FLUID STRUCTURE INTERACTIONS

PREAMBLE

There are two types of vibrations: resonance and instability. Resonance occurs when a structure is excited at a natural frequency. When damping is low, the structure is able to absorb energy each oscillation cycle and dangerous amplitudes can build up. There are two types of instability: static and dynamic. Static instability occurs when a negative fluid stiffness overcomes a positive structural stiffness. Usually, because of nonlinearity, this instability is oscillatory: oscillations are often referred to as relaxation oscillations. Examples are wing stall flutter and gate valve vibration. Dynamic instability occurs when a negative fluid damping overcomes a positive structural damping. Examples include galloping of slender structures and tube bundle vibrations. In many cases, a system oscillates at a structural natural frequency. In these cases, frequency is a parameter in a semi empirical critical speed equation. Natural frequencies depend on the inertia of the structure and its stiffness. Usually the damping of the structure is ignored. It usually has only a small influence on periods. If the structure has a heavy fluid surrounding it, some of the fluid mass must be considered part of the structure. The structure appears more massive than it really is. For a simple discrete mass stiffness system, there is only one natural period. For distributed mass/stiffness systems, like wires and beams, there are an infinite number of natural periods. For each period, there is a mode shape. This shows the level of vibration at points along the structure. In some cases, the fluid structure interaction is so complex that vibration frequencies depend on both the structure and the fluid. Examples include flutter of wings and panels and pipe whip due to internal flow.

VORTEX SHEDDING PHEMOMENA

When vortices are being shed from a cylinder in an asymmetric pattern, they induce a lateral oscillatory load on the cylinder. When the vortex shedding frequency is close to a natural frequency of the cylinder, it causes it to oscillate laterally. Once the cylinder begins to oscillate, it causes a phenomenon known as lock in. The vortices shed at the natural frequency of the cylinder. In other words, the cylinder motion controls the vortex shedding. It also increases the correlation length along the span. This means that vortex shedding along the span occurs at the same time. This gives rise to greater lateral loads. So, once shedding starts, it quickly amplifies motion. The Strouhal Number gives the vortex shedding frequency of the cylinder. Basically, this is structure transit time T divided by the vortex shedding period τ. For a circular cylinder, the Strouhal Number is around 0.2. This means that the vortex shedding period τ is approximately 5 times the diameter transit time T.

GALLOPING VIBRATIONS

Galloping is a dynamic instability of a structure in a flow. It occurs when a positive damping load due to structural and viscous phenomena is overcome by a negative damping load due to flow. Only certain shapes gallop. When such a shape is moving laterally in a flow, a very strong vortex forms on one side that pulls it even more laterally! The structure moves until its stiffness stops it. The vortex disappears and the structure starts moving back the other way. As it does so, the vortex appears on the other side of the structure which pulls it the other way.

TUBE BUNDLE VIBRATIONS

There are three mechanisms that can cause tube bundles in a flow to vibrate. One is known as the displacement mechanism. As tubes move relative to each other, some passageways narrow while others widen. Fluid speeds up in narrowed passageways and slows down in widened passageways. Bernoulli shows that in the narrowed passageways pressure decreases while in the widened passageways it increases. Common sense would suggest that if tube stiffness and damping are low, at some point as flow increases, tubes must flutter or vibrate. Another mechanism known as the velocity mechanism is based on the idea that, when a tube is moving, the fluid force on it due its motion lags behind the motion because the upstream flow which influences the force needs time to redistribute. This time lag introduces a negative damping which can overcome the positive damping due to structural and viscous phenomena. The time lag is roughly the tube spacing divided by the flow speed within the bundle. Details of this model are beyond the scope of this note. The third mechanism for tube vibration involves vortex shedding and turbulence within the bundle.

CRITICAL SPEED EQUATIONS

For a slender structure, the Strouhal Number S is the transit time T divided by the vortex shedding period τ: $S=T/\tau$. The transit time T is D/U. Solving for flow speed U gives: $U = D/[S\tau]$. During resonance, $\tau=\mathbf{T}$ where $\mathbf{T}$ is the structural period. So the critical flow speed is:

$$U = D/[S\ \mathbf{T}]$$

For the lateral vibration of a slender structure known as galloping, the critical flow speed U is

$$U = U_o\ M/M_o\ \zeta\ \mathbf{a}$$

where

$$U_o = D/\mathbf{T} \qquad M_o = \rho D^2$$

The factor ζ accounts for damping: it is typically in the range 0.01 to 0.1. The parameter **a** accounts for the shape of the structure. For a square cross section structure **a** is 8 while for a circular cross section structure **a** is ∞.

For tube bundle vibration, the critical flow speed is

$$U = \beta/\mathbf{T}\ \sqrt{[M\delta/\rho]} \qquad U = \beta U_o\ \sqrt{[\delta M/M_o]}$$

The factor δ accounts for damping, and the parameter β accounts for the bundle geometry. Typically δ is in the range 0.05 to 0.25 while β is in the range 2.5 to 6.0.

VIBRATION MODES OF SIMPLE WIRES AND BEAMS

The natural periods of a simple wire are:

$$\mathbf{T}_n = [2L/n] \sqrt{[m/T]}$$

where m is the mass per unit length of the wire, L is the length of the wire and T is the tension in the wire. The natural periods of a beam with pivot supports are:

$$\mathbf{T}_n = [L/n]^2 \; [2/\pi] \sqrt{[m/EI]}$$

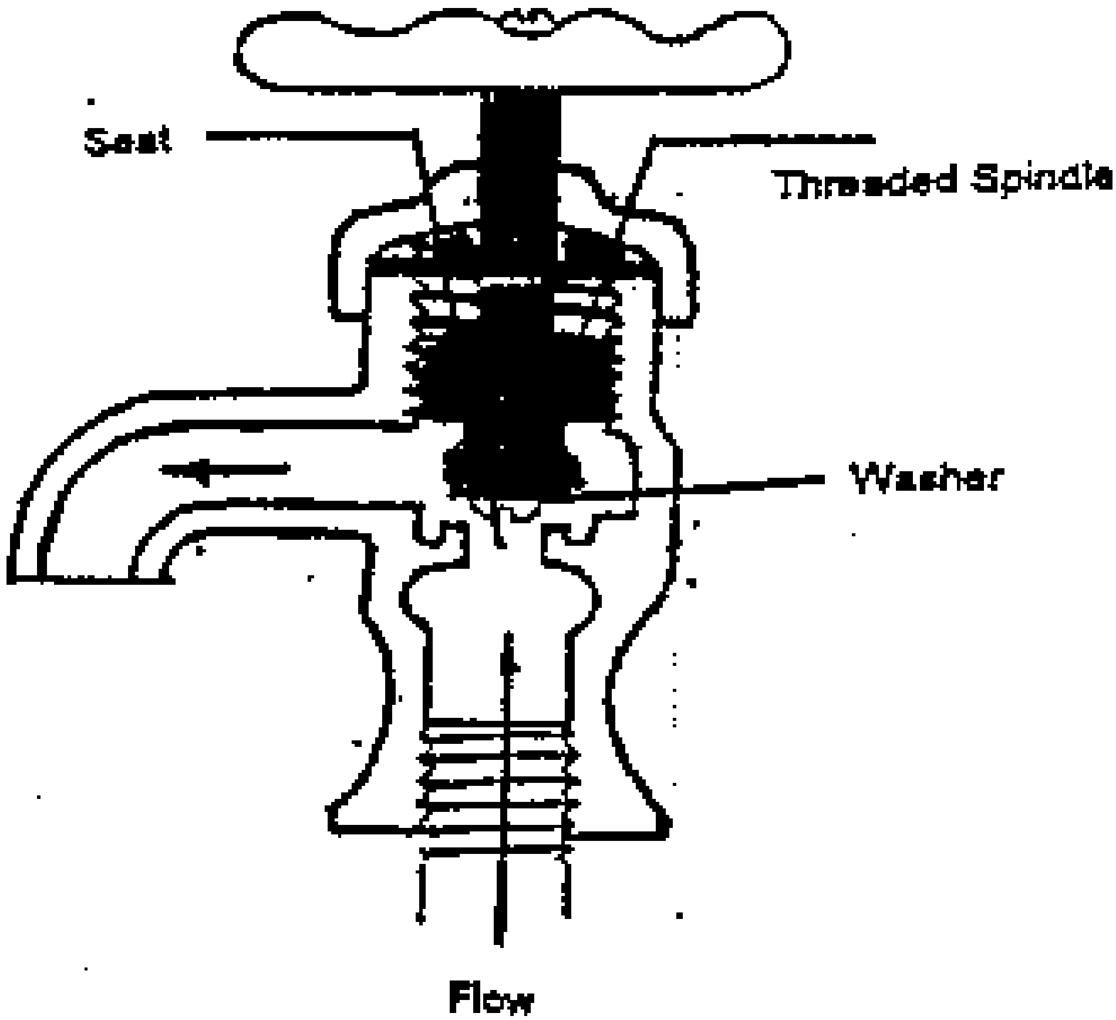
where m is the mass per unit length of the beam, L is the length of the beam, E is the Elastic Modulus of the beam material and I is the second moment of area. The natural periods of a beam with one or more clamped supports are:

$$\mathbf{T}_n = 2\pi L^2/K_n \; \sqrt{[m/EI]}$$

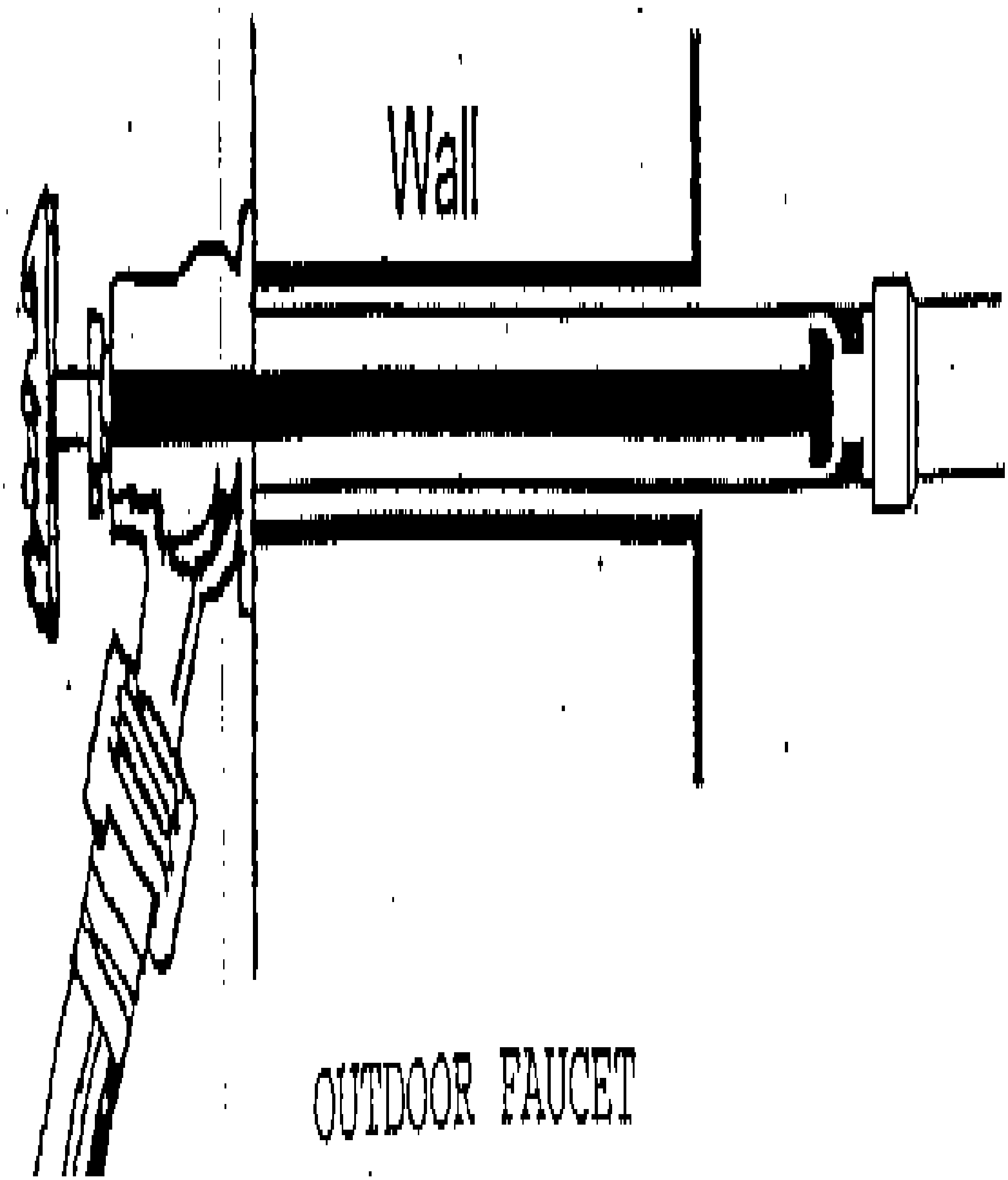
For a cantilever or clamped-free beam, the constants are: K_1=3.52; K_2=22.0; K_3=61.7; K_4=120.9. For a clamped-clamped beam, the constants are: K_1=22.4; K_2=61.7; K_3=120.9; K_4=199.9.

INSTABILITY OF VALVES

Valves exhibit two types of unstable behaviour. One type is basically a static instability. It occurs when a positive structural stiffness is overcome by a negative fluid stiffness. It usually occurs when the valve is almost shut, and there is a flow through a small gap. An oscillation results because the negative fluid stiffness creates suction forces that cause the valve to slam shut. This stops the flow and allows pressure to build up. This allows the valve to recover. Indoor faucets, such as that shown in the sketch on the next page, are prone to such instability. Outdoor faucets are prone to a completely different type of instability. Whereas indoor faucets are prone to an axial, opening and closing, type of instability, outdoor faucets are prone to a lateral, back and forth, type of instability. Consider the outdoor faucet shown page after next. When the valve stem is moved laterally, say upward, a suction force is created momentarily of the upward side of the valve. This tends to move the valve even further upward. An oscillation develops which is basically a dynamic instability. It is caused by a time lag between valve motion and fluid reaction.



INDOOR FAUCET



OUTDOOR FAUCET

PIPE INSTABILITIES DUE TO INTERNAL FLOW

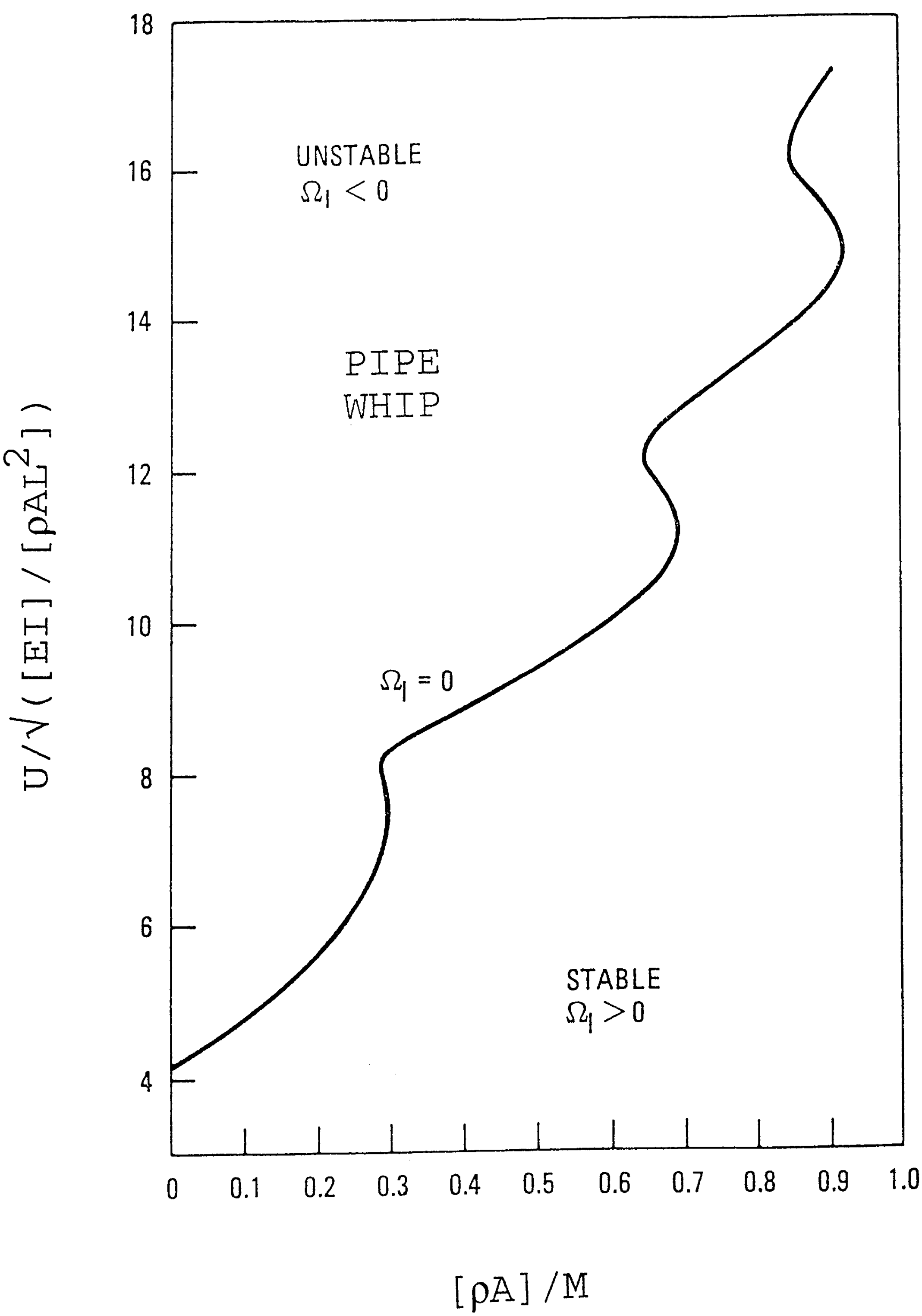
For a pipe pivoted at both ends, a static force balance shows that centrifugal forces generated by internal fluid motion can cause buckling when U is greater than

$$U^2 = [\ [EI]/[\rho A]\ [\pi^2/L^2] + T/[\rho A] - P/\rho\ ]$$

where EI is the flexural rigidity of the pipe, L is the pipe length, A is its cross sectional area, T is the tension in the pipe and P is the internal gage pressure. For a pipe clamped at one end and open and free at the other end, a stability analysis shows that the pipe can undergo a flutter like phenomenon known as pipe whip. The critical speed U can be obtained from the sketch on the next page. A straight line fit to the wavy curve there is

$$U = [4 + 14\ M_o/M]\ U_o$$

$$U_o = \sqrt{[EI]/[M_o L^2]} \qquad M_o = \rho A$$



18
16
14
12
10
8
6
4
UNSTABLE
$\Omega_I < 0$
PIPE
WHIP
$\Omega_I = 0$
STABLE
$\Omega_I > 0$
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
$U/\sqrt{([EI]/[\rho AL^2])}$
$[\rho A]/M$

PANEL FLUTTER

Consider a panel with a fluid on top and a fluid on the bottom. Assume also that the panel is exposed to a horizontal flow on the top. Waves in the panel extract energy from the passing stream when the flow speed U is greater than:

$$U^2 = S\ V/W$$

$$S = + Tk^2 + Dk^4 + K/w - \rho_T\ g + \rho_B\ g$$

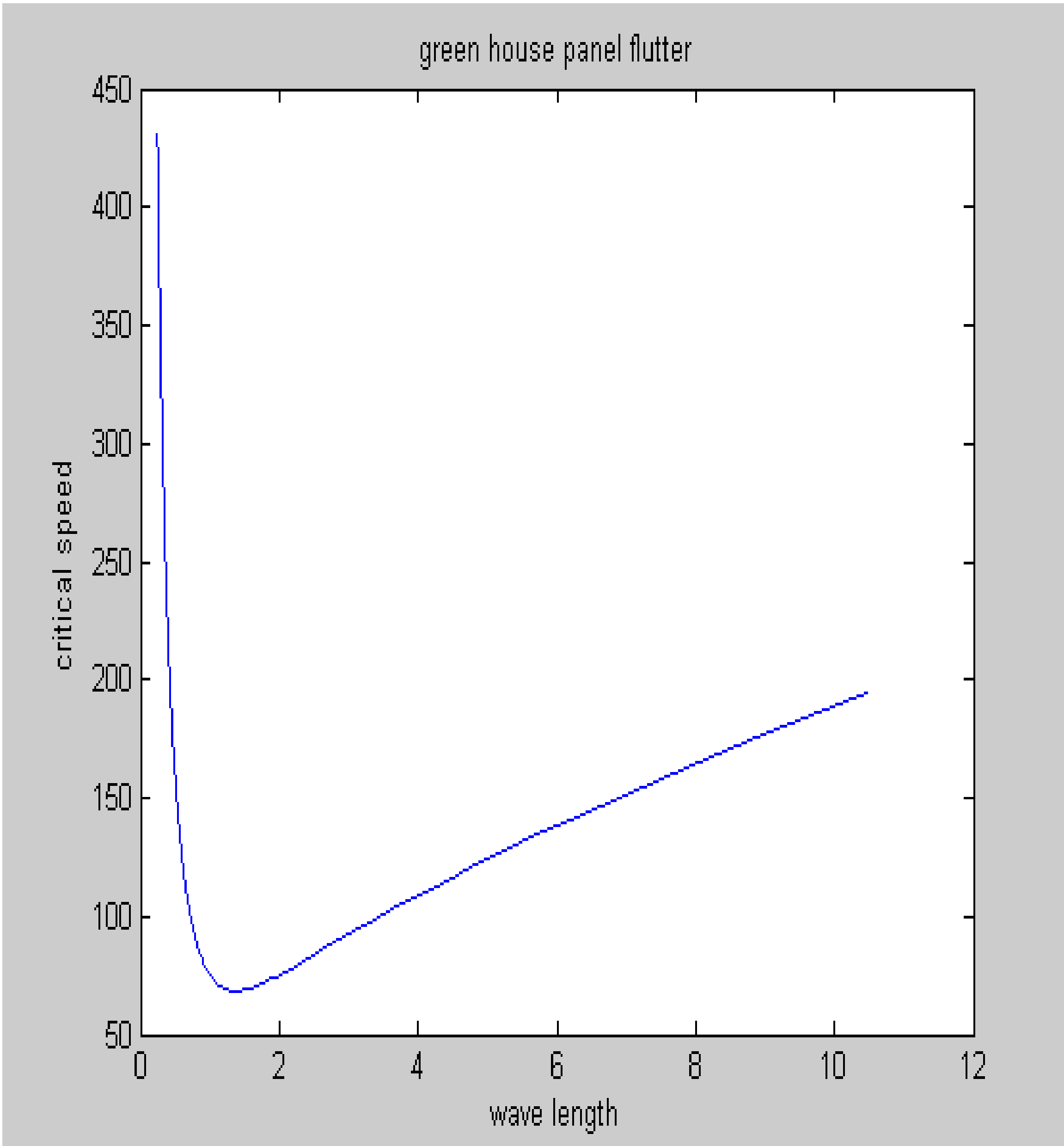
$$V = \rho_T / [k\ \mathrm{Tanh}[kd_T]] + \rho_B / [k\ \mathrm{Tanh}[kd_B]] + \sigma$$

$$W = [\rho_B\ \rho_T] / [\mathrm{Tanh}[kd_T]\mathrm{Tanh}[kd_B]] + [k\sigma]\rho_T / \mathrm{Tanh}[kd_T]$$

The details of the analysis are beyond the scope of this note. In the critical speed equation, T is the tension in the panel, D is the EI of the panel, K is the panel side support, w is the width of the panel, σ is the panel sheet density or mass per unit surface area, ρ is the fluid density, d is flow depth, g is gravity and k is 2π divided by the wavelength λ. The code on the next page calculates the critical speed for the panels on a greenhouse. It gives the plot of critical speed versus wavelength shown on the page after next.

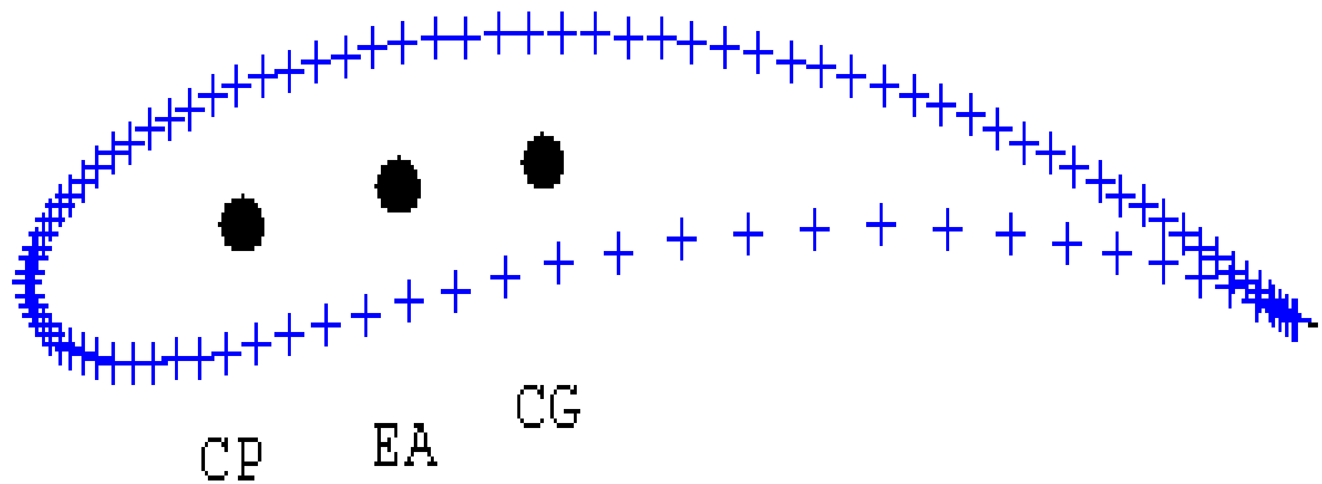
```matlab
% PANEL FLUTTER ON GREENHOUSE
% KELVIN HELMHOLTZ MECHANISM

COUNT=250;
PI=3.14159; GRAVITY=9.81;
ABOVE=1.0; BELOW=1.0;
SHEET=0.25; TENSION=10.0;
RIGIDITY=10.0;SUPPORT=10000.0;
CHANGE=0.1; NUMBER=0.5;
for STEP=1:COUNT
SPEED=((TENSION*NUMBER^2+RIGIDITY* ...
 NUMBER^4+SUPPORT+GRAVITY*(BELOW-ABOVE)) ...
 *((ABOVE+BELOW)/NUMBER+SHEET)/(BELOW* ...
 ABOVE+SHEET*ABOVE*NUMBER))^0.5;
NUMBER=NUMBER+CHANGE;
WAVE(STEP)=2.0*PI/NUMBER;
WIND(STEP)=SPEED;
end
plot(WAVE,WIND)
xlabel('wave length')
ylabel('critical speed')
title('green house panel flutter')
```


green house panel flutter
critical speed
wave length
450
400
350
300
250
200
150
100
50
0
2
4
6
8
10
12

DIVERGENCE AND FLUTTER OF LIFTING BODIES

Lifting bodies include wings, elevators, fins and rudders. Flutter is a dynamic instability. When it occurs, the heave and pitch motions of the body are 90° out of phase. The passing stream does work on the body over an oscillation cycle. Divergence is a static instability. It occurs when the pitch moment due to fluid dynamics overcomes the moment due to the structural pitch stiffness of the body. The sketch on the next page shows a foil, which is section of a wing. It shows 3 very important points on foils. They form lines which run along the wing span. The point labelled **CP** is the center of the pressure load on the foil. It is usually located a quarter chord length back from the leading edge of the foil. The point labelled **EA** is the elastic axis of the foil. A load applied at the elastic axis produces pure heave of the foil without any pitch rotation. The **EA** is usually located near where the main beam runs along the wing span, which means its position can be controlled. The point labelled **CG** is the center of mass of the foil. Again, its position can be controlled. If the **CP** is at the **EA**, then the foil cannot undergo divergence because no pitch moment can be generated. If the **CG** is at the **EA**, then inertia coupling is zero. This lowers the probability of the wing undergoing flutter.


CP
EA
CG