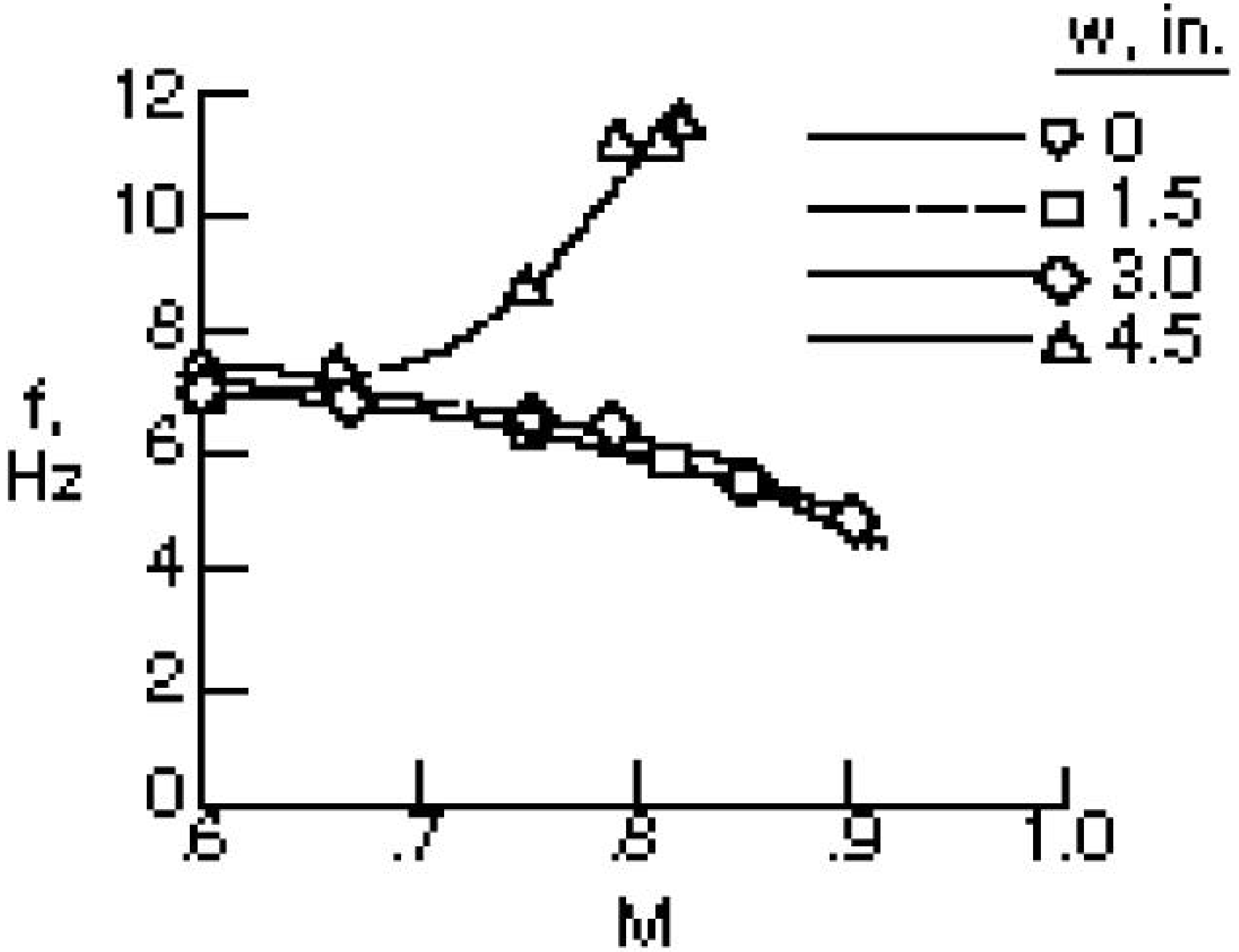
SPOILER WIDTH EFFECTS

(h=0.5”)

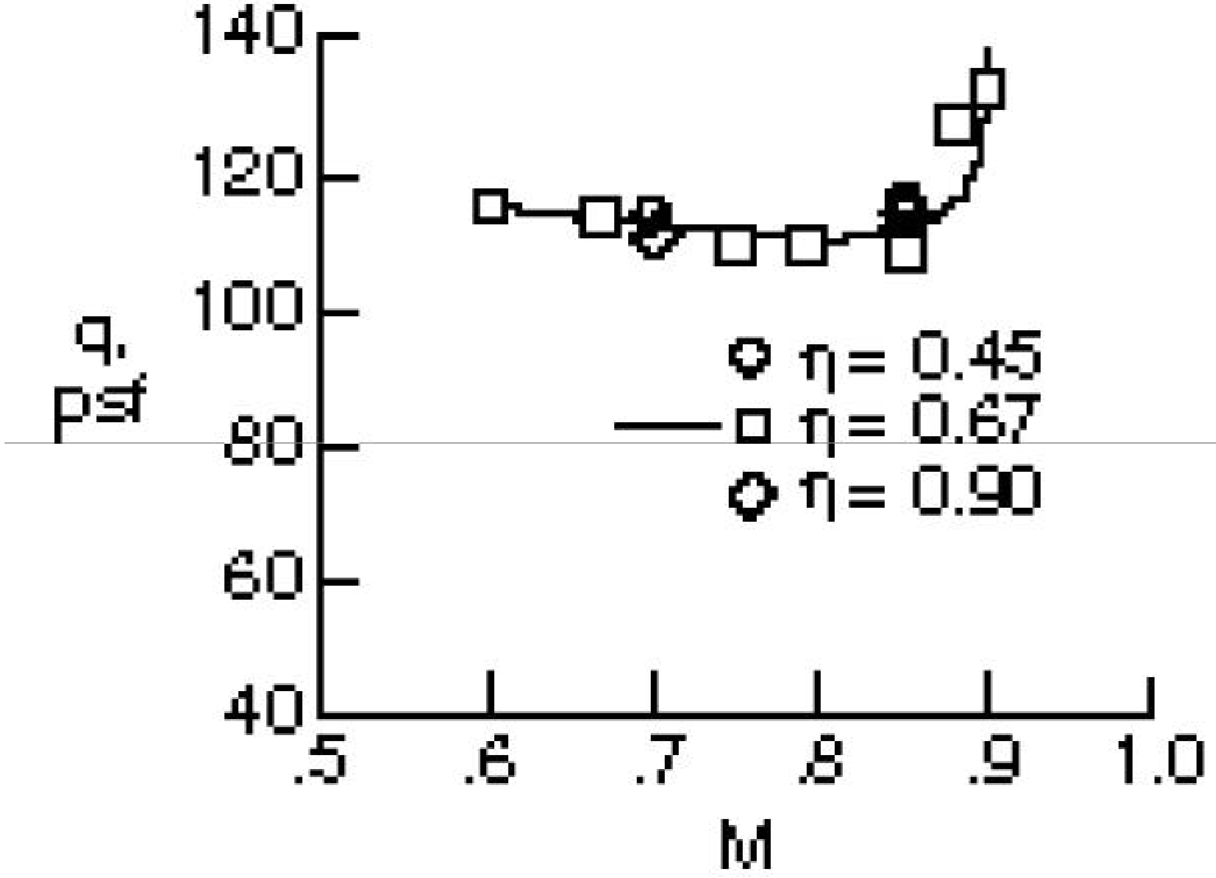


SPOILER WIDTH EFFECTS

(h=0.5”)

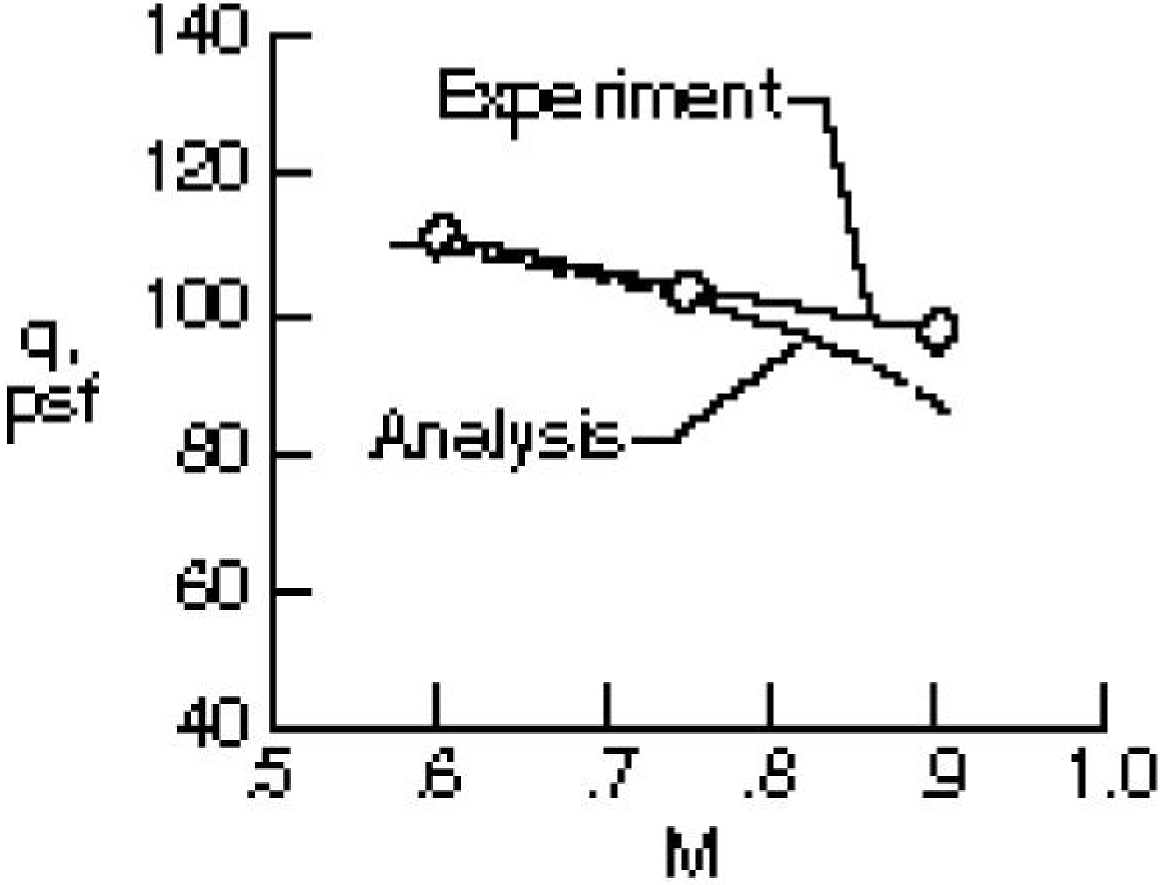


SPOILER LOCATION EFFECTS

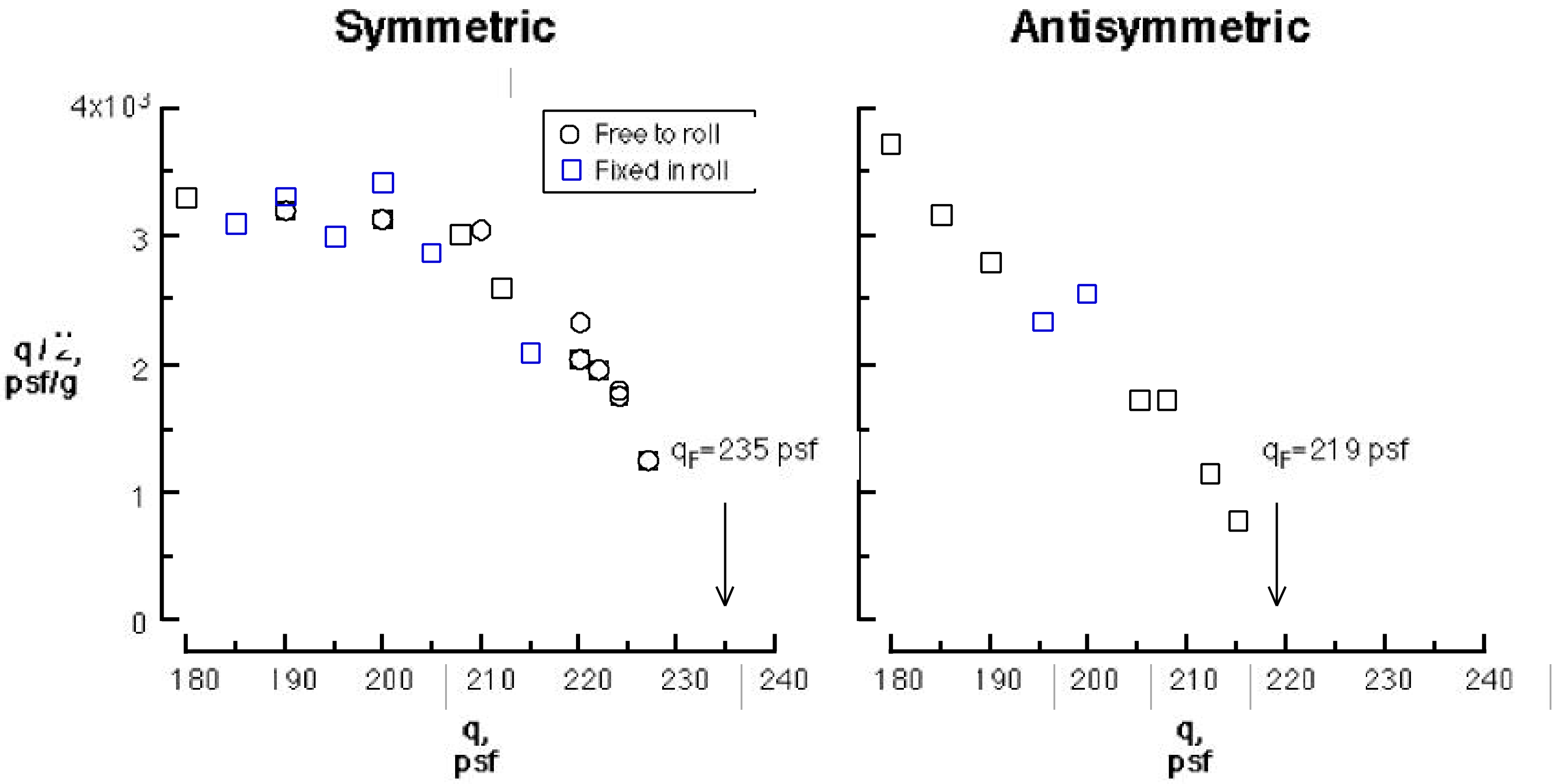


FLUTTER RESULTS COMPARISON

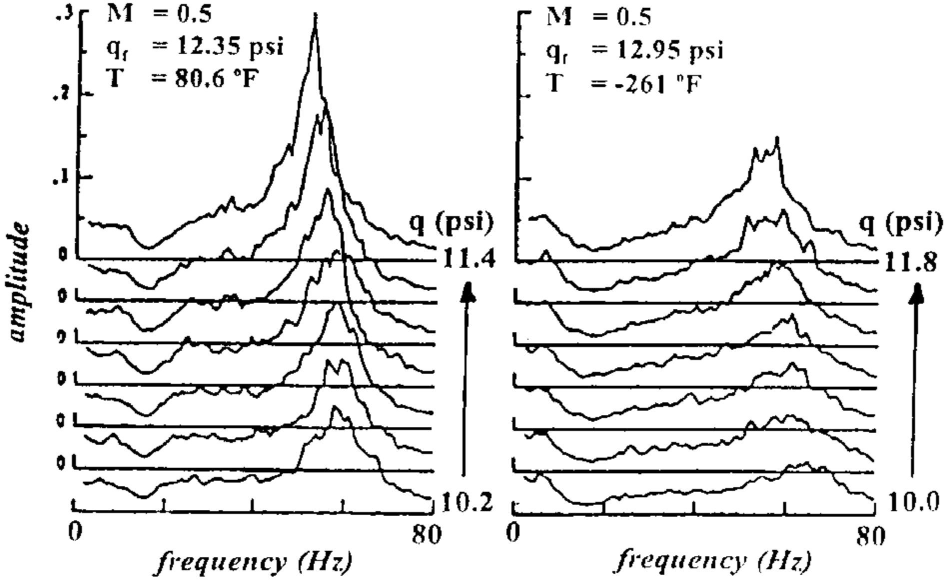
(Clean wing)

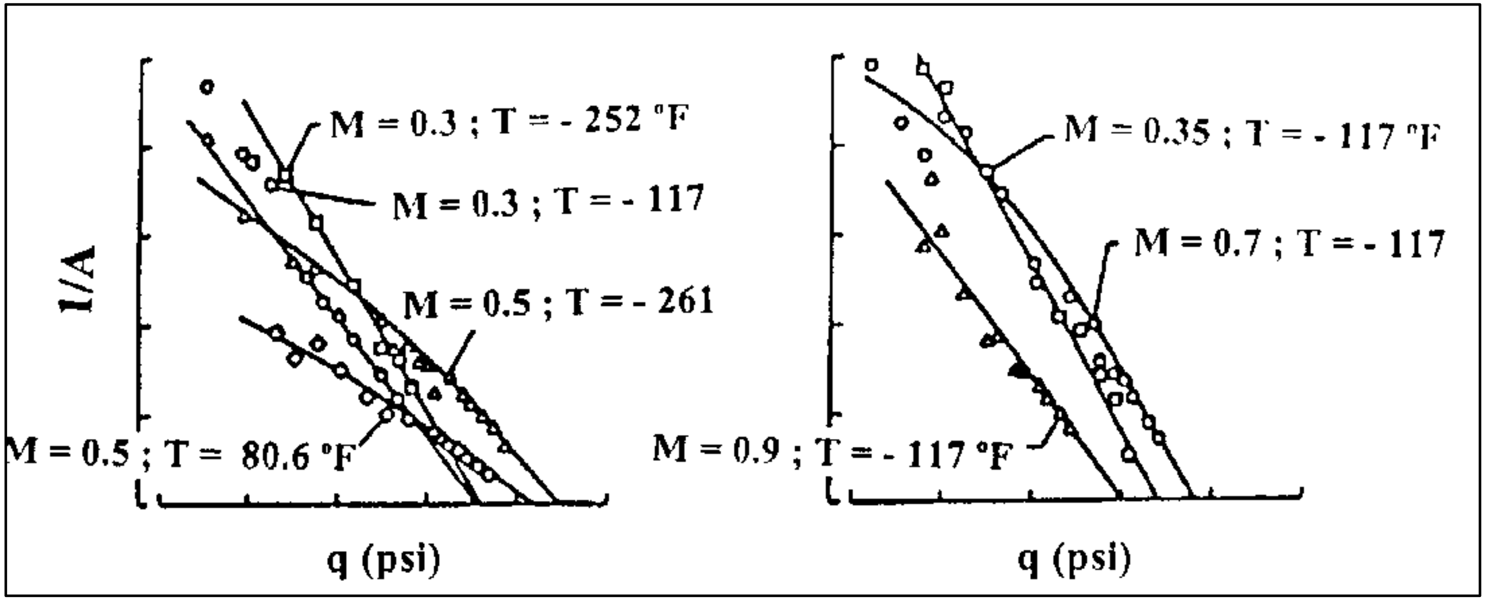


FLUTTER SUBCRITICAL RESPONSE TECHNIQUES

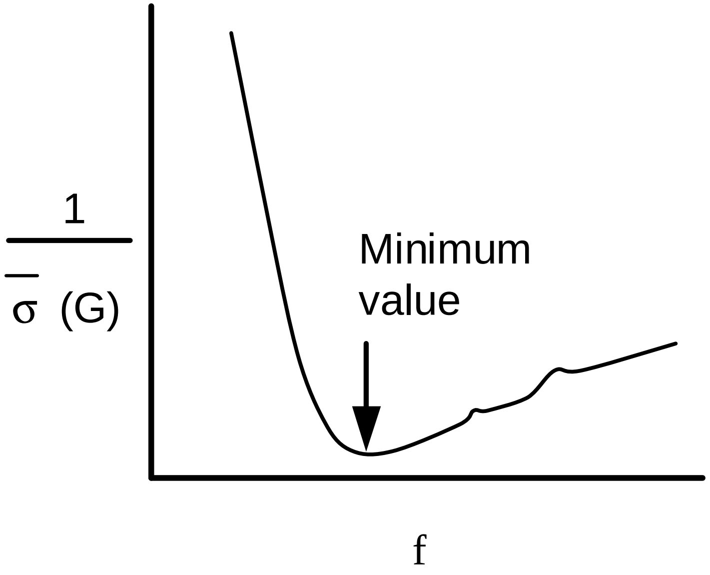


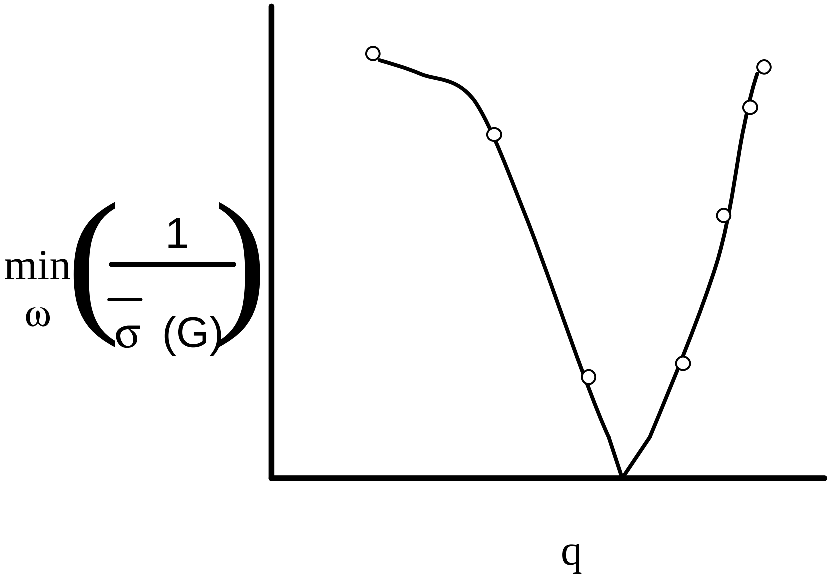
SUBCRITICAL RESPONSE





MIMO FLUTTER INSTABILITY PREDICTION





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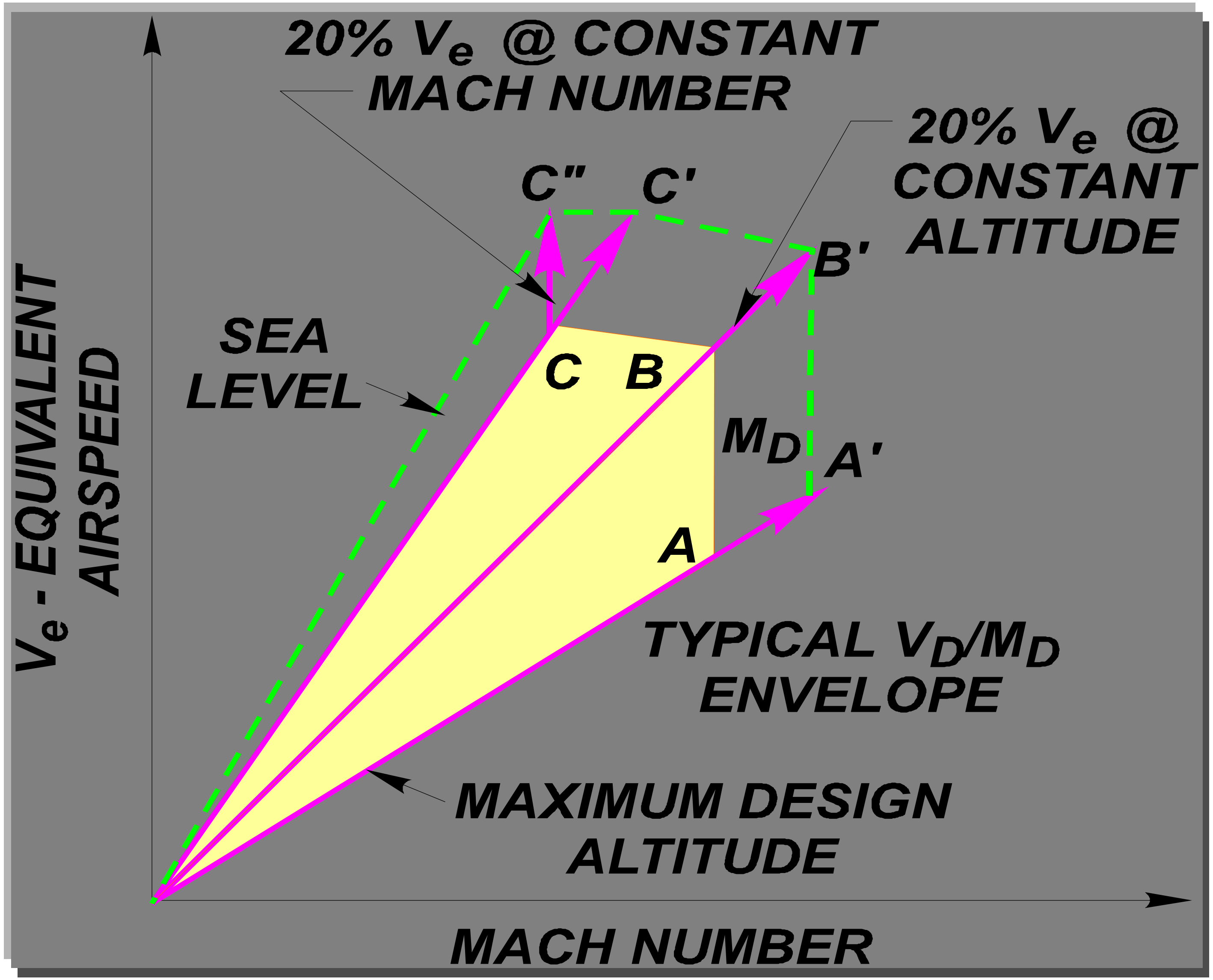
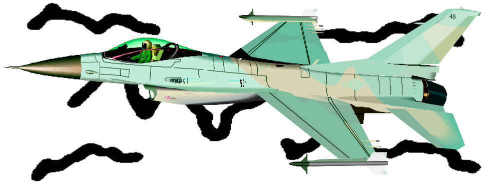
CLEARANCE REQUIREMENTS

- **Construction of flutter envelopes are described in AC 25.629.1**

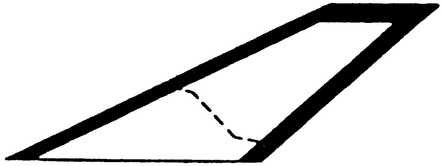


FLUTTER : FLIGHT TEST METHODS

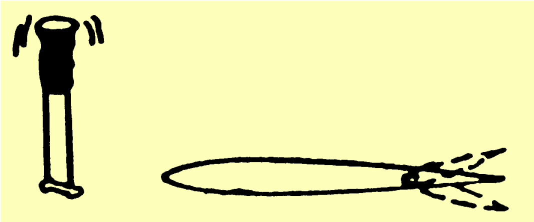
- **Several Methods Exist to Excite Structural Modes During Flight Tests**



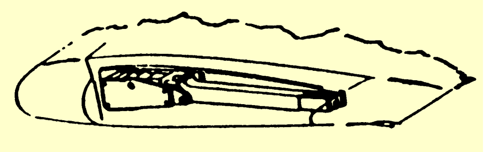
Amospheric Turbulence



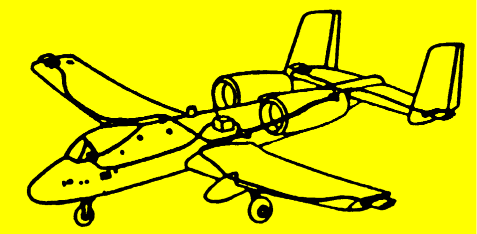
Planform Modification



Pilot Induced Oscillations



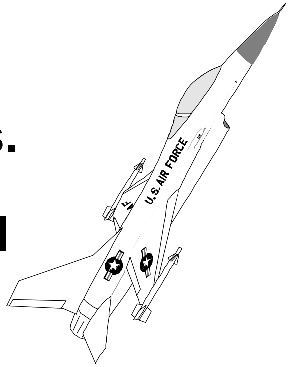
Inertia Exciter



Control System Input

Pyrotechnic Bonker

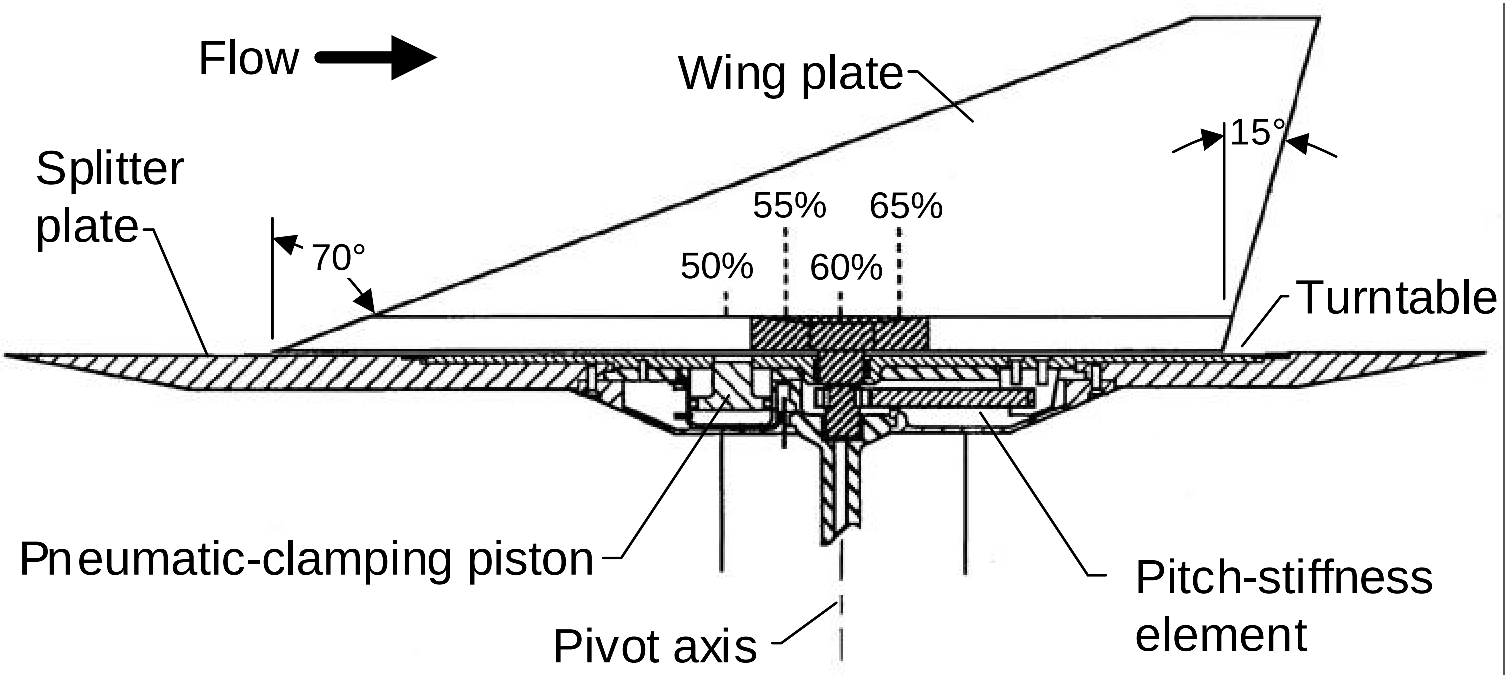
FLIGHT FLUTTER TESTING



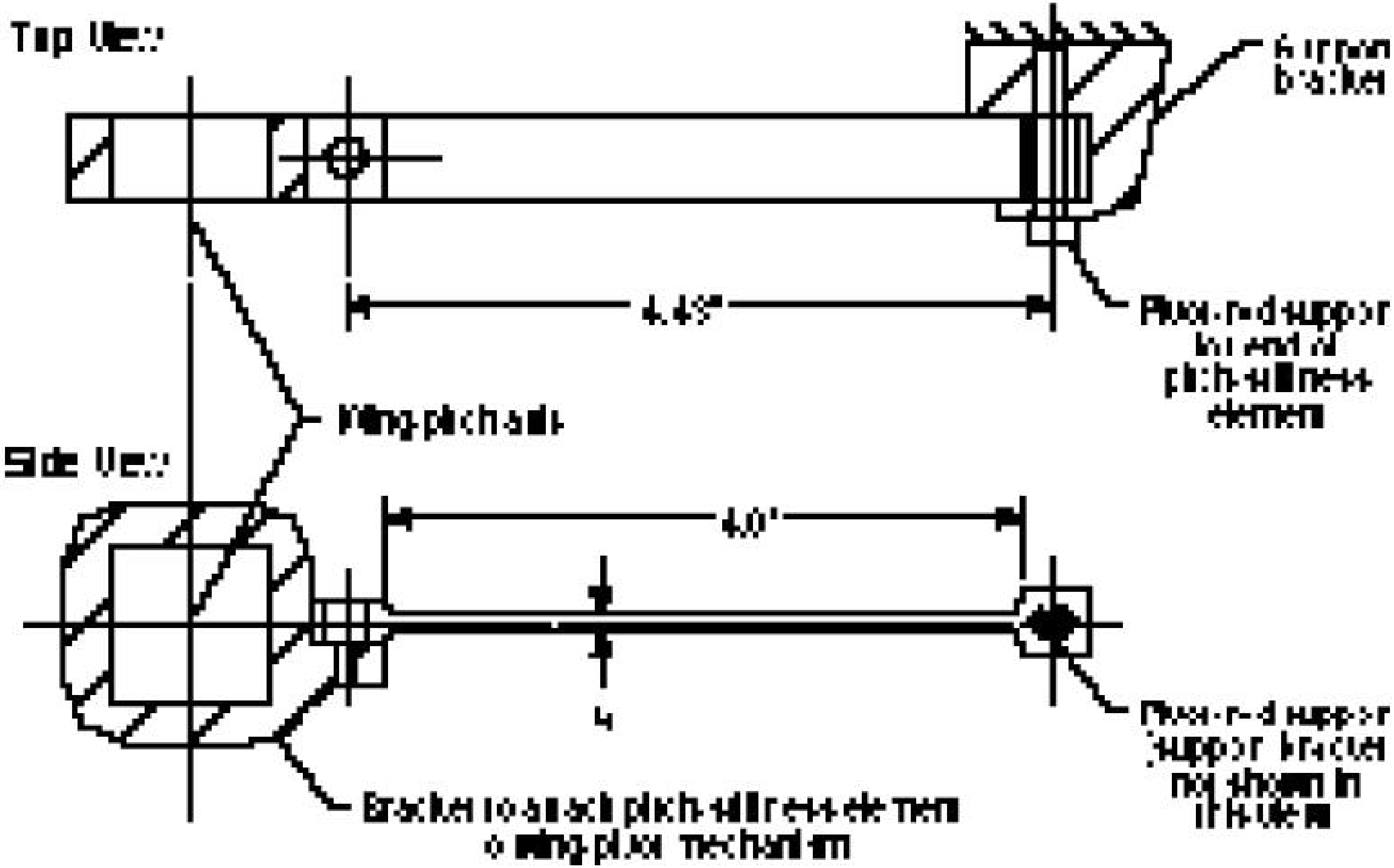
Dives are used to attain higher airspeeds and dynamic pressures.

- **An altitude band of approximately ±1000 feet near the nominal test condition is suggested.**
  - Sweep rate may be changed to complete test within the altitude band.
  - Large dive angles may not permit completion of the sweep.
  - Averages of data can be obtained, but several passes through the band may be required for a statistically significant data set.
- **Test points flown in a dive with excitation done by the pilot are usually applied about one axis at a time.**
- **Frequency dwells may be performed in a dive if a suitable forced excitation system is installed.**
- **Care must be taken in dive procedures to guarantee that airspeed increments are controlled.**

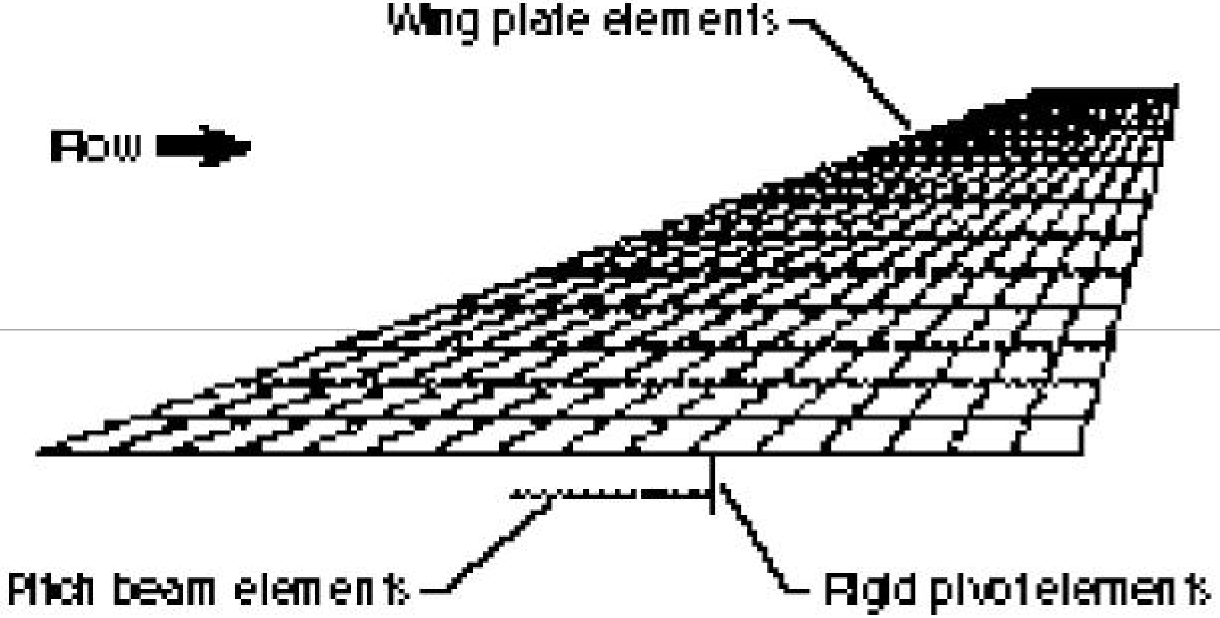
SUPERSONIC DIVERGENCE MODEL



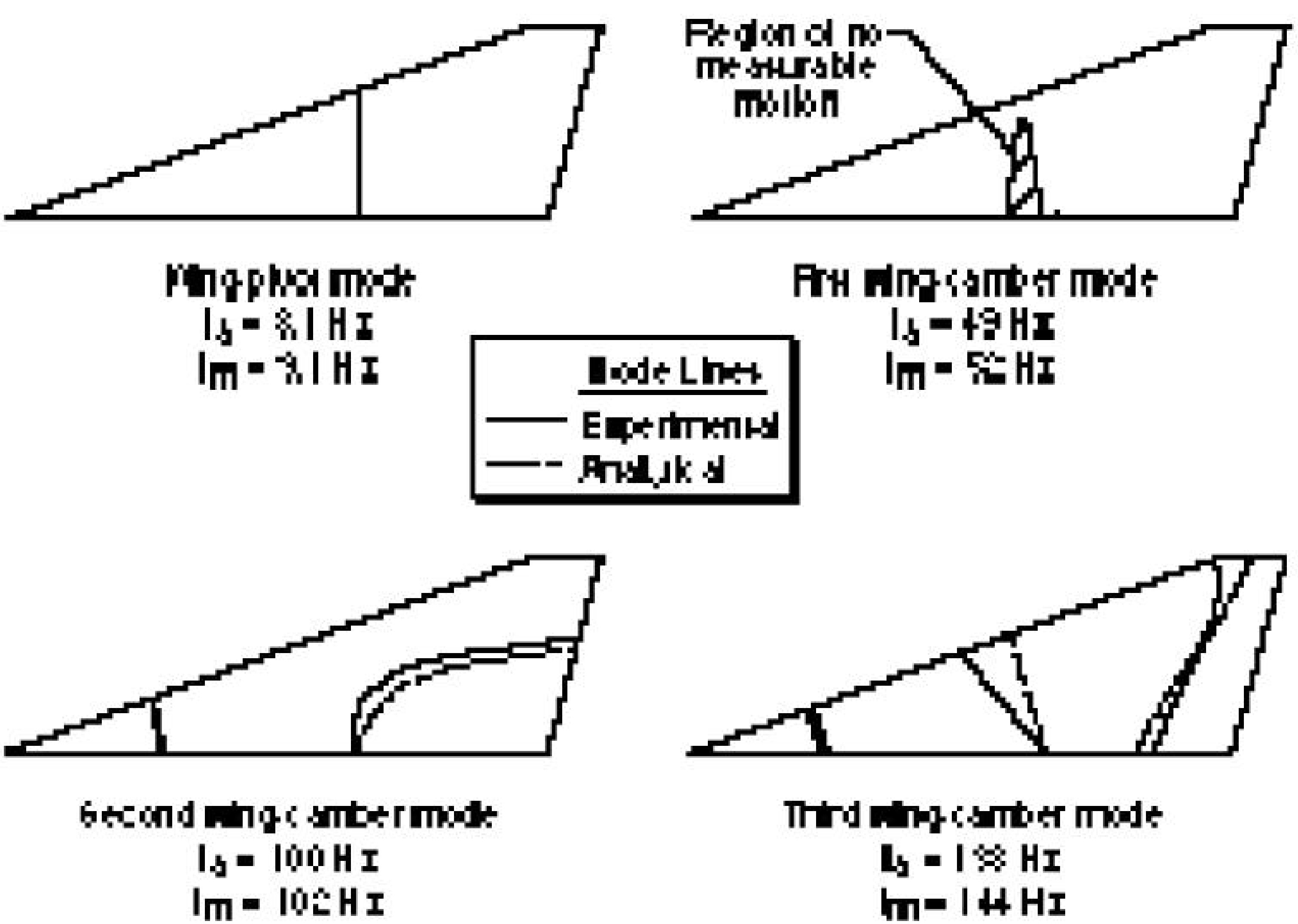
PITCH STIFFNESS ELEMENTS



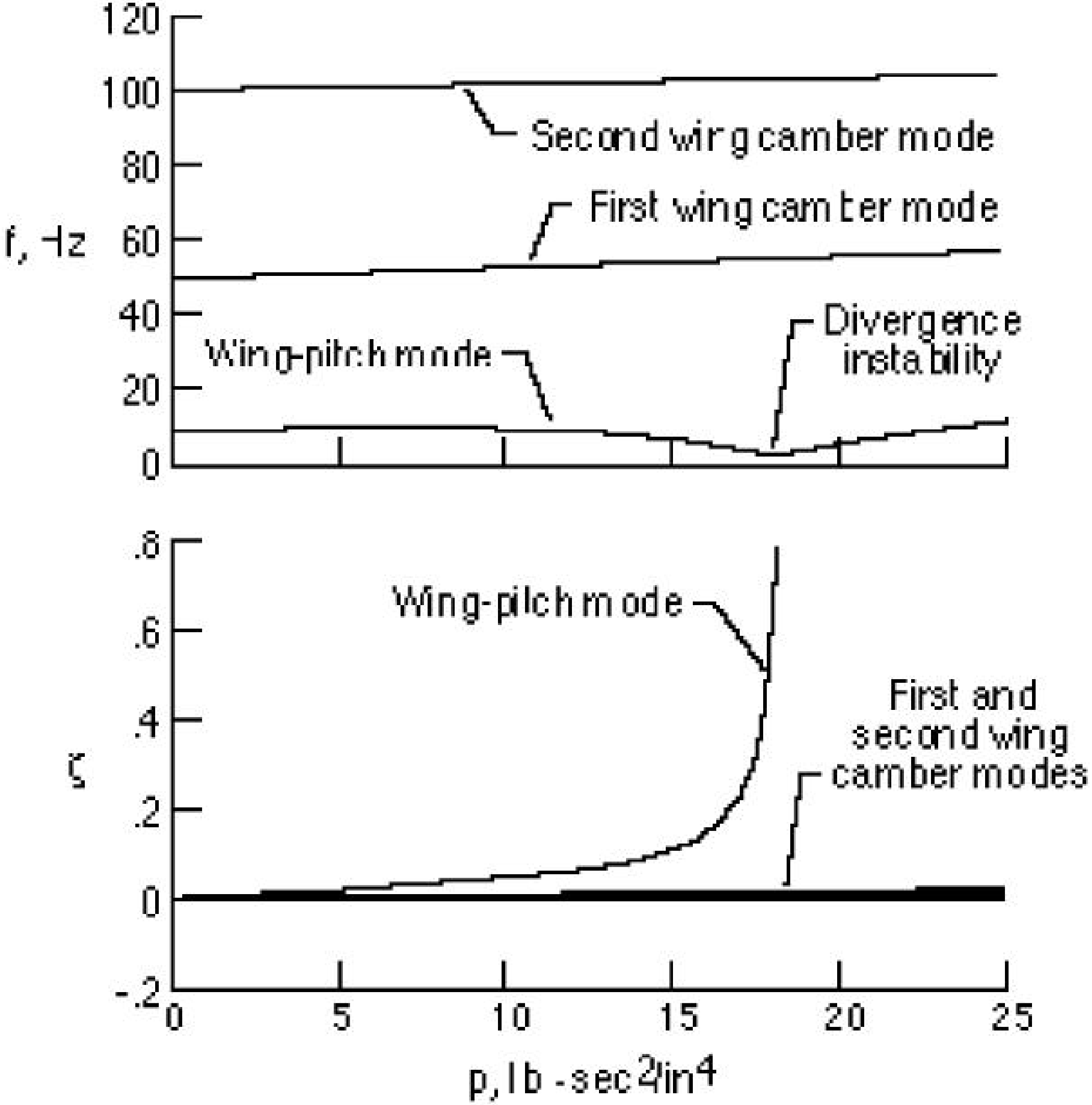
FINITE ELEMENT MODEL



STRUCTURAL DYNAMIC PROPERTIES



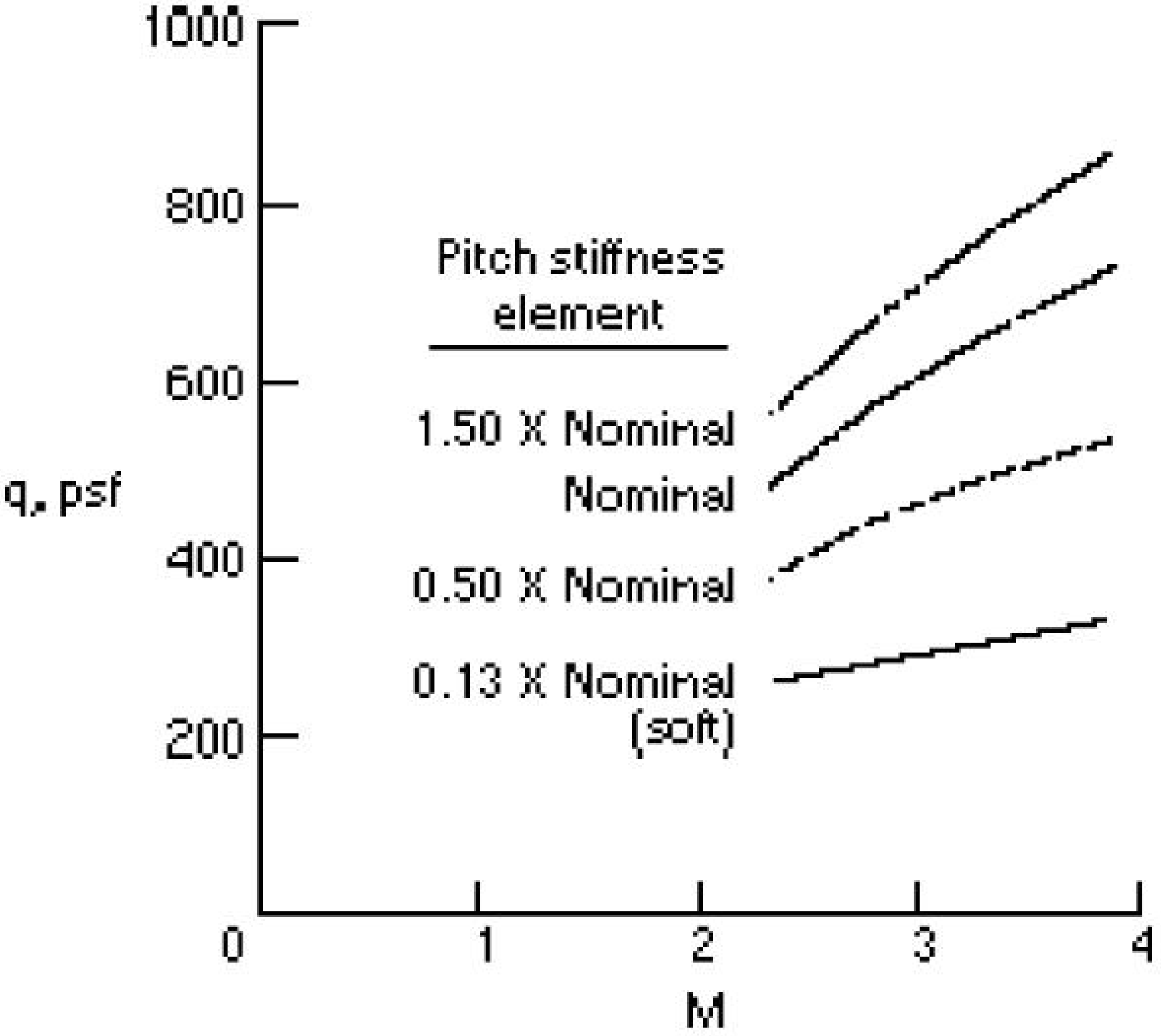
TYPICAL ANALYSIS RESULTS



ANALYTICAL DIVERGENCE BOUNDARIES

Pitch stiffness effects

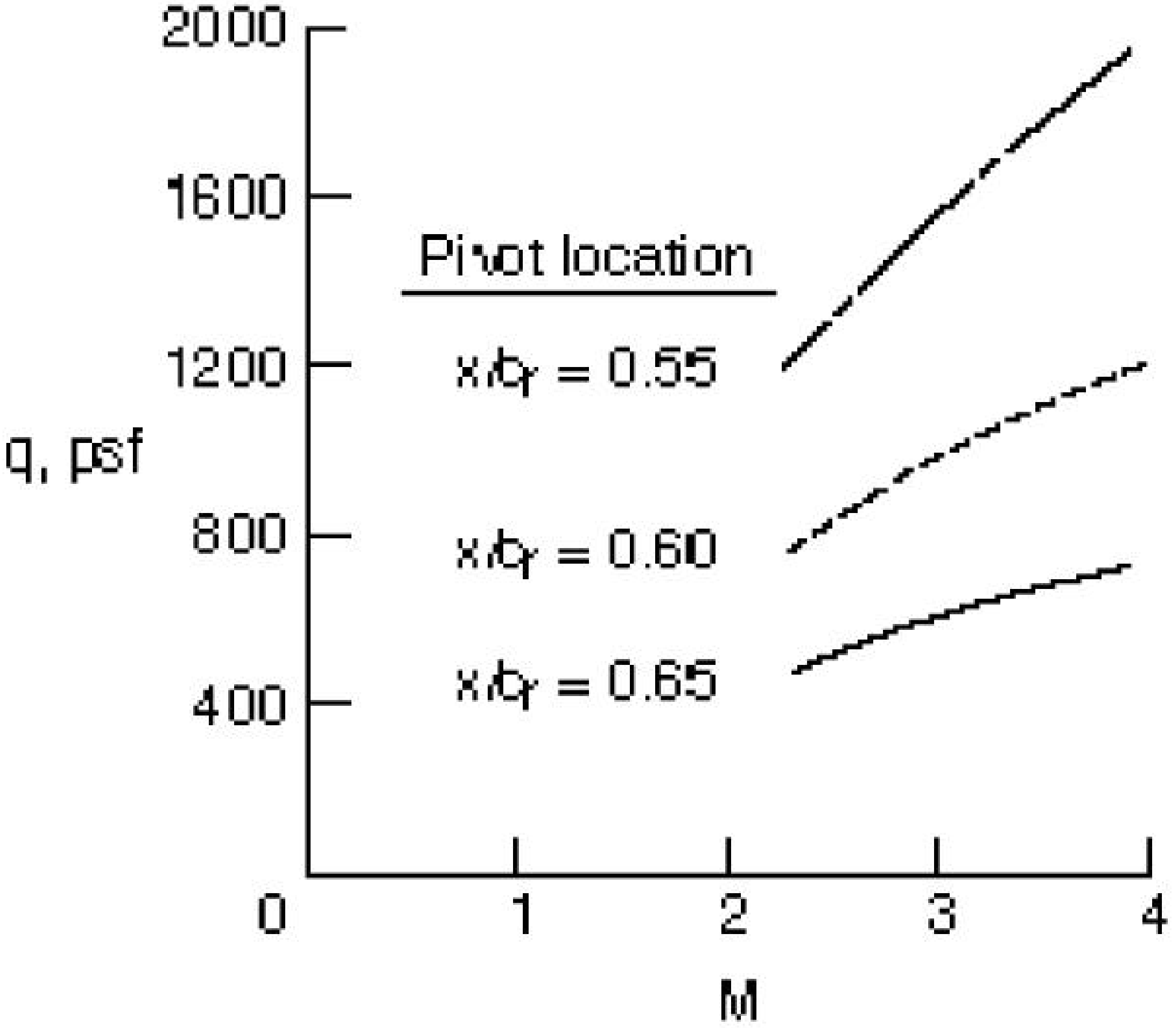
(4% think airfoil, pivot at x/c=0.65)



ANALYTICAL DIVERGENCE BOUNDARIES

Pitch-pivot location effects

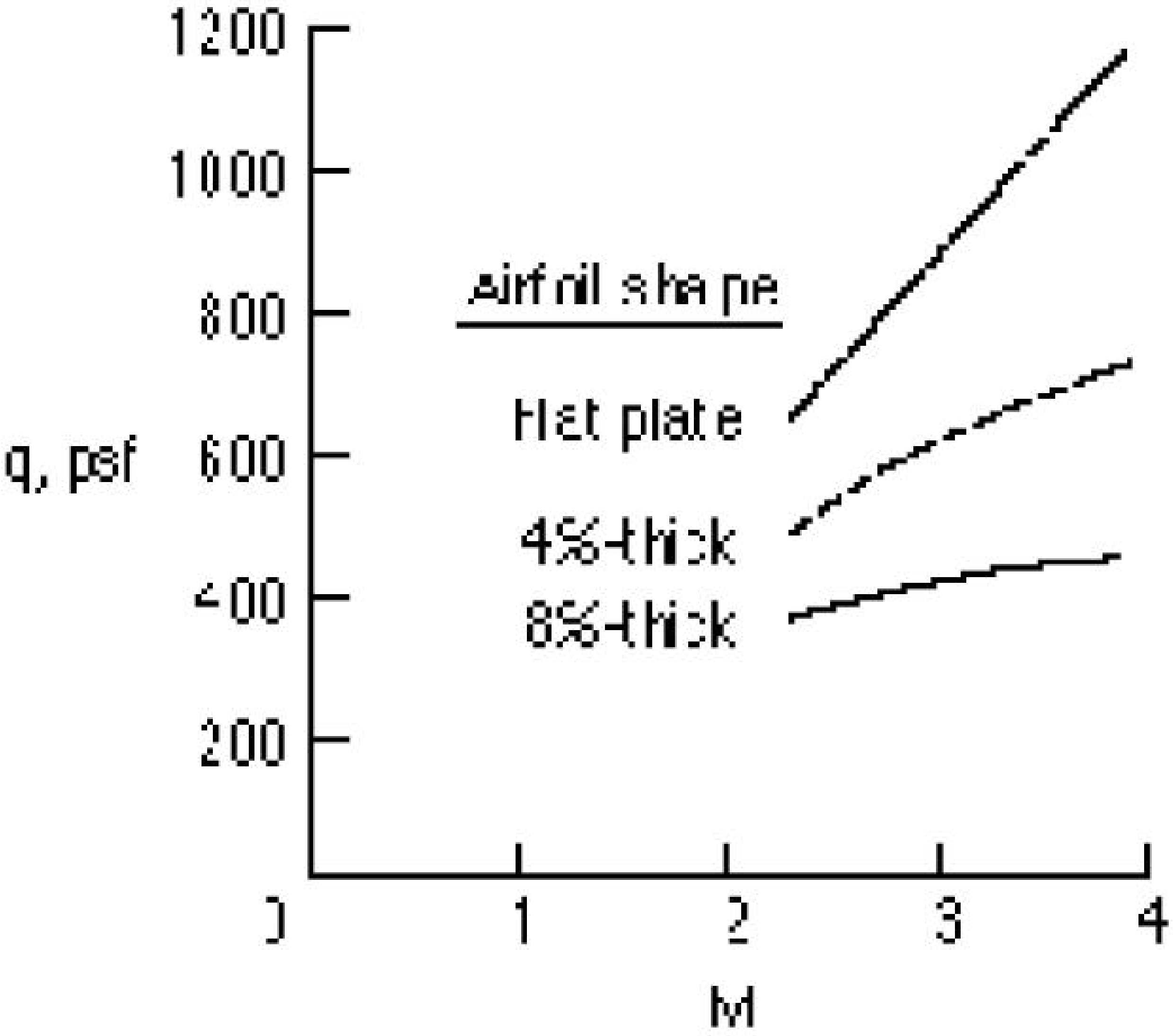
(4% think airfoil, nominal pitch stiffness)



ANALYTICAL DIVERGENCE BOUNDARIES

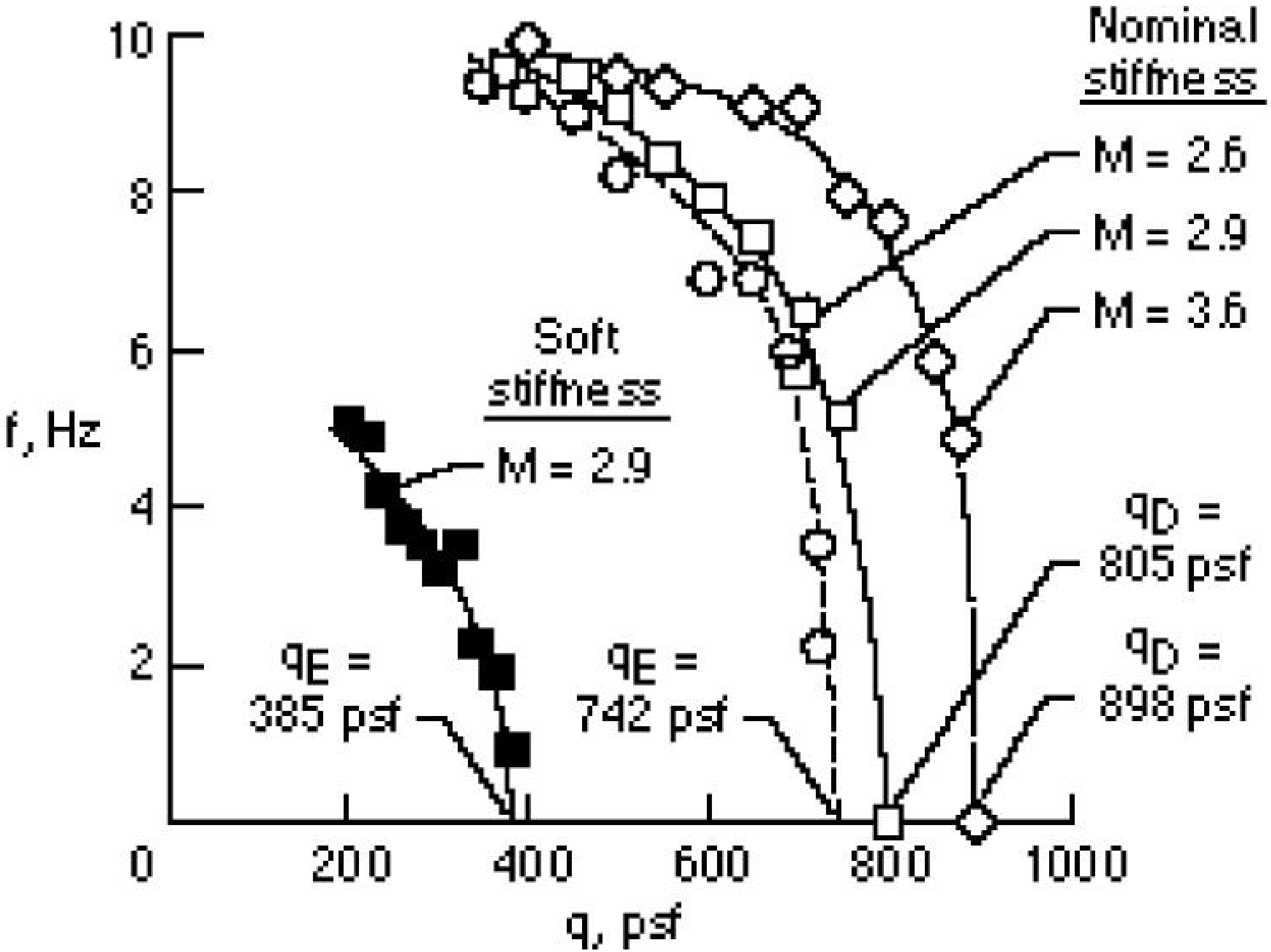
Airfoil thickness effects

(Nominal pitch stiffness, pivot at x/c=0.65)



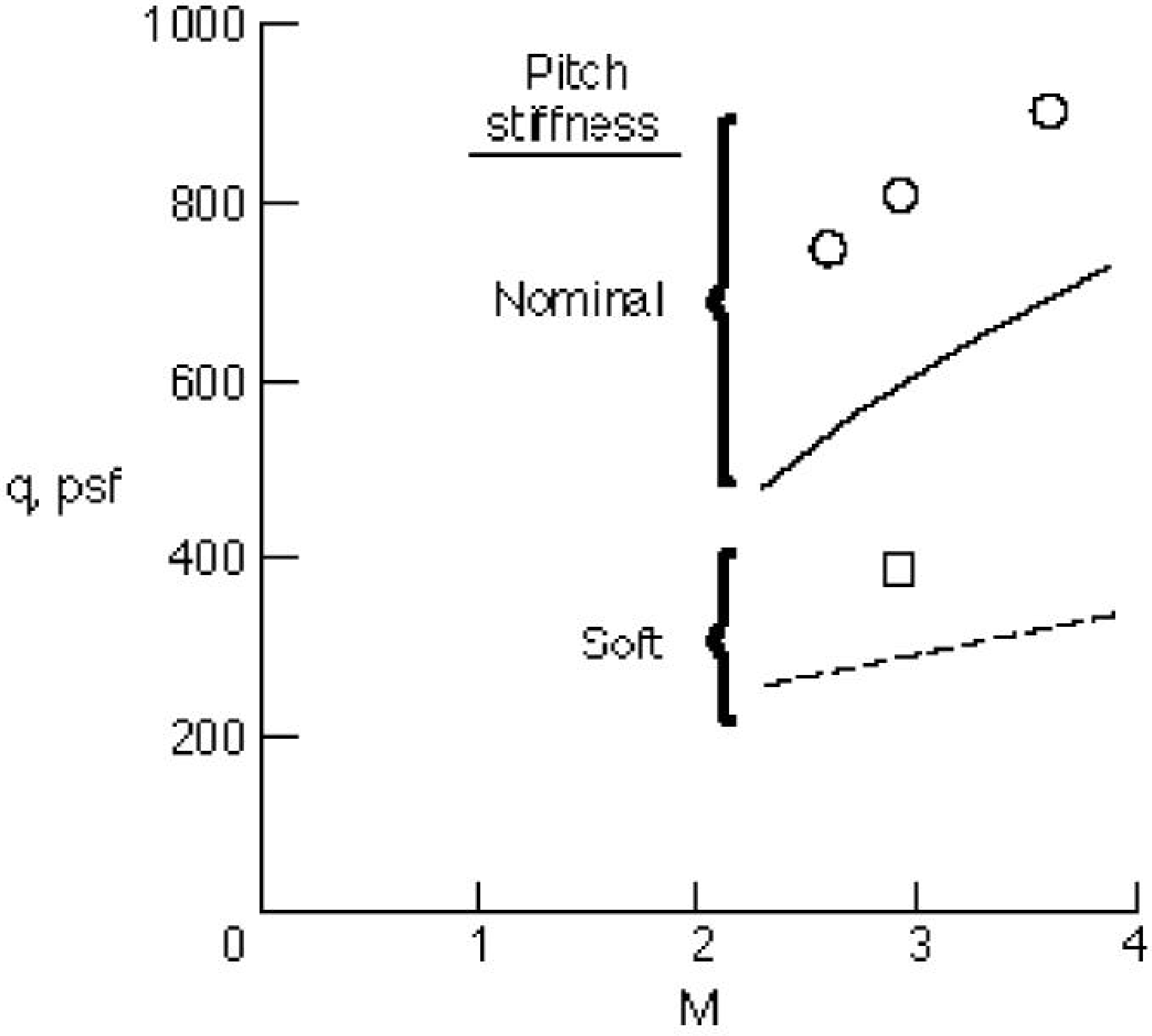
SUBCRITICAL RESPONSE MEASUREMENTS

(4% think airfoil, pivot at x/c=0.65)

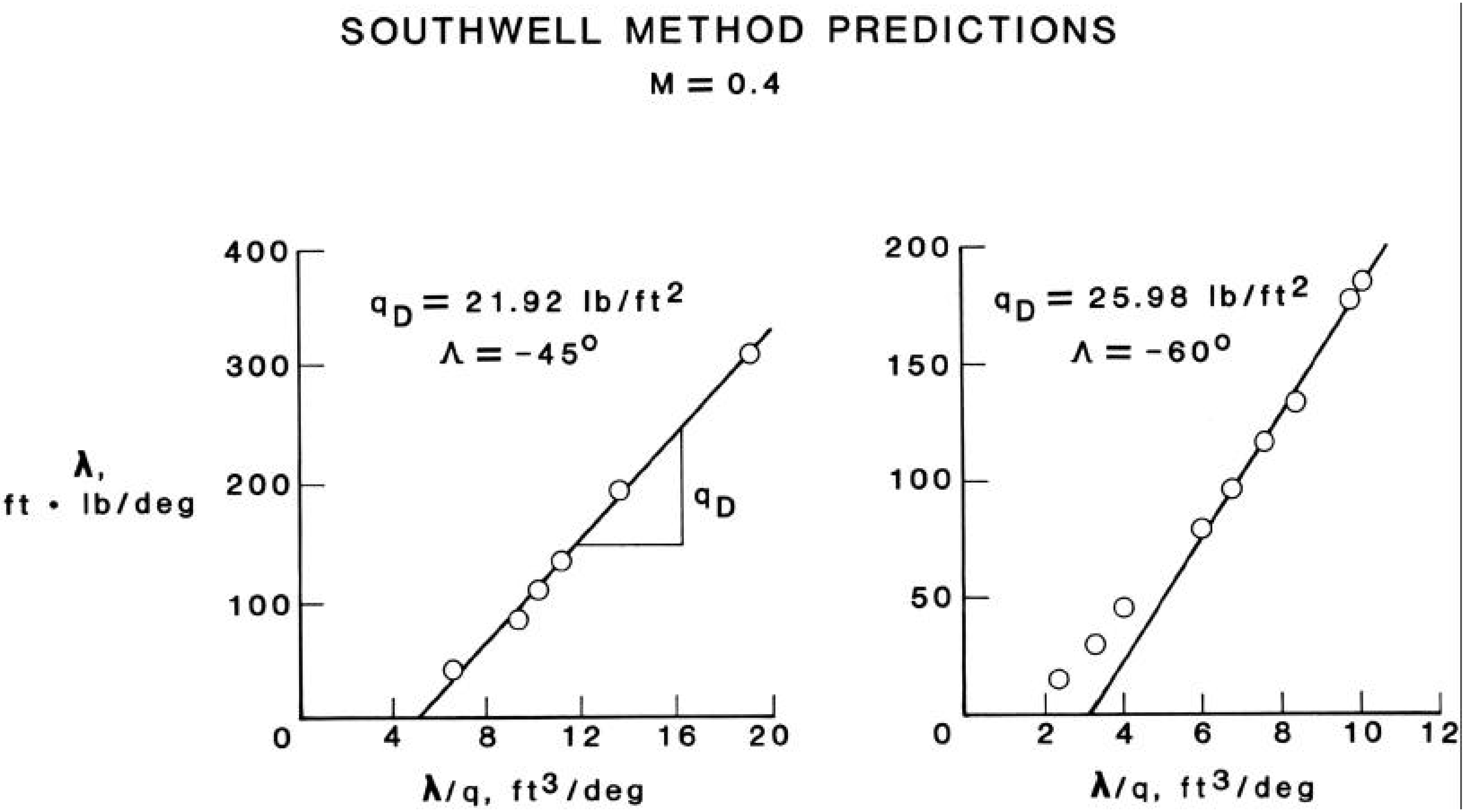


SUPERSONIC DIVERGENCE RESULTS

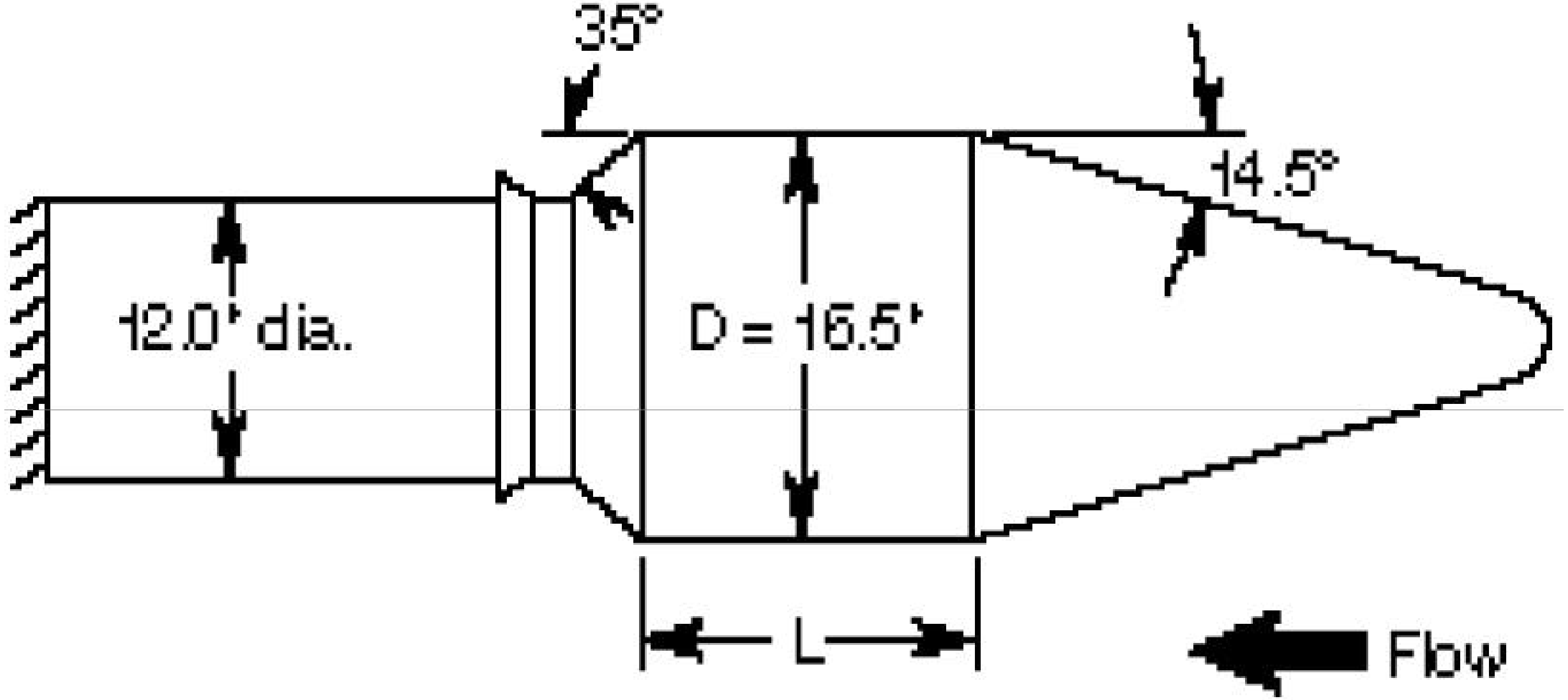
(4% think airfoil, pivot at x/c=0.65)



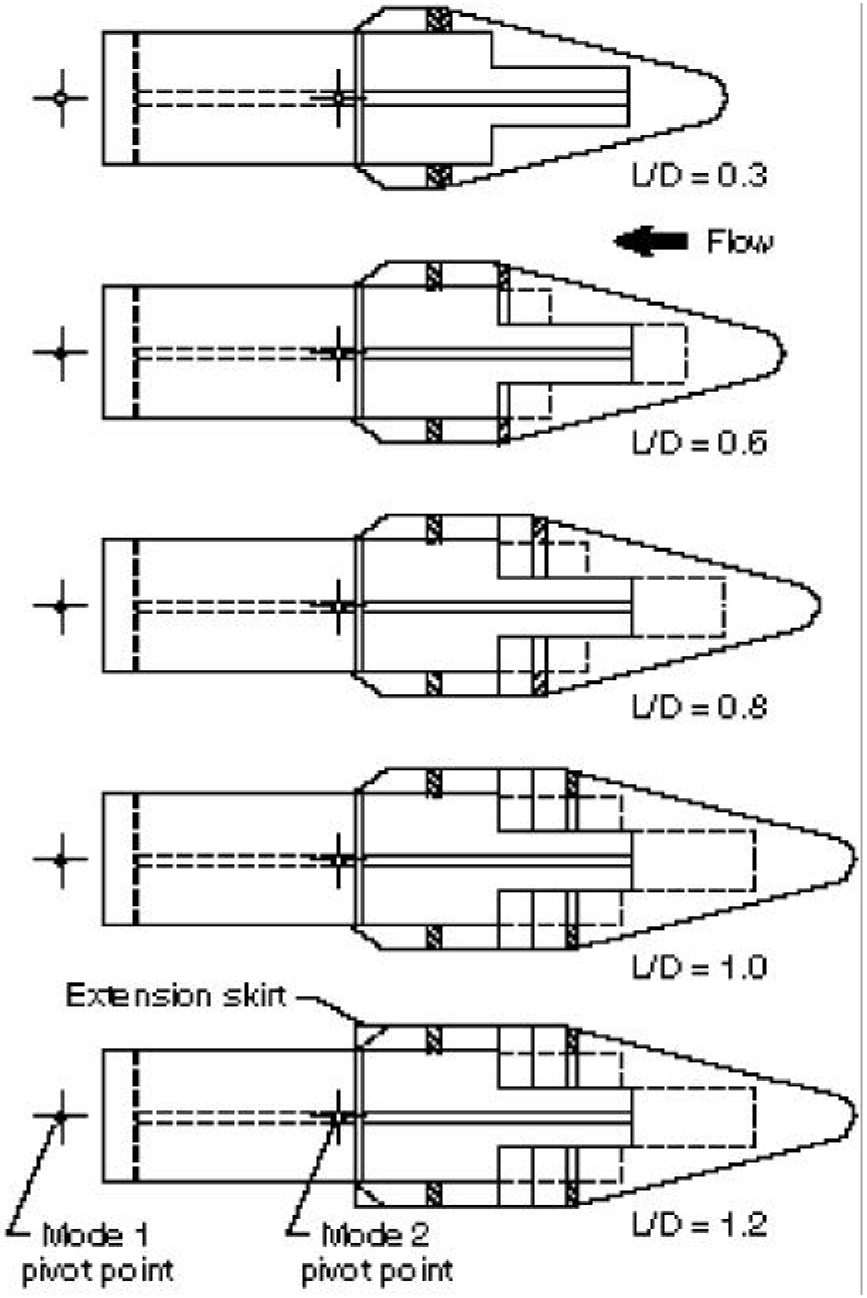
DIVERGENCE PREDICTION



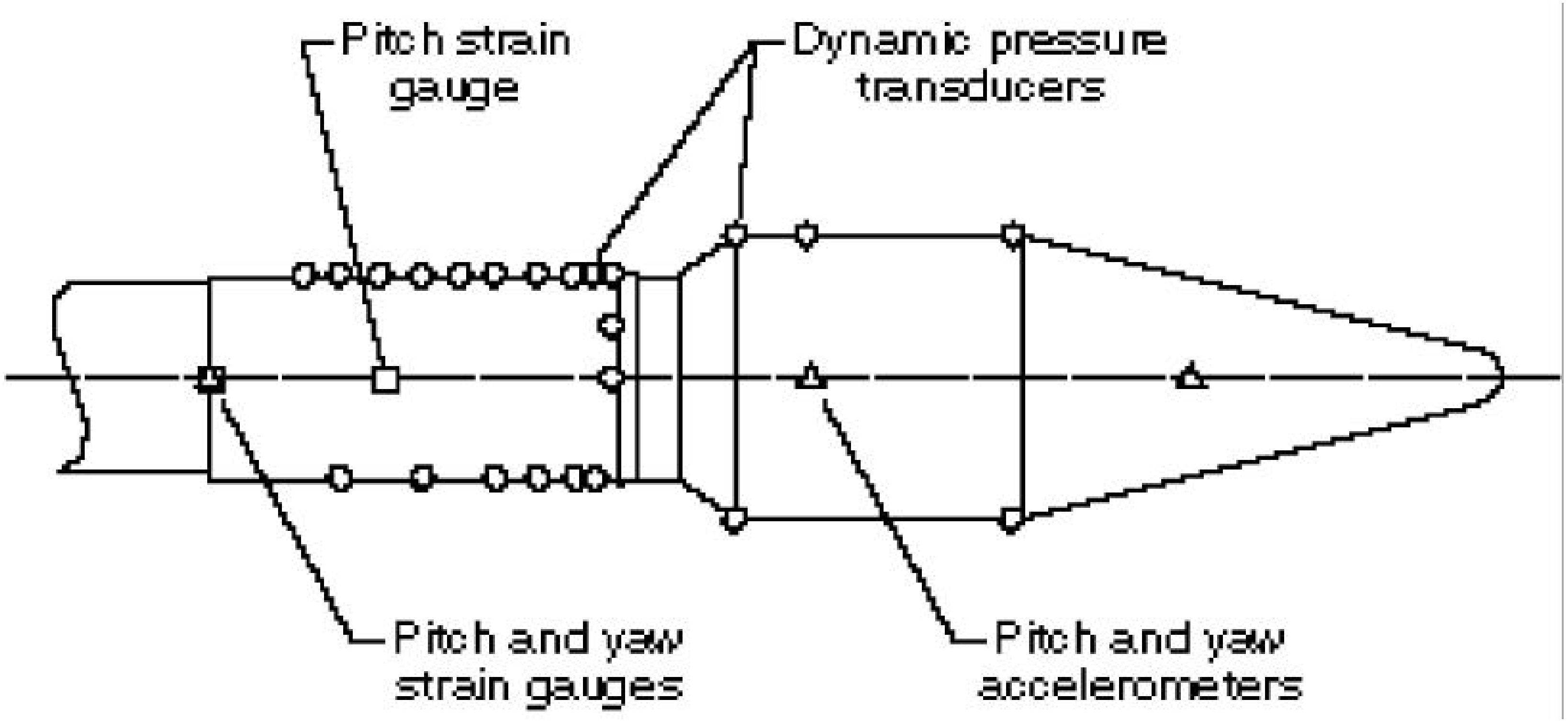
DRAWING OF ATLAS-I LPF MODEL



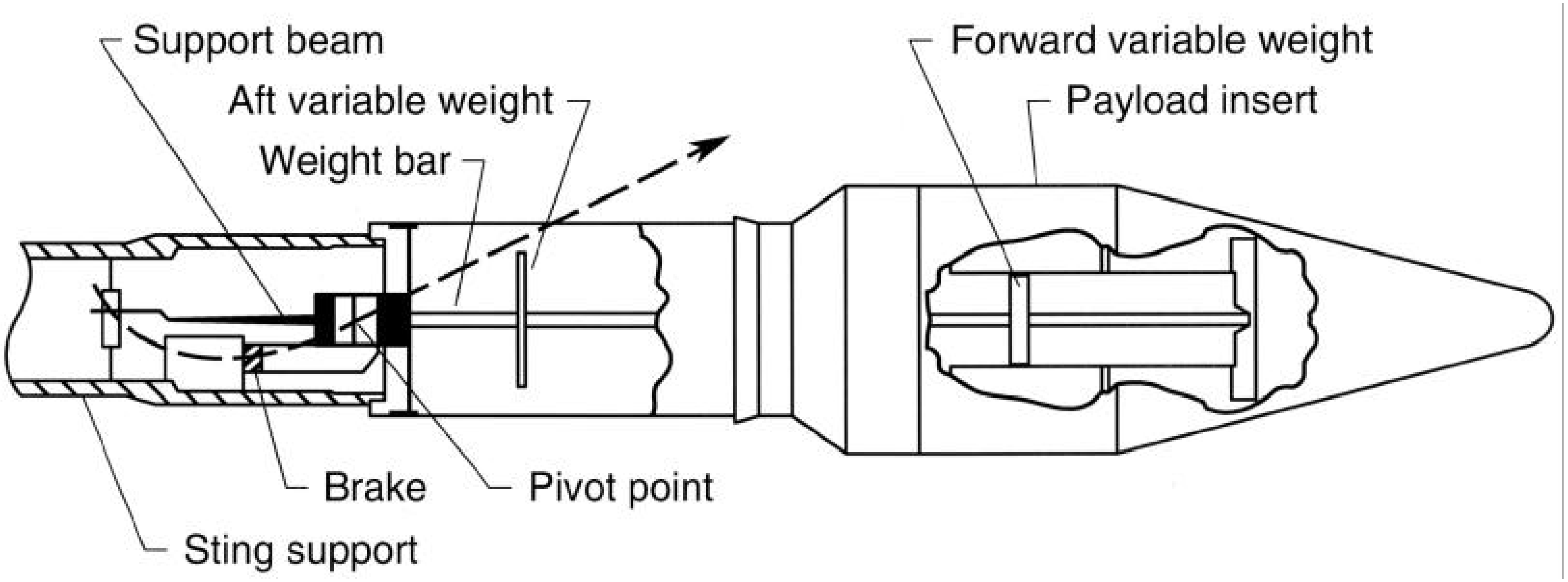
L/D CONFIGURATIONS



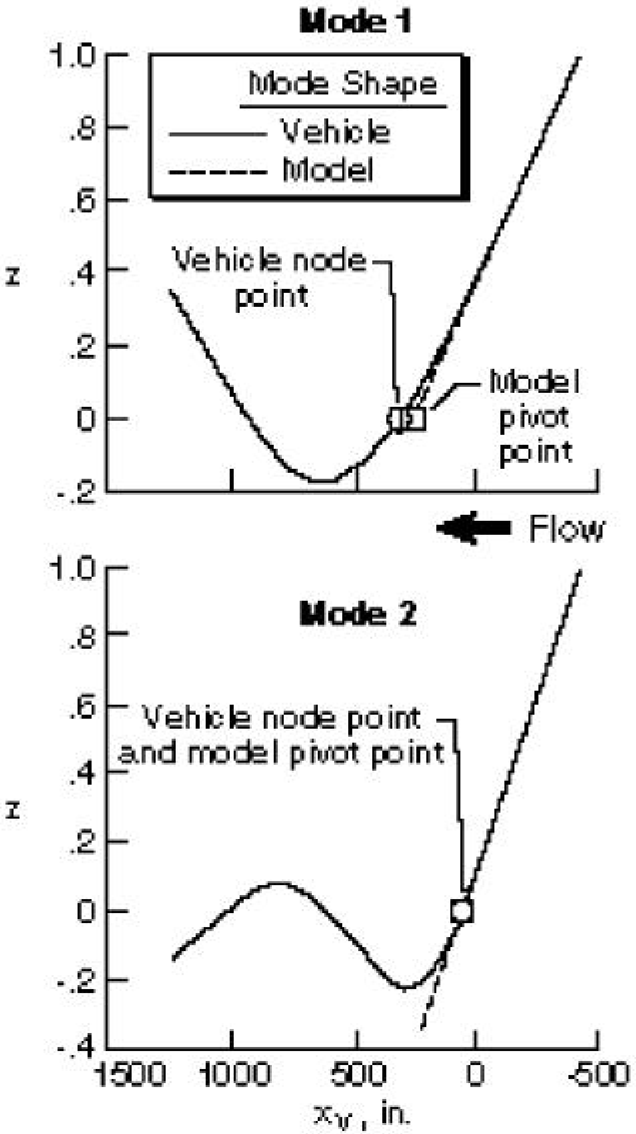
MODEL INSTRUMENTATION



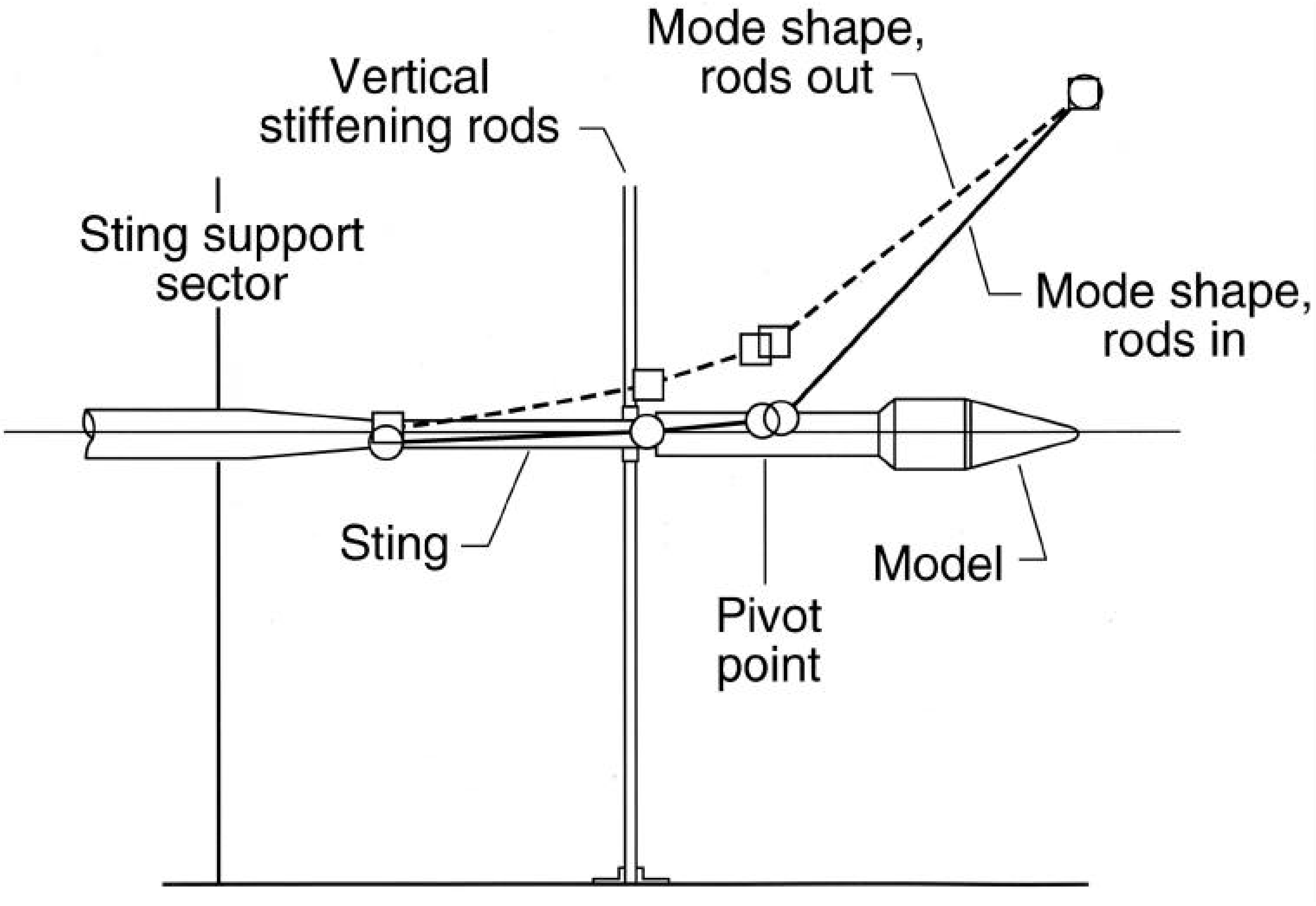
ATLAS-CENTAUR SIMULATION



DESIGN PHILOSOPHY

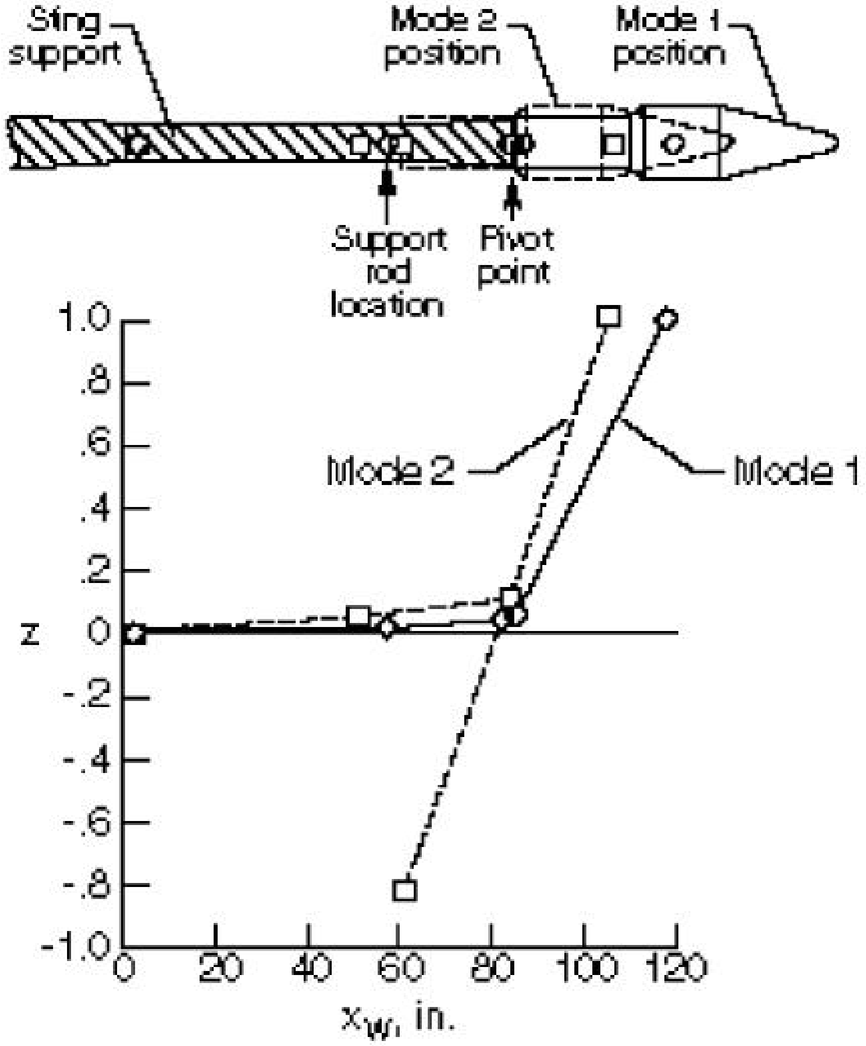


ATLAS-CENTAUR STIFFENING RODS



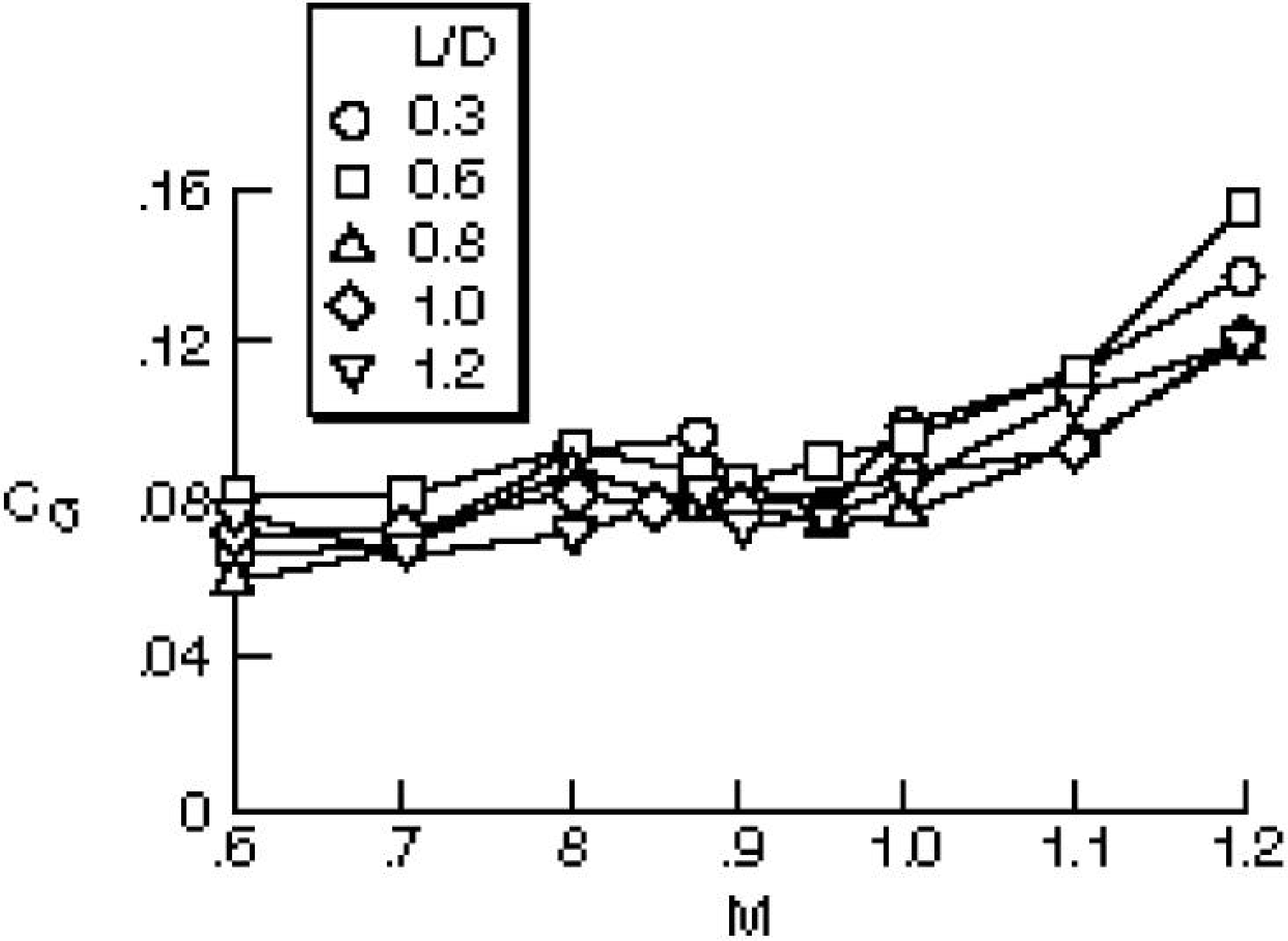
NORMALIZED MODE SHAPES

Vertical Stiffening Rods Installed



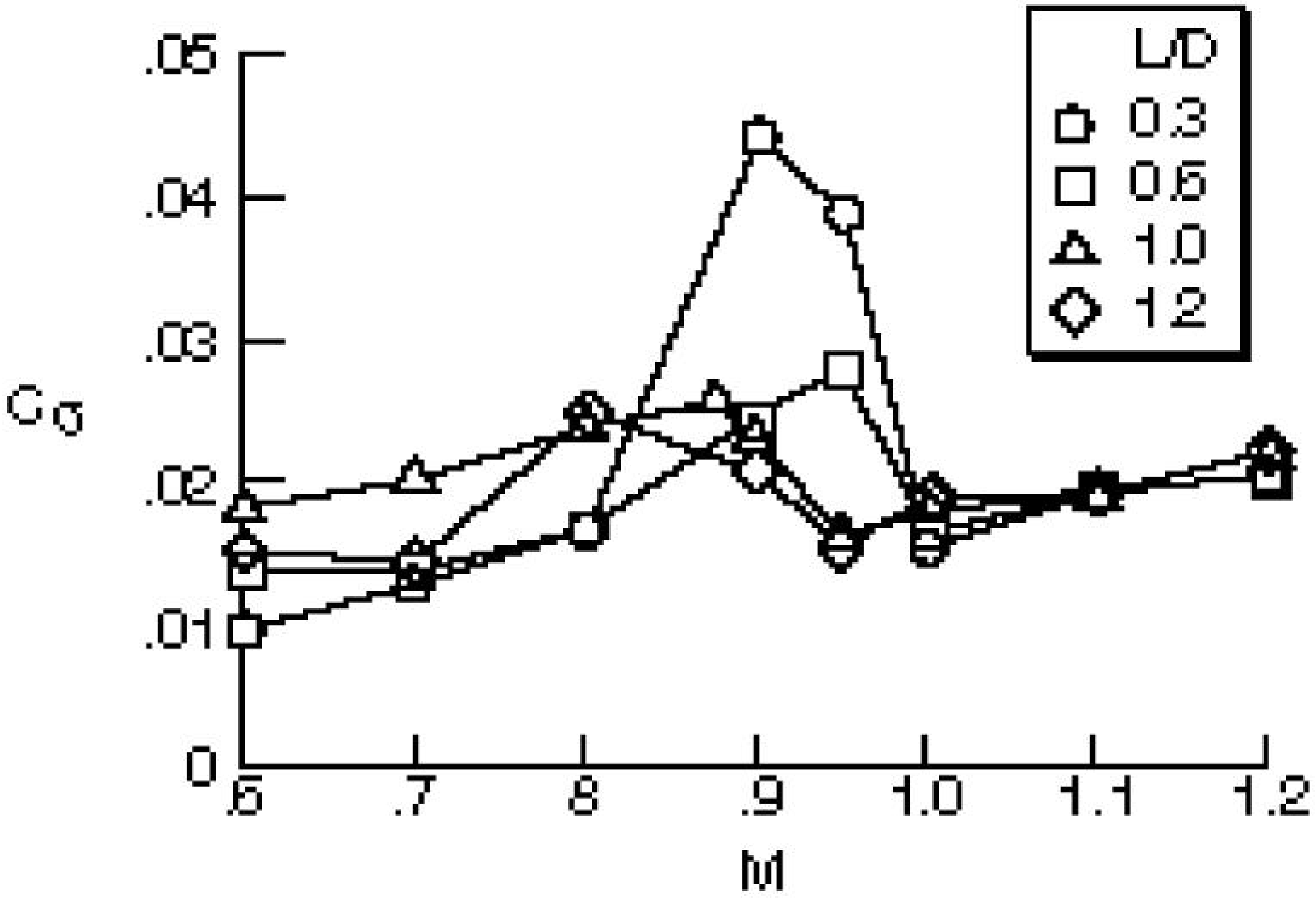
FIRST MODE L/D EFFECTS

Without vertical stiffening rods



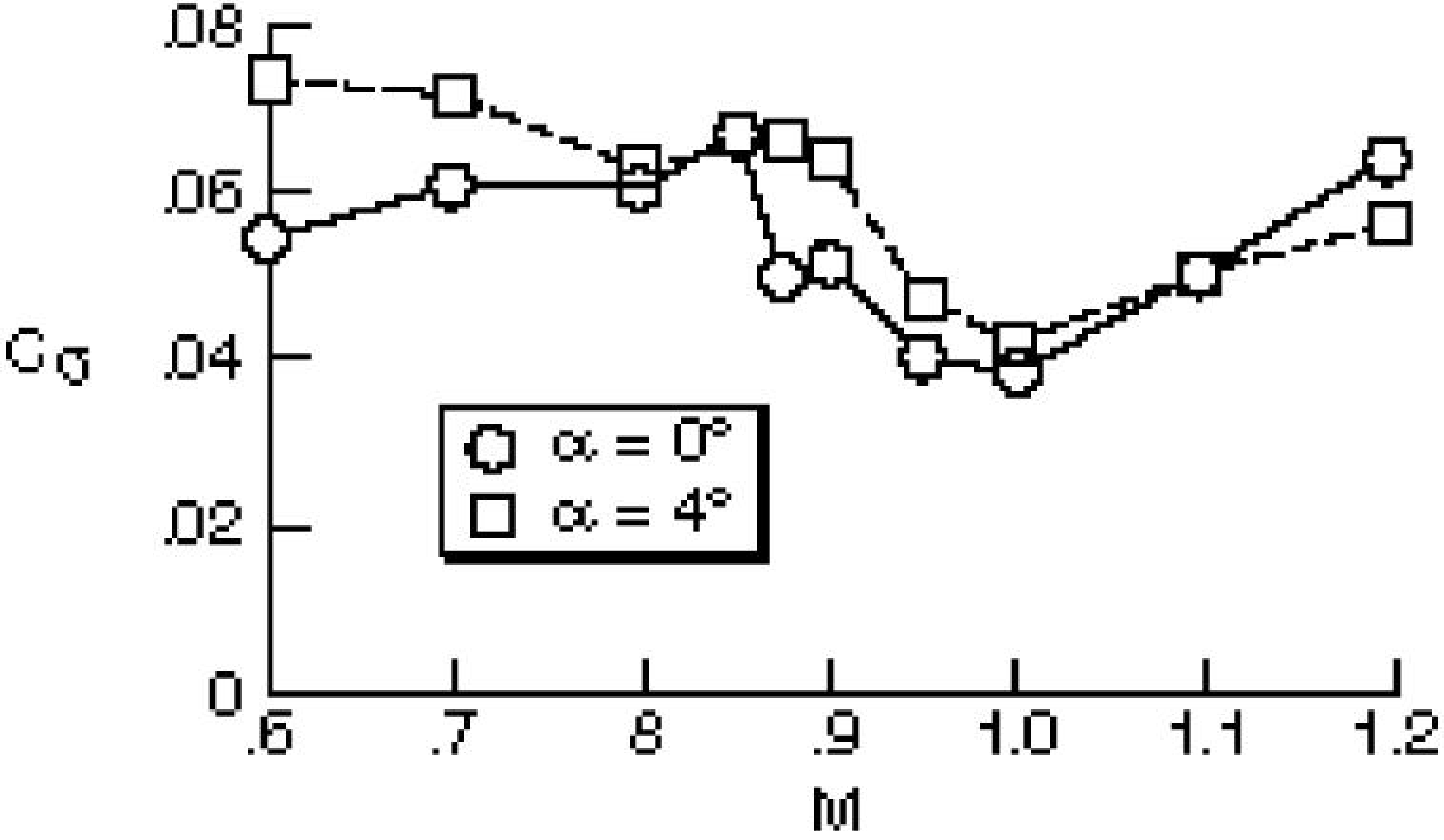
SECOND MODE L/D EFFECTS

Without vertical stiffening rods



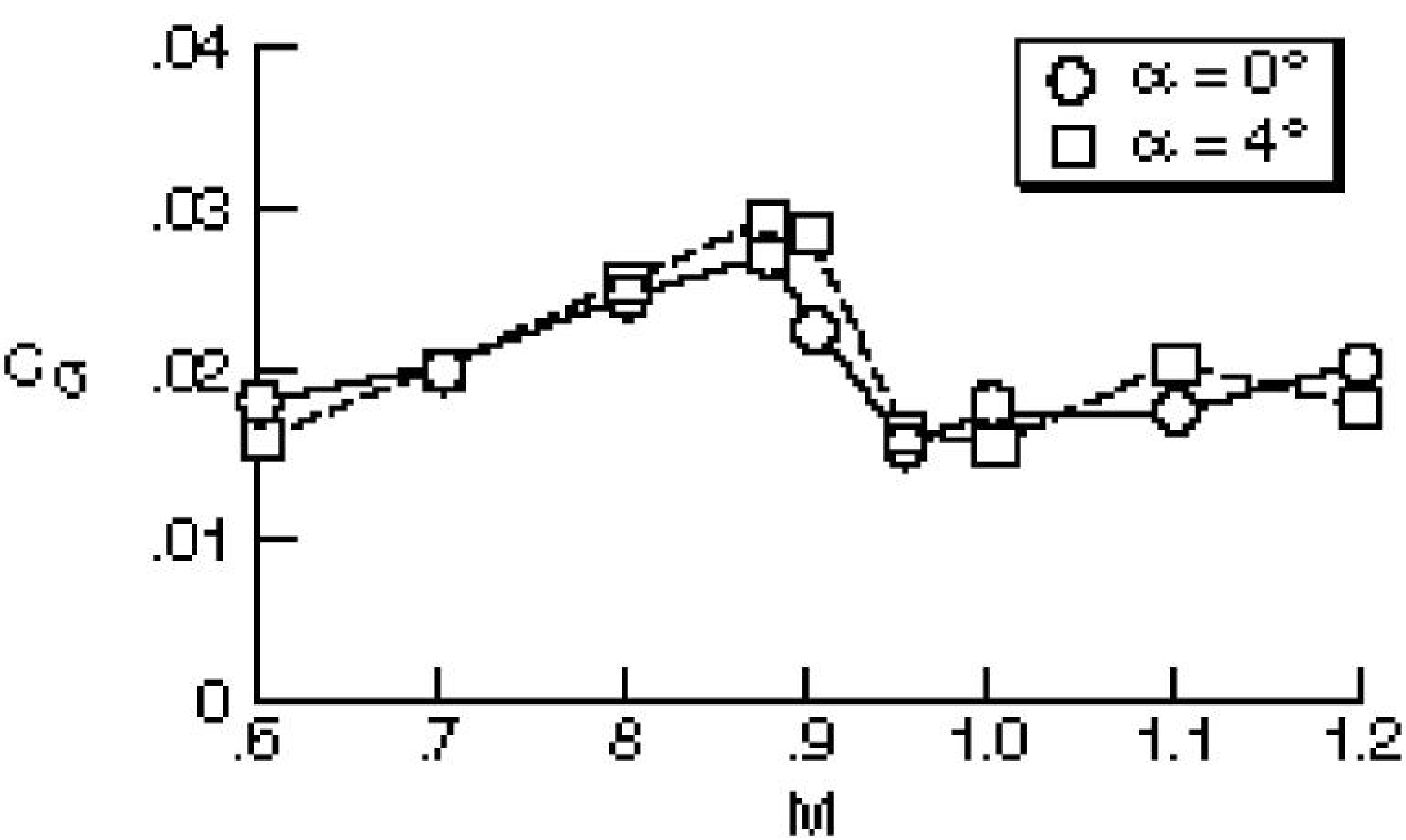
FIRST MODE a EFFECTS

With vertical stiffening rods



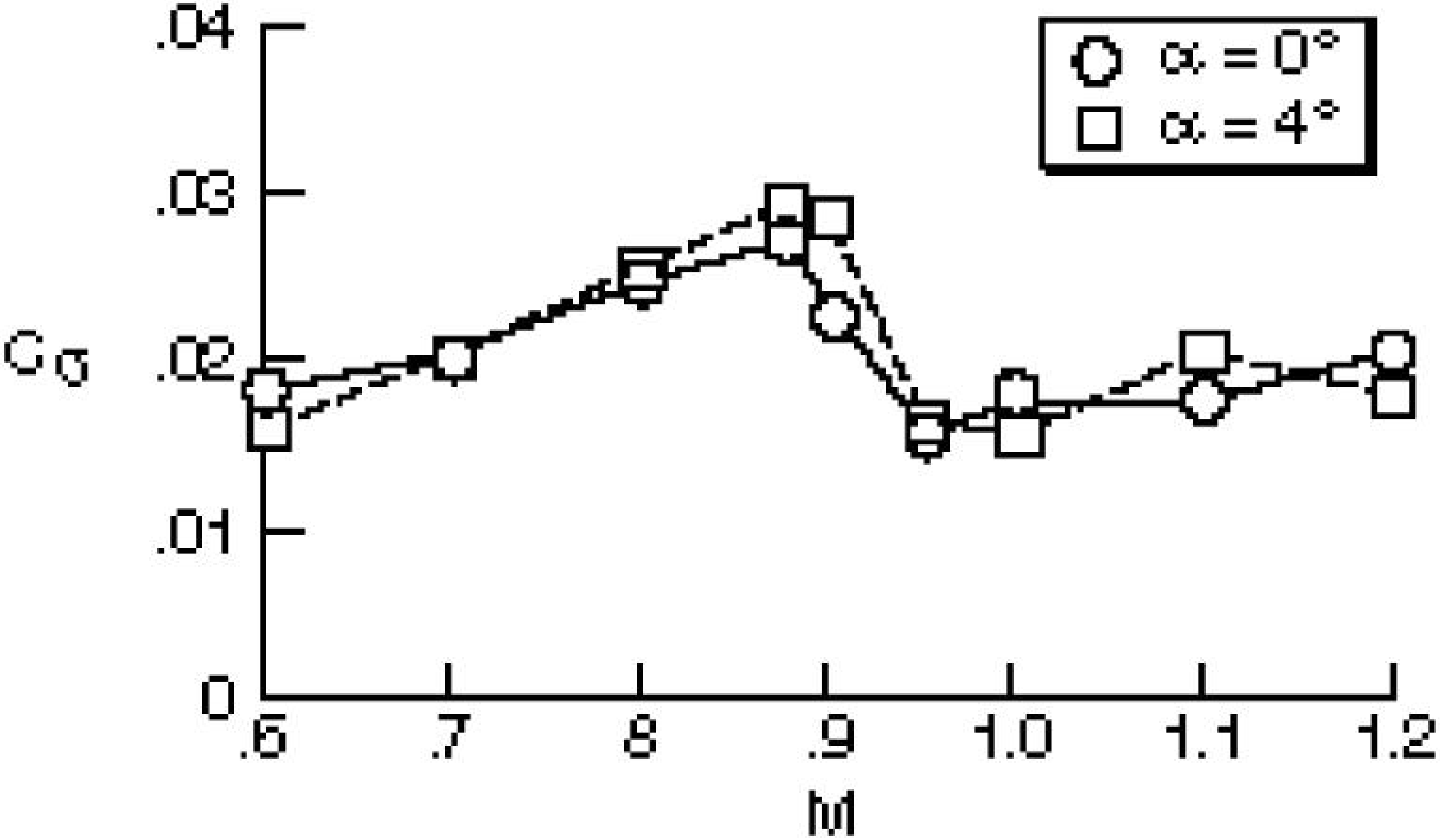
SECOND MODE a EFFECTS

Without vertical stiffening rods

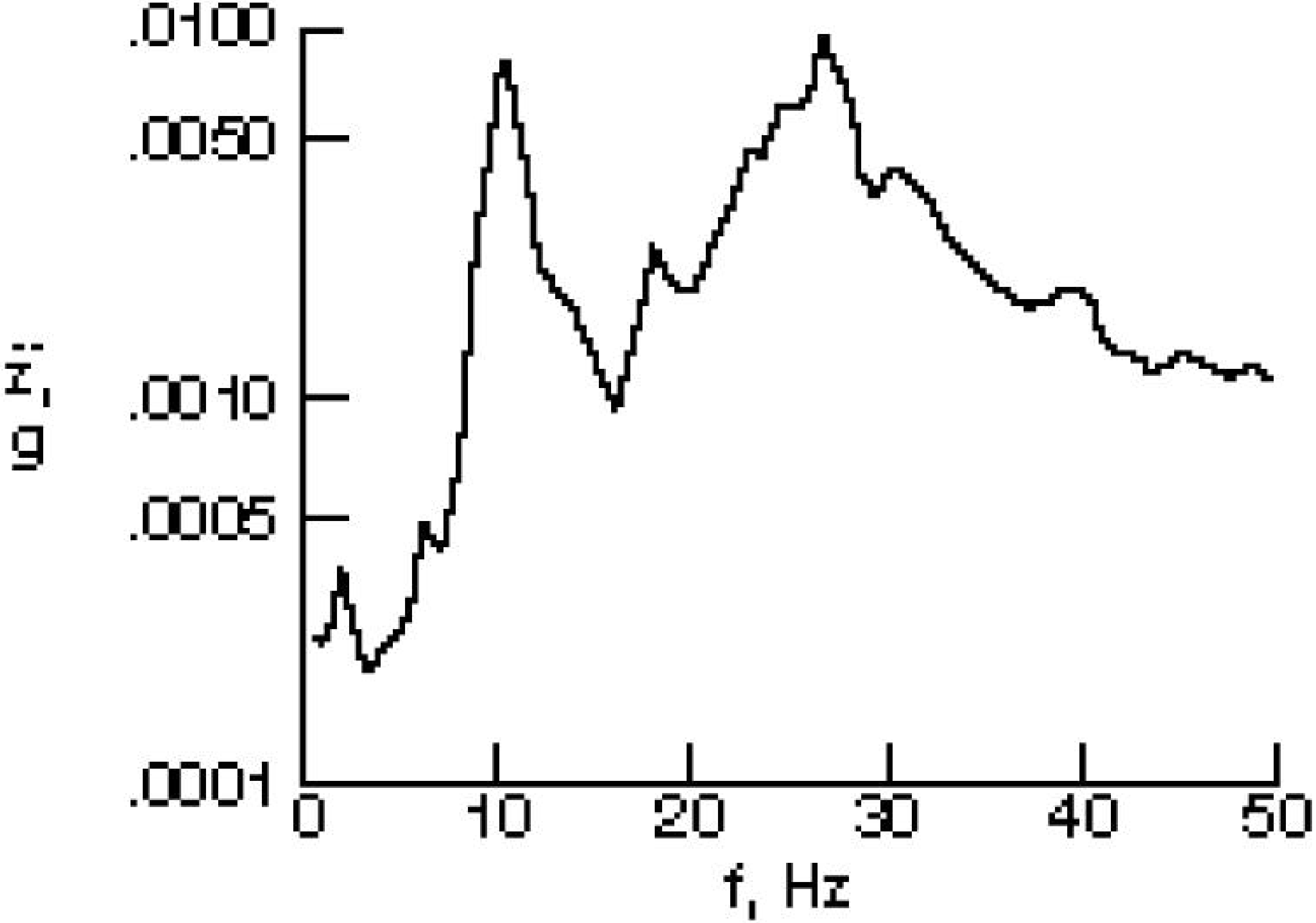


SECOND MODE a EFFECTS

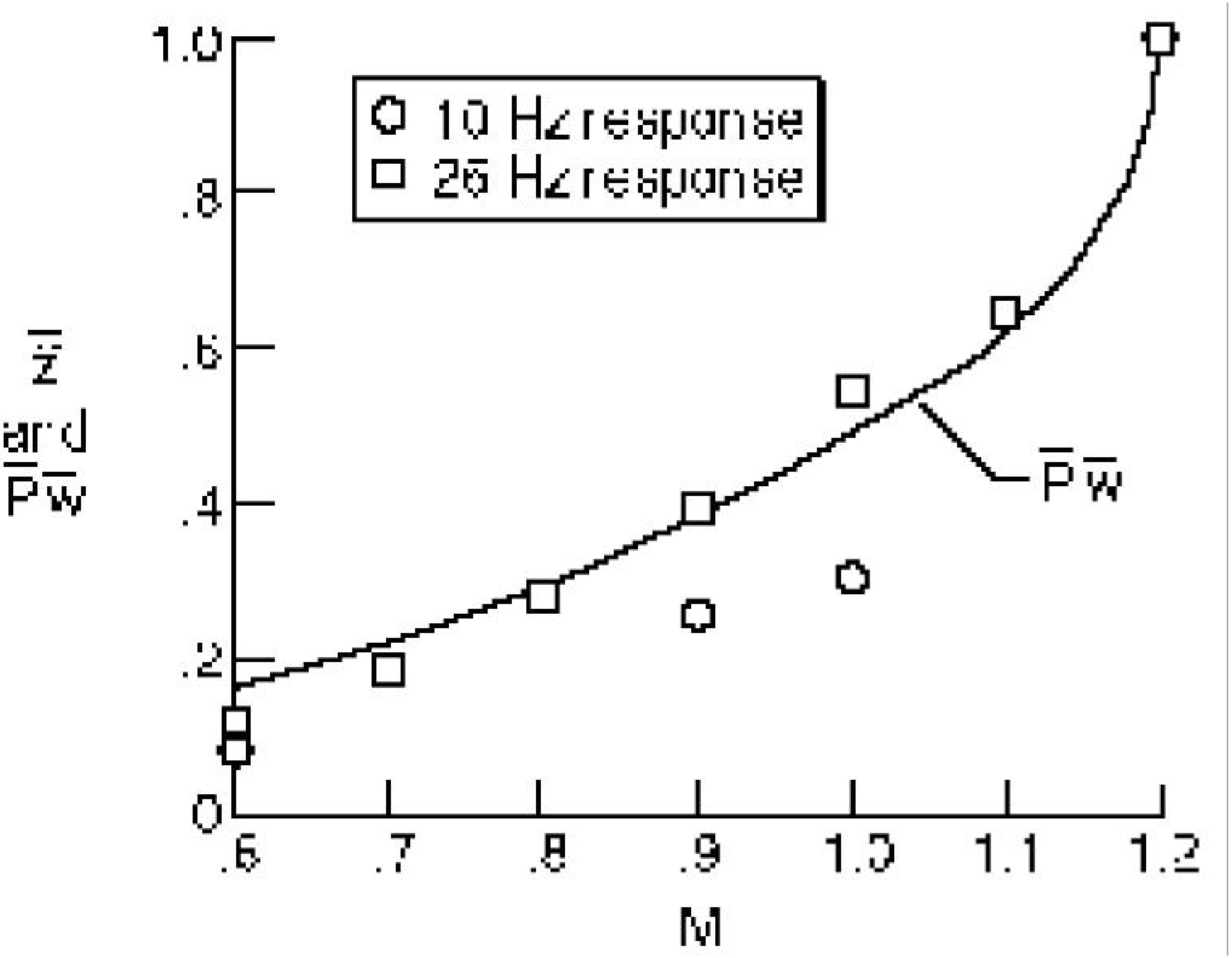
Without vertical stiffening rods



STING SECTOR RESPONSE



NORMALIZED RESPONSE OF STING SECTOR



FIRST MODE STIFFENING ROD EFFECTS

L/D=1.0 configuration