Aeroelasticity

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What is Aeroelasticity

- Aeroelasticity is broadly defined as the interaction between the aerodynamic forces and the structural forces causing a deformation in the structure of the aerospace craft as well as in its control mechanism or in its propulsion systems.

Importance of Aeroelasticity

- Aeroelasticity has become a very important force especially after the 1950's.
- The interaction between aerodynamic loads and structural deformations have gained great importance in view of factors related to the design of aircraft as well as missiles.
- Aeroelasticity plays at least some part on fuel sloshing as well as on the reentry of spacecraft in astronautics.

Trends in Technology

- Due to the advancements in technology, it has become quite common to see the slenderness ratio (ratio of length of wing span to thickness at the root) increase.
- The wing span area as well as the length of aircrafts have increased causing aircraft to become much more susceptible to interaction between structural loads and aerodynamic loads

Slenderness Ratio

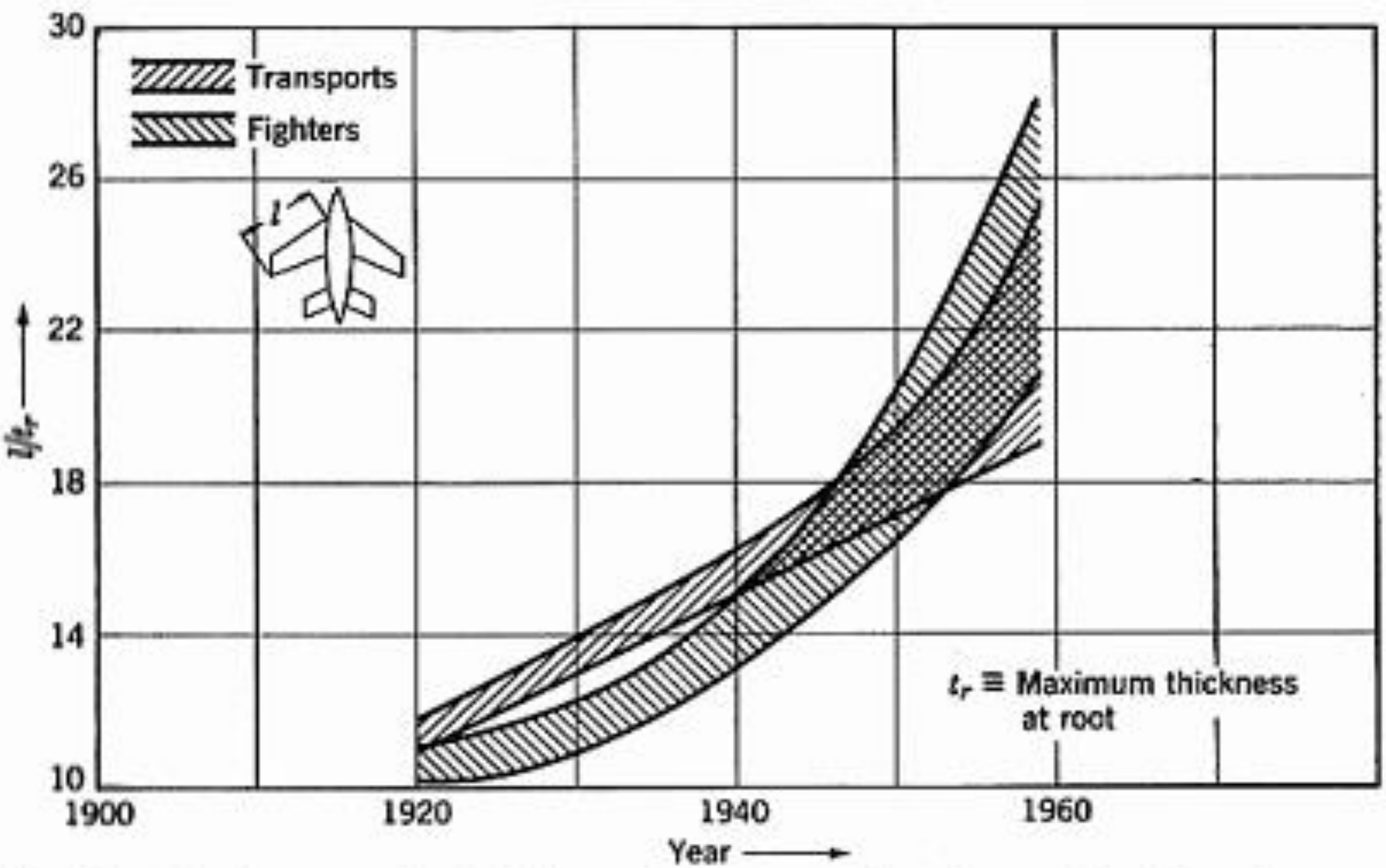
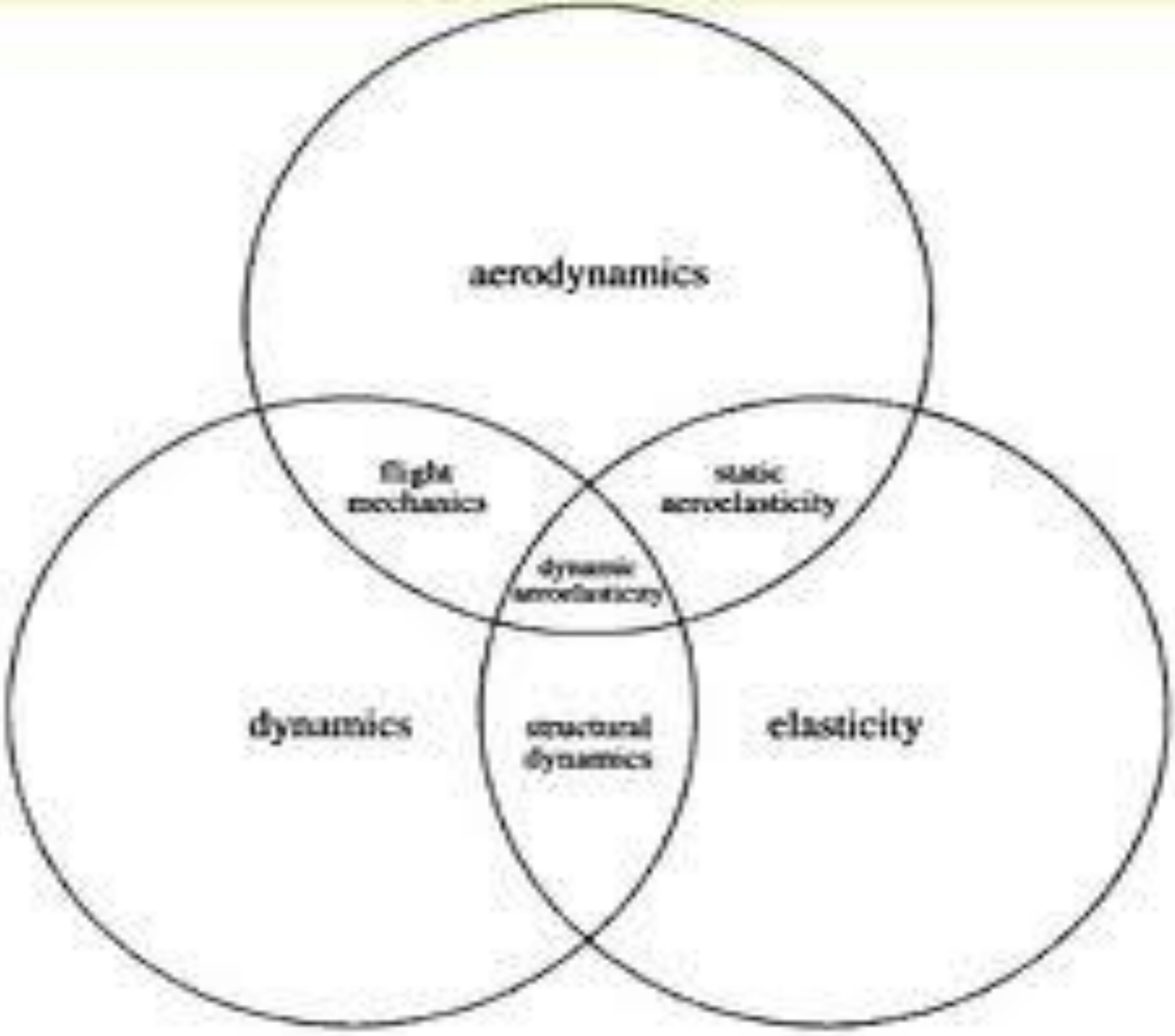


Fig. 1-1. Slenderness ratio of fighter and transport aircraft as a function of year of first flight.

Effect of Aerodynamic Loads

- The forces of lift and drag as well as torsion moment will have some sort of effect on the structural integrity of the spacecraft.
- In many cases, some parts of aircraft or spacecraft may bend or ripple slightly due to these loads.
- The frequency of these loads and effects can also cause the aircraft's structure to suffer from metal fatigue in the long run.

Scope of Aeroelasticity



Vibration

- One of the ways in which aerodynamic and structural forces collide with each other is through vibration.
- Much like a harp, the structural forces and the aerodynamic forces will cause vibration to set place in the aerospace structure.
- Over time, this vibrational effect can have long term as well as short term damaging effects on the plane, missile or spacecraft.

Some Effects of Aeroelastic Forces

- Divergence
- Control Surface Reversal
- Flutter
- Buffeting
- Thermal Instabilities

Divergence

- Divergence occurs when a lifting surface deflects under aerodynamic load so as to increase the applied load, or move the load so that the twisting effect on the structure is increased.
- The increased load deflects the structure further, which brings the structure to the limit loads and to failure.

Control Surface Reversal

- Control surface reversal is the loss (or reversal) of the expected response of a control surface, due to structural deformation of the main lifting surface.
- This can be a very dangerous phonemenon since the deformation of control surfaces can cause major flight instability problems especially during takeoff and landing.

Flutter

- **Flutter** is a self-feeding and potentially destructive vibration where aerodynamic forces on an object couple with a structure's natural mode of vibration to produce rapid periodic motion.
- Flutter can occur in any object within a strong fluid flow, under the conditions that a positive feedback occurs between the structure's natural vibration and the aerodynamic forces

Buffeting

- **Buffeting** is a high-frequency instability, caused by airflow separation or shock wave oscillations from one object striking another.
- It is caused by a sudden impulse of load increasing. It is a random forced vibration
- Generally it affects the tail unit of the aircraft structure due to air flow down stream of the wing.

Thermal Instability

- Aerothermoelasticity deals with the deformation of the aircraft due to cyclic thermal changes or thermal loads.
- In aerospace vehicles, stress induced by high temperatures is important
- Hence, most composite materials used in aerospace vehicles are designed by keeping this in mind.

Effects of Aeroelasticity

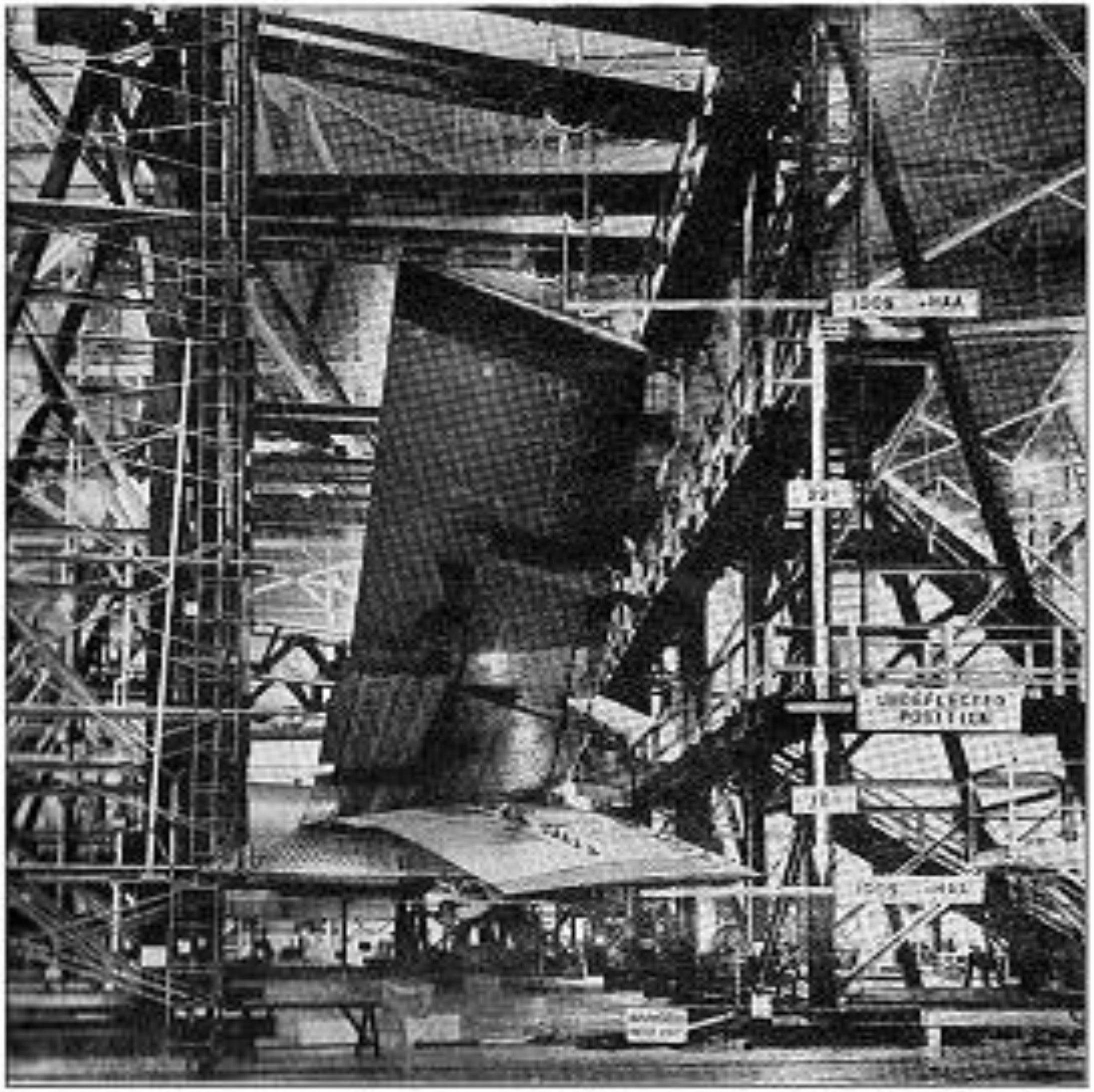


Fig. 1–3. Composite photograph of the maximum upward and downward deflections, at limit load conditions, of the B-52 wing during static tests. (Courtesy of Boeing Airplane Company.)

Effects of Aeroelasticity

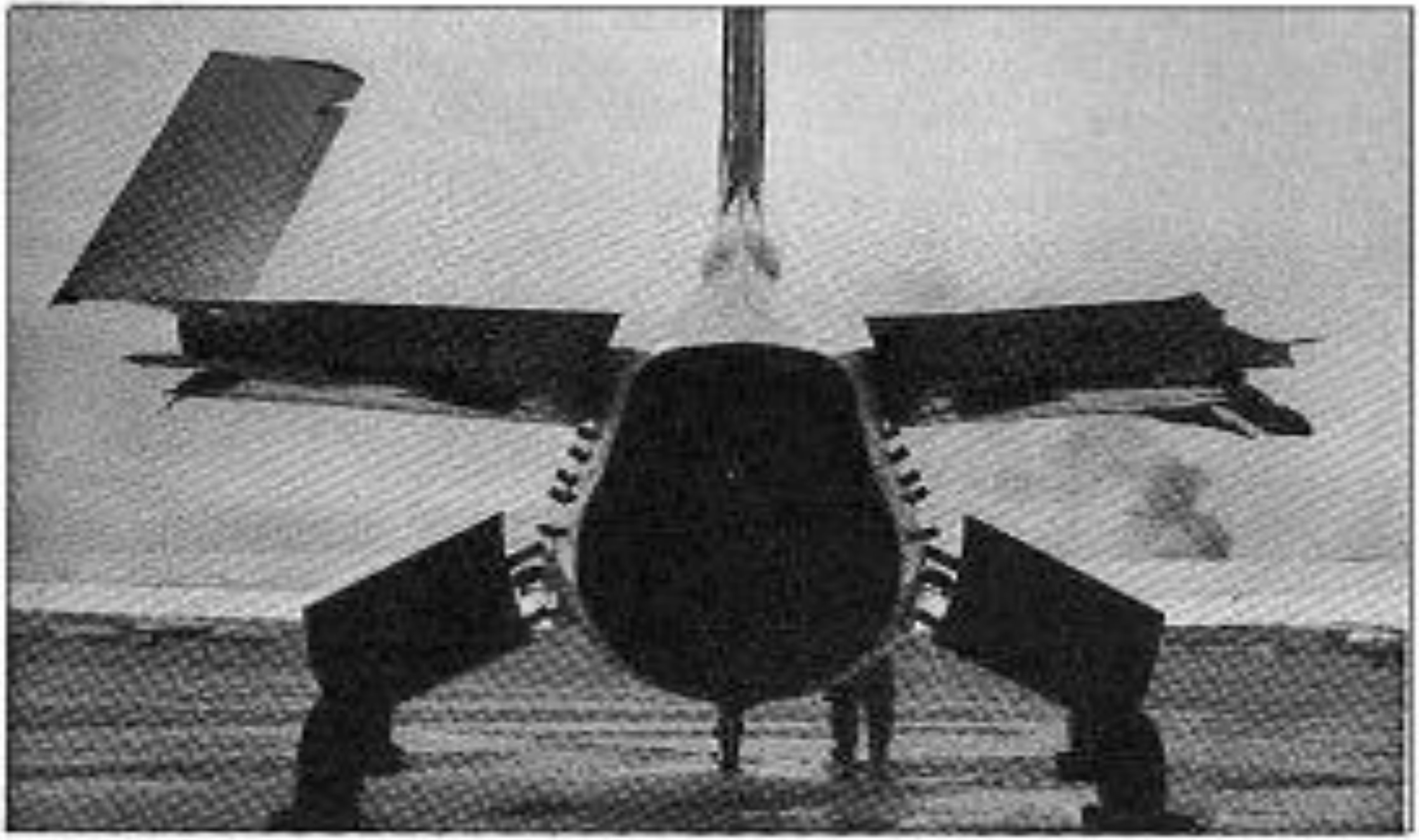
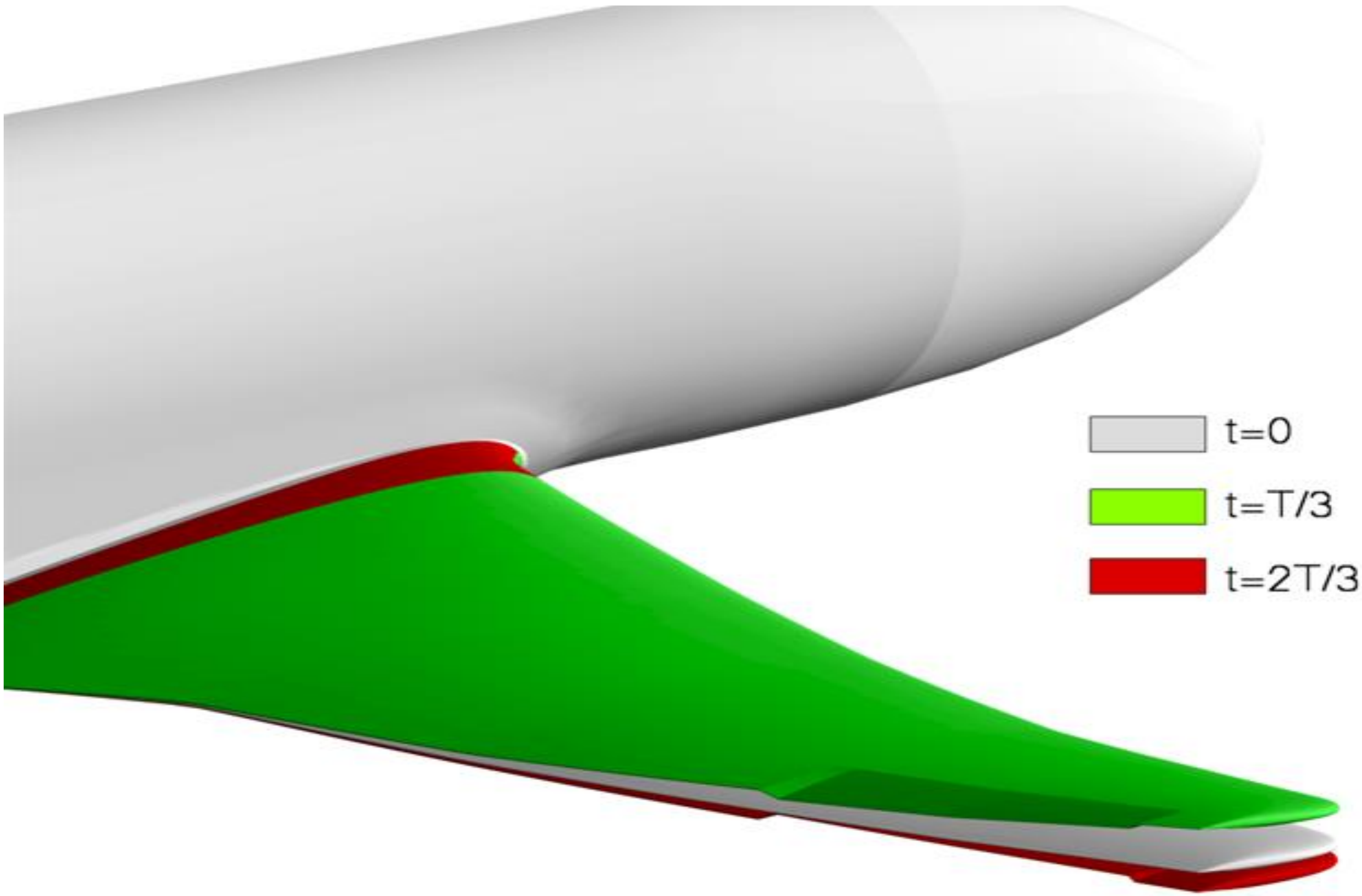
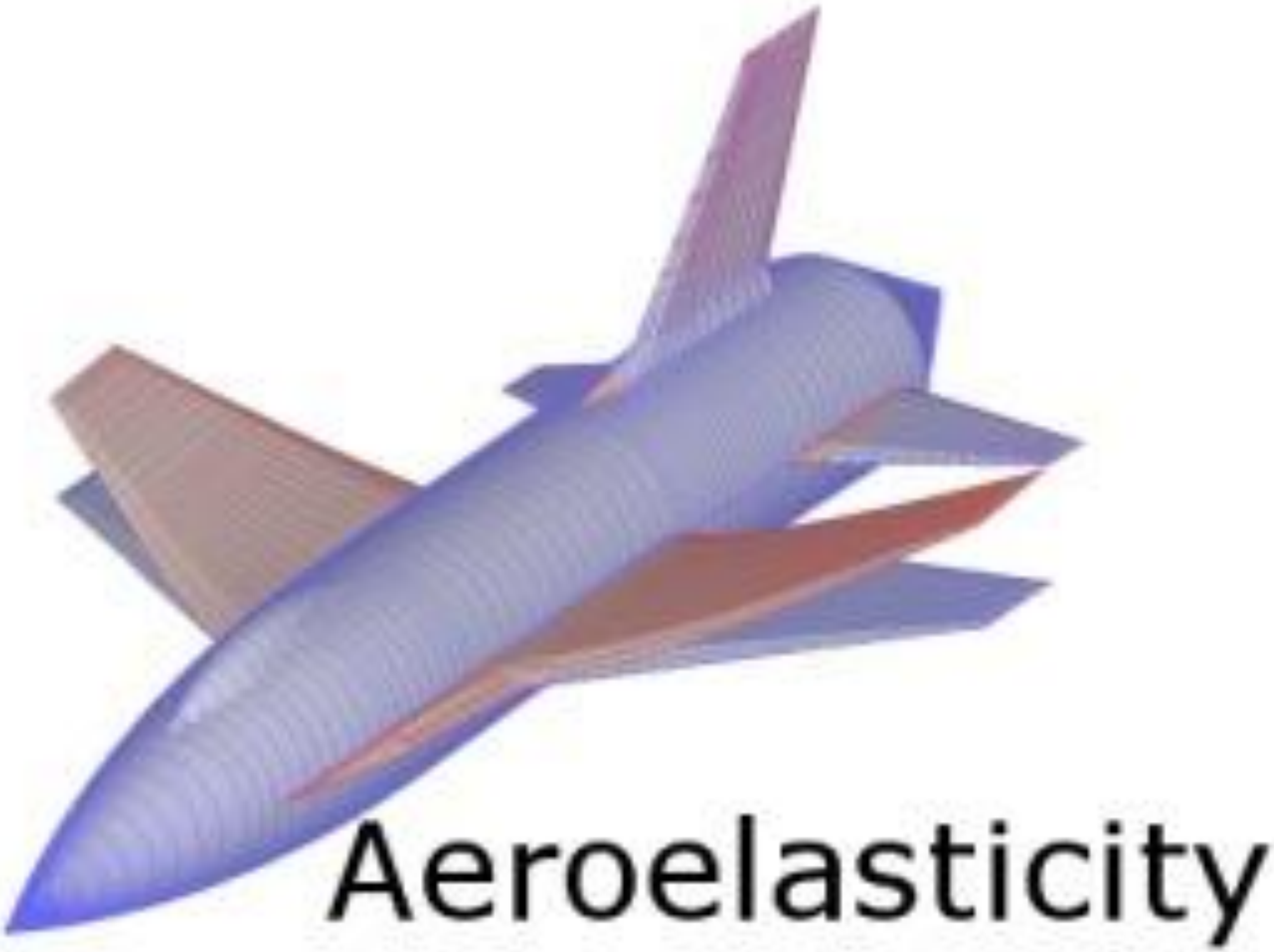


Fig. 1–4. Rear view of empennage of jet fighter which was successfully landed after encountering flutter of the horizontal stabilizer in transonic flight. (Courtesy of North American Aviation, Inc.)

Effects of Aeroelasticity



Effects of Aeroelasticity



Aeroelasticity in Spacecraft

- Aeroelasticity is not just confined to aircraft. Although buffeting and flutter have become a major concern for the aeronautics industry, aerospace vehicles are also effected.
- For aerospace craft, takeoff and landing are two distinct phases where the spacecraft are subjected to aerodynamic loads.
- For long range missiles, this can especially become a very important problem in high speed flights.

Aeroelastic Forces on a Missile

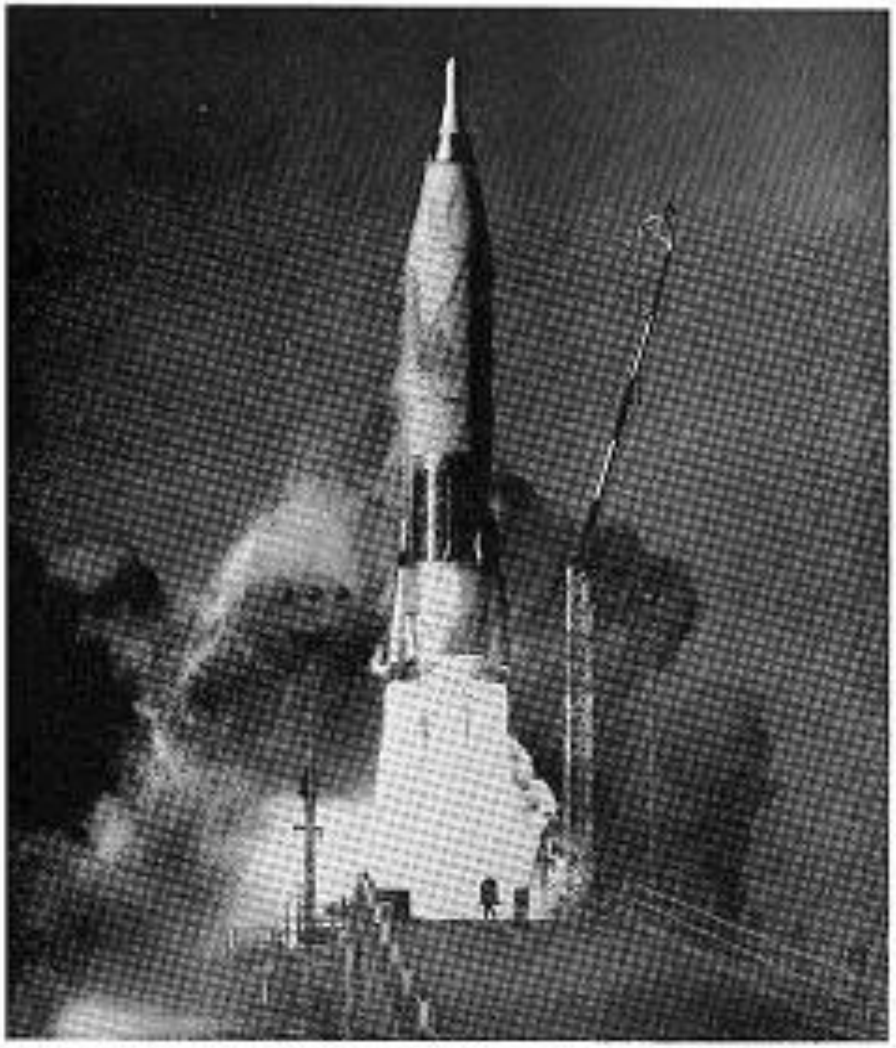


Fig. 1–5. Atlas missile rising from its launching pad. (Courtesy of Convair Astronautics Division of General Dynamics Corporation.)

Aeroelastic Forces on a Missile

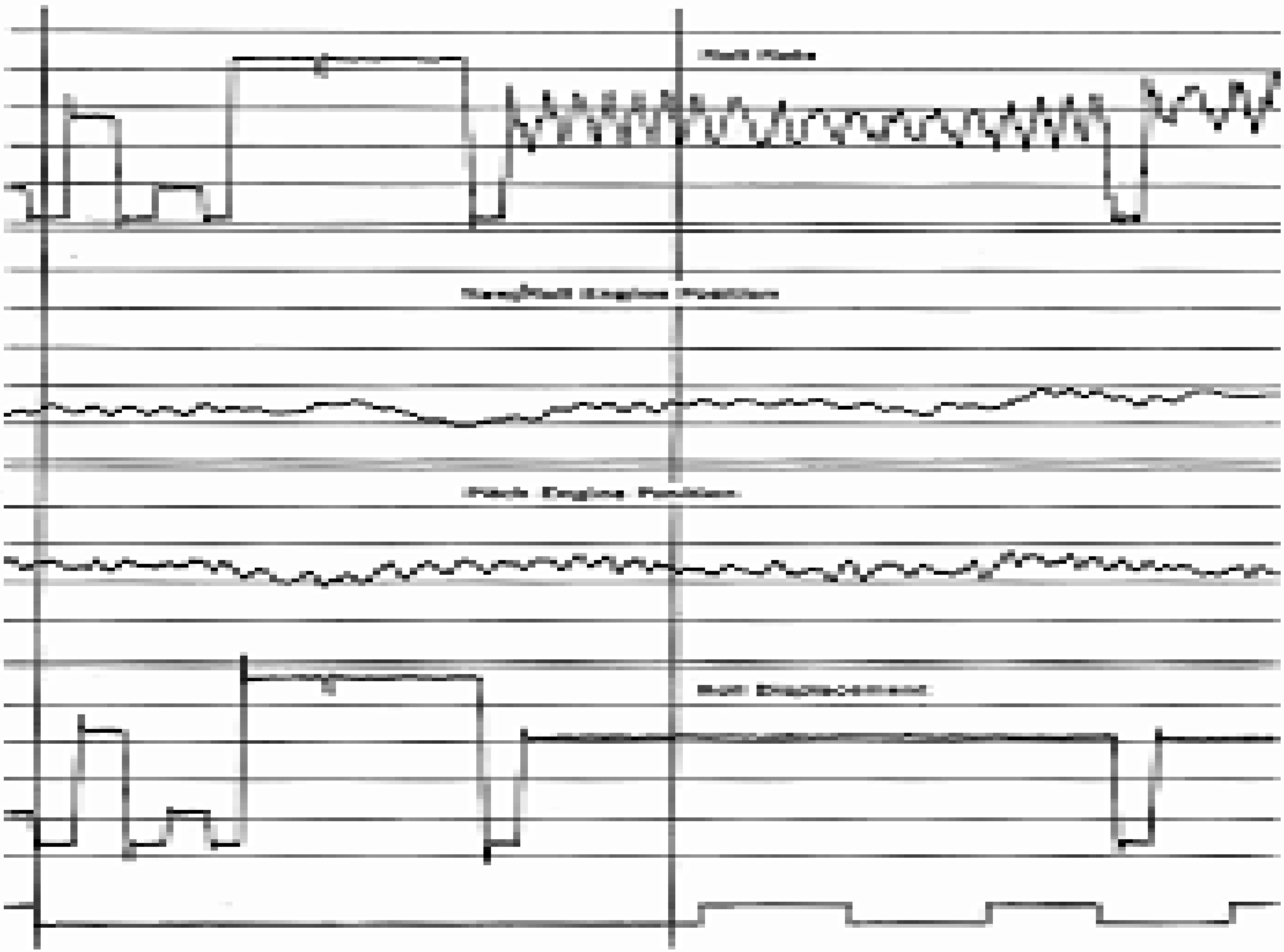


Fig. 1-6. Data recorded during an unstable flight of an Atlas missile; see text for details. (Courtesy of Convair Astronautics Division of General Dynamics Corporation.)

Aeroelasticity Problems for Spacecraft

Dynamic and aeroelastic problems of space vehicles requiring increased research activity

Launching	Space flight	Entry and landing
Determination of free vibration characteristics	Determination of free vibration characteristics	Determination of free vibration characteristics
Aero-structural interaction (including aeroelastic stability and possible thermal effects)		Aero-thermal-structural interaction (including aeroelastic stability)
Dynamic modeling	Dynamic modeling	Dynamic modeling
Dynamics of stage separation, rocket firing, and burnout	Dynamics of stage separation, rendezvous, mass transfer, and construction in space	Recovery and impact dynamics
Dynamic problems of propulsion systems	Dynamic problems of propulsion systems (thrust-structure interaction)	
Flight-testing techniques	Flight-testing techniques	Flight-testing techniques
Nonlinear mechanics	Nonlinear mechanics and free-body mechanics	Nonlinear mechanics
Effects of noise and vibration	Effects of noise and vibration	Effects of noise and vibration
Influence of transient environment (time-dependent inputs, including atmospheric turbulence and blasts)	Influence of transient environment and dynamic response to fields (electromagnetic, gravitational, space detonations, X-ray, colliding particles)	Influence of transient environment
Pre-launch and launching dynamics, including crosswind effect		
Unsteady gasdynamics		Unsteady gasdynamics (hypersonic and viscous flow)
Structural-control-system interaction	Structural-control-system interaction (including stability)	Structural-control-system interaction
	Orbital perturbation dynamics	

Various Effects on Aerospace Vehicles

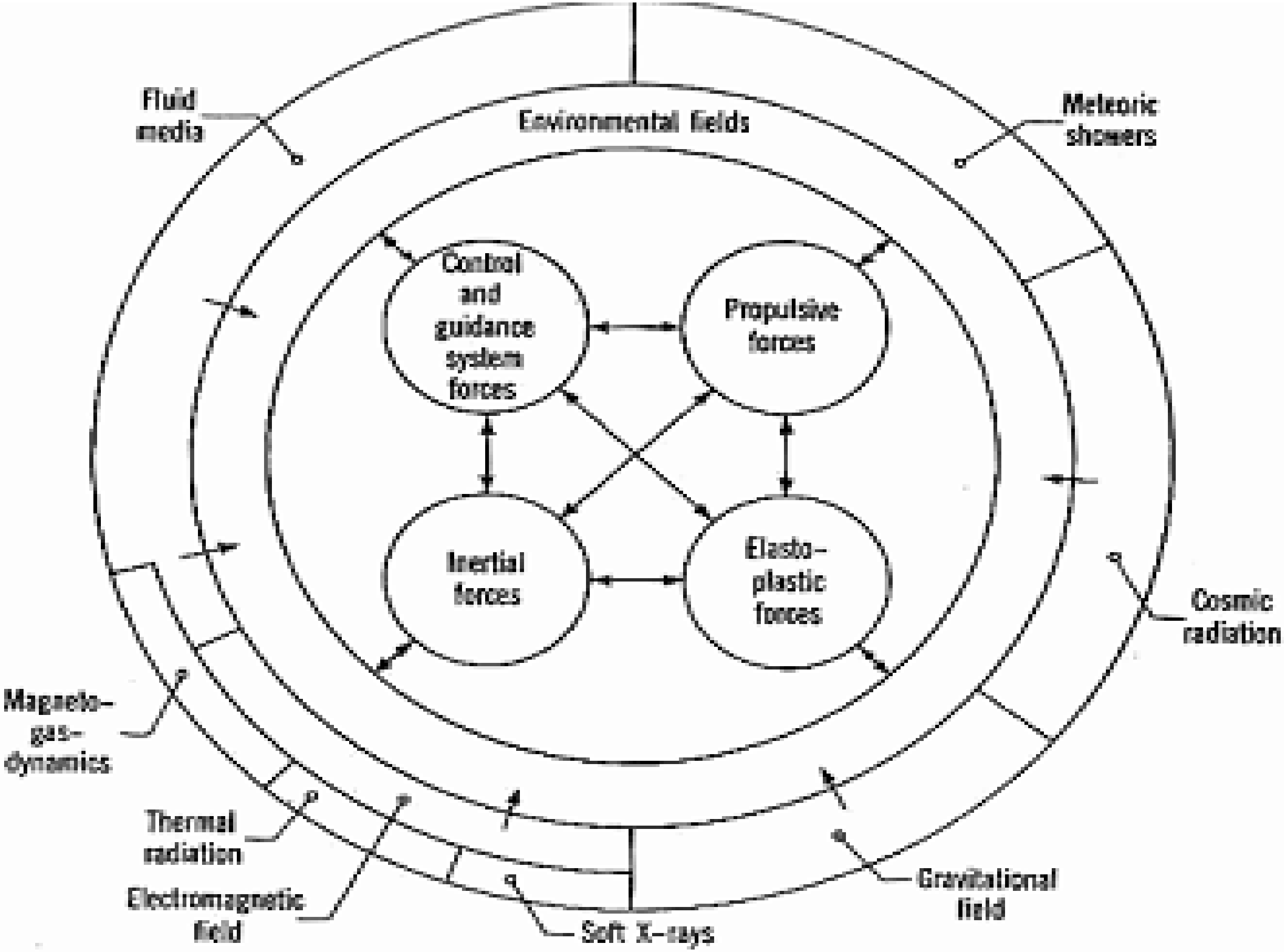
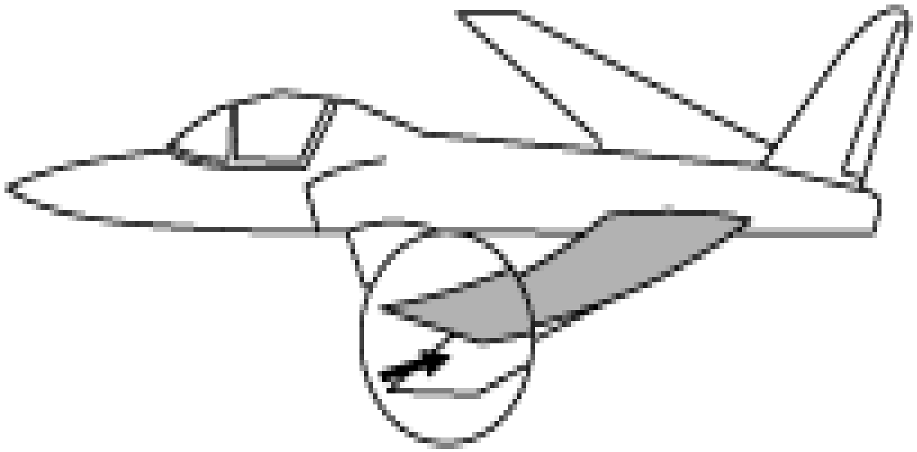


Fig. 1–7. The flight vehicle conceived as a collection of interacting forces surrounded by environmental fields.

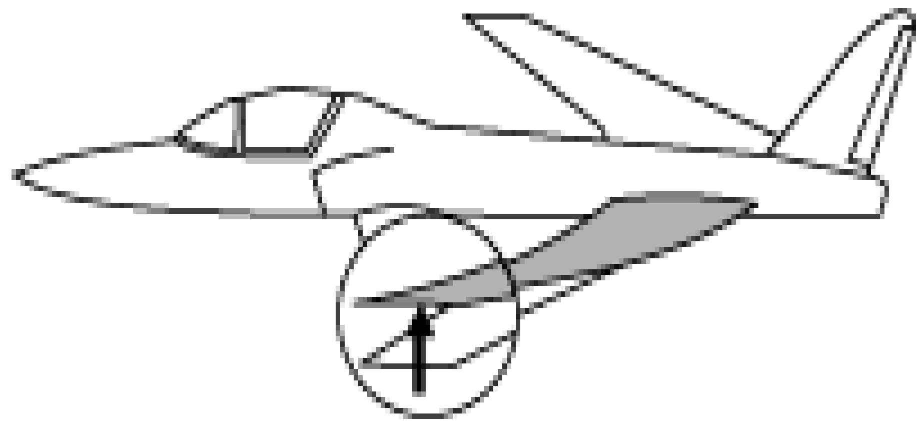
Aeroelastic Tailoring

- Due to the high level of concern for negative Aeroelastic events such as flutter, a new branch of aerospace engineering called Aeroelastic tailoring has submerged.
- Once an aerospace vehicle is designed, techniques of Aeroelastic tailoring is used to make changes in the craft to resist Aeroelastic effects.
- Usually this is done not by changing the design, but by changing the structural material such as by using composite materials on aircraft

Aeroelastic Tailoring

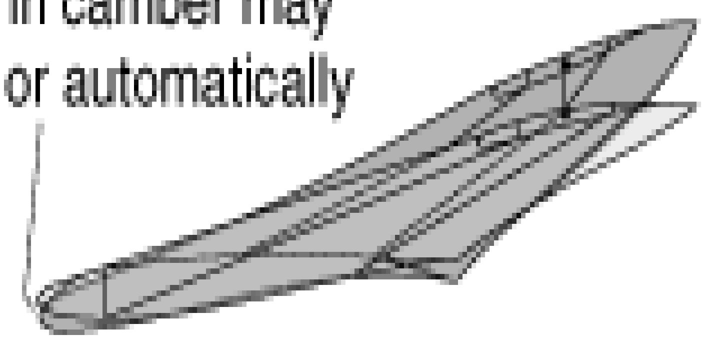


Conventional metal wing twists under load

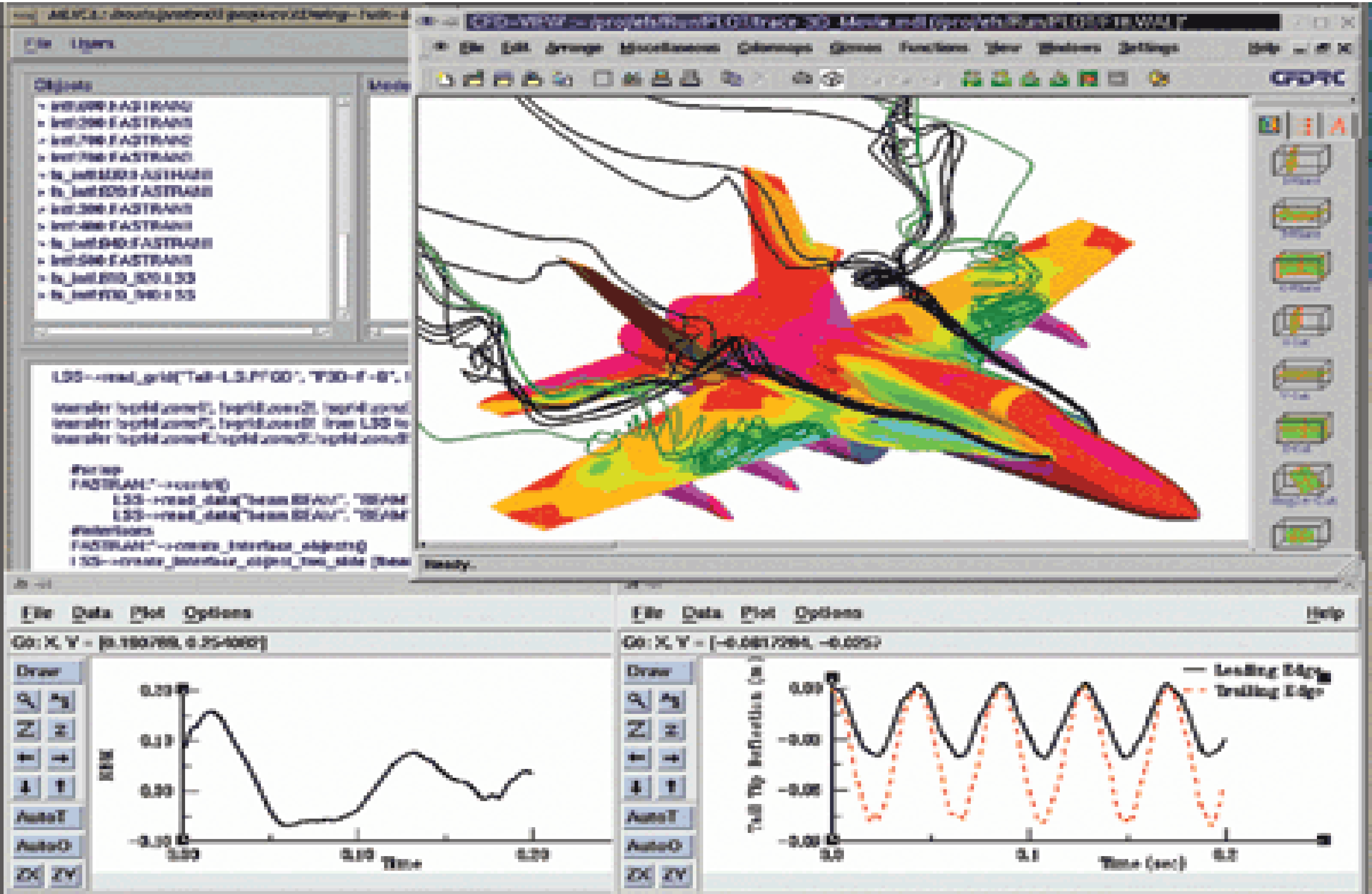


Composite wing: structure bends but does not twist

Variable camber on leading and trailing edges of a wing changes in camber may be effected mechanically or automatically



Aeroelastic Tailoring



Aeroelasticity and Engineering

- Aeroelasticity is not just confined to aerospace engineering as it is also used in several areas of mechanical and civil engineering.
- Especially in civil structures like power lines as well as suspension bridges, aeroelasticity can play a very important rule due to vibrational effects caused by aerodynamic loads.

Power Lines

- Among examples of engineering significance, the most familiar is probably the oscillation of telephone wires, with high frequency and small amplitude, producing musical tones.
- Smokestacks, submarine periscopes, oil pipe lines, television antennas, and other cylindrical
- Structures often encounter vibrational troubles of Aeroelastic origin.
- These may be cured either by stiffening the structures so that the natural frequency is much higher then the resonance frequency or by introducing vibrational dampers into the system

Vortex Shedding and Flow Separation

- Whenever vortex shedding is induced in a structure, it will cause vibrations that will effect the structure. This phenomena is especially observed with power lines.

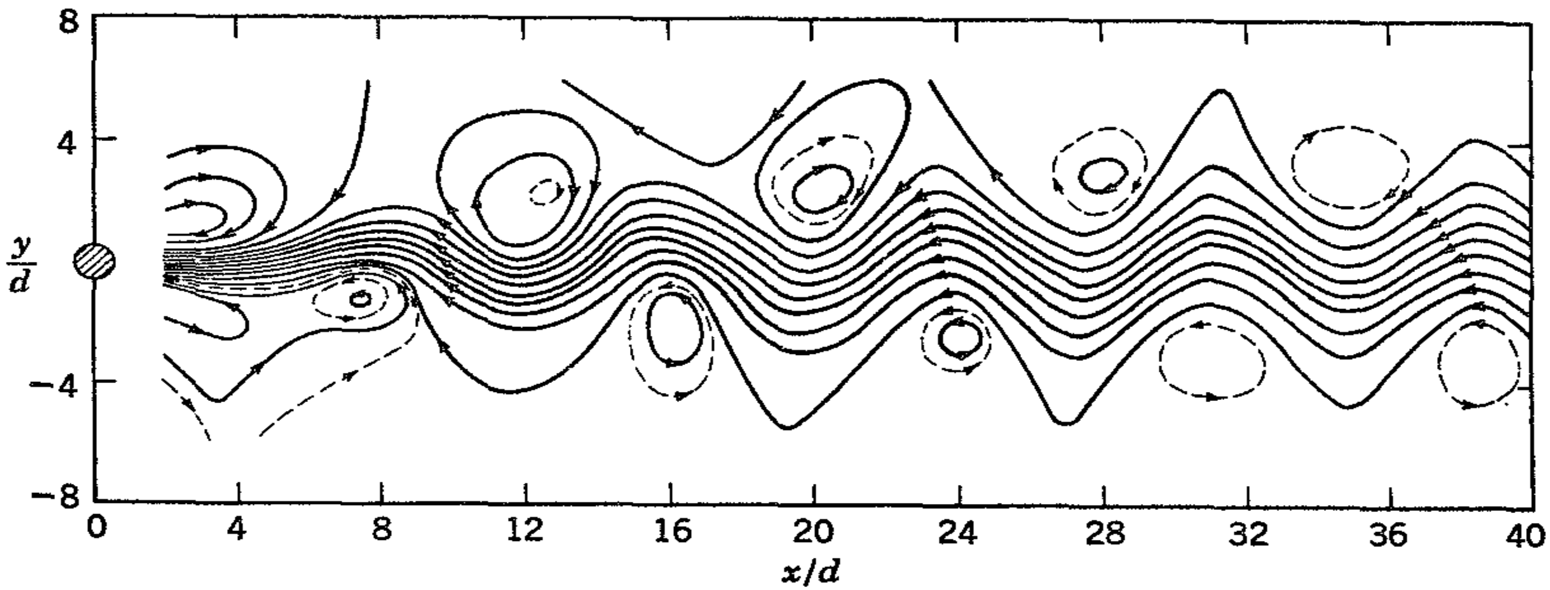


Fig. 2.1. The wake behind a circular cylinder. Reynolds number 56. Measurements by Kovasznay, Ref. 2.26. Figure shows the streamline pattern viewed relative to the undisturbed flow at infinity. The development and decay of the vortices can be seen. The lines correspond to differences in the stream function $\Delta\psi = 0.1\ Ud$; the dotted lines are half-values between two full lines. (Figure reproduced by courtesy of the Royal Society of London.)

Flutter

- Flutter is a self excited oscillation that does not necessarily involve flow separation or vortex shedding
- Flutter can occur in any object within a strong fluid flow, under the conditions that a positive feedback occurs between the structure's natural vibration and the aerodynamic forces. That is, that the vibrational movement of the object increases an aerodynamic load, which in turn drives the object to move further.

Flutter

- If the energy during the period of aerodynamic excitation is larger than the natural damping of the system, the level of vibration will increase, resulting in self-exciting oscillation. The vibration levels can thus build up and are only limited when the aerodynamic or mechanical damping of the object matches the energy input, which often results in large amplitudes and can lead to rapid failure

Flutter

- Even changing the mass distribution of an aircraft or the stiffness of one component can induce flutter in an apparently unrelated aerodynamic component
- At its mildest this can appear as a "buzz" in the aircraft structure, but at its most violent it can develop uncontrollably with great speed and cause serious damage to or the destruction of the aircraft

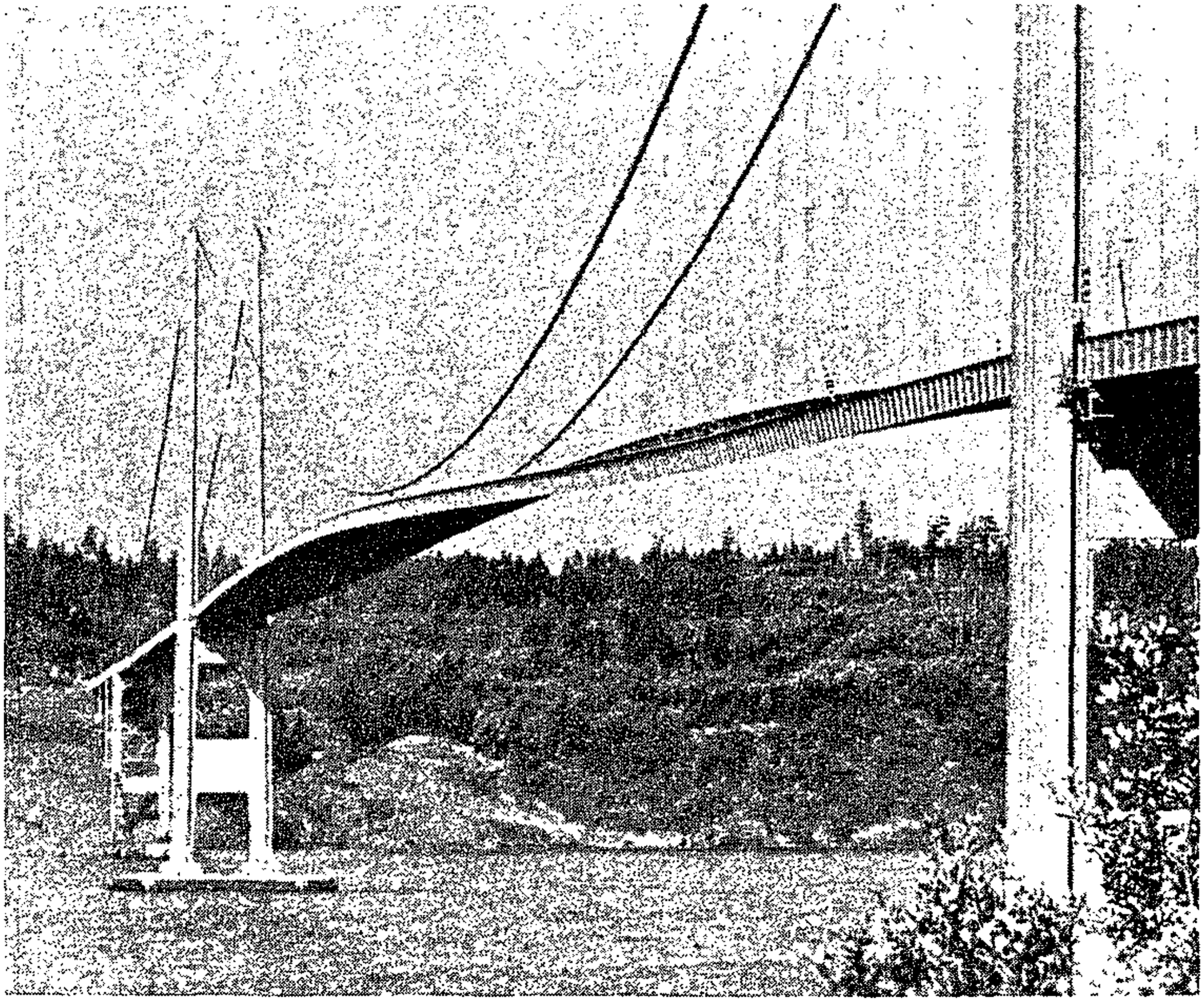
Flutter in Civil Structures

- Flutter can be of main concern in civil structures where separation of the flow may occur due to the oscillation of the structure due to aerodynamic loads.
- Especially suspension bridges are very susceptible to flutter. Even though they are streamlined so that flow separation doesn’t occur, high vibrational frequency near the resonance frequency can seriously effect the structural integrity

Tacoma Narrows Bridge

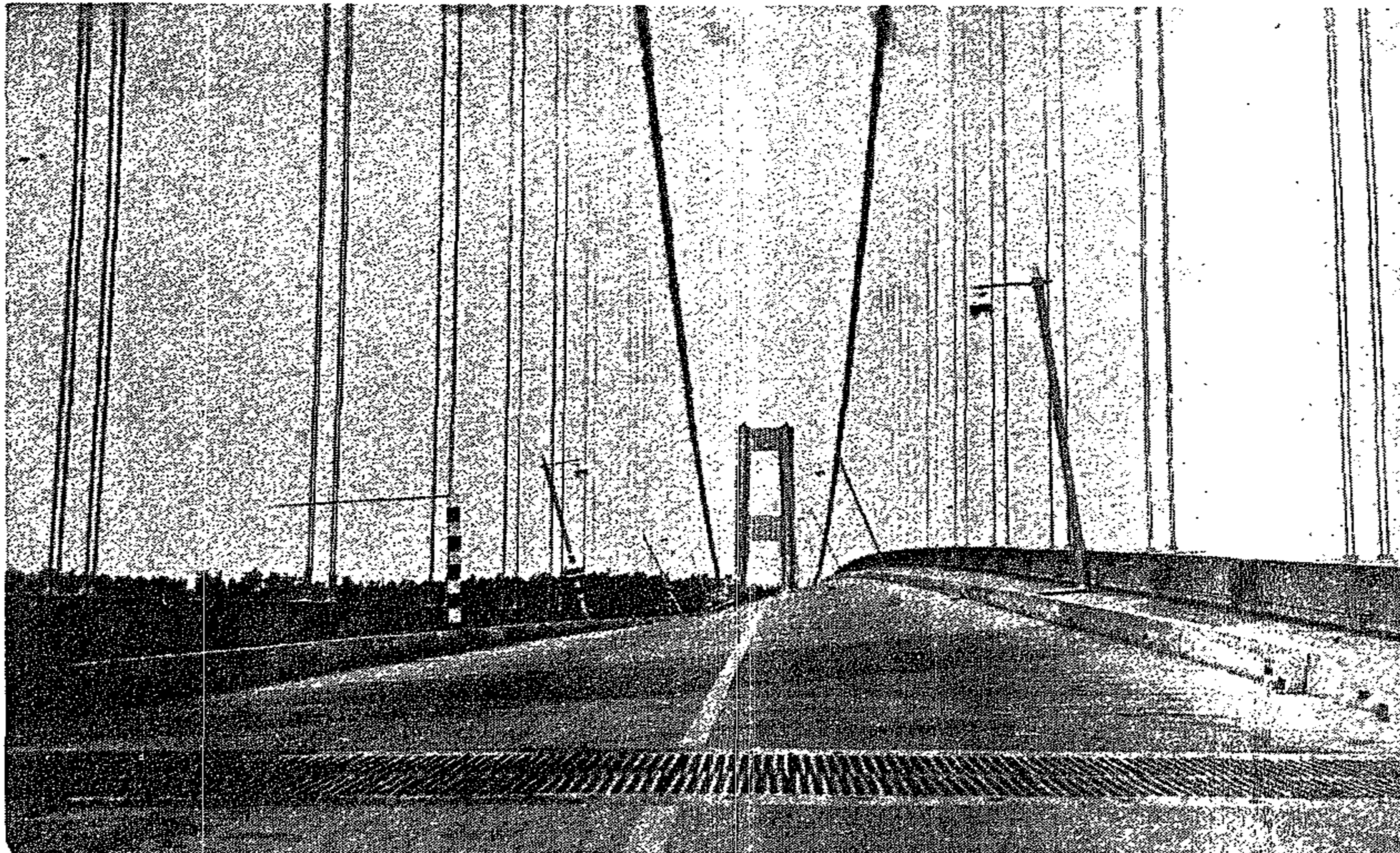
- The biggest example of flutter in civil structures has been the collapse of the Tacoma Narrows Bridge in which the structure collapsed only 4 months after opening.
- The collapse occurred when the wind speed was around 42mph and the frequency of the oscillation changed from 14 to 37 cycles per minutes
- The bridge collapsed under 30 minutes from its midpoint.

Tacoma Narrows Bridge



Stall flutter of the original Tacoma Narrows Bridge, Puget Sound, Washington. (Courtesy of F. B. Farquharson)

Tacoma Narrows Bridge



Tacoma Narrows Bridge

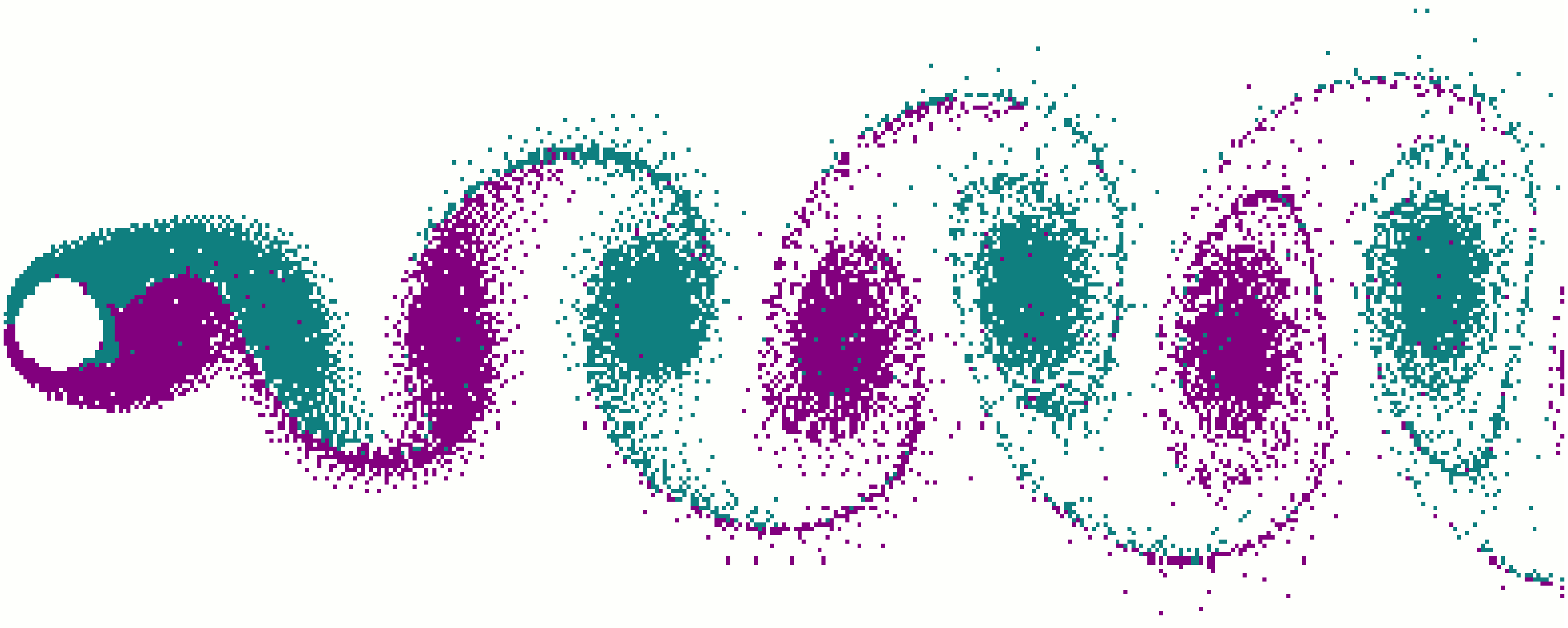
Flutter Velocity

- Movement inserts energy to the bridge during each cycle so that it neutralizes the natural damping of the structure; the composed system (bridge-fluid) therefore behaves as if it had an effective negative damping (or had positive feedback), leading to an exponentially growing response.
- In other words, the oscillations increase in amplitude with each cycle because the wind pumps in more energy than the flexing of the structure can dissipate, and finally drives the bridge toward failure due to excessive deflection and stress. The wind speed that causes the beginning of the fluttering phenomenon (when the effective damping becomes zero) is known as the **flutter velocity**

Karman Vortex Street

- Another Aeroelastic phenomena besides flutter is vortex shedding in the form of Karman Vortex Street.
- It is repeating pattern of swirling vortices caused by the unsteady separation of flow of a fluid over bluff bodies
- It can effect telephone wires as well as tall buildings and extremely large aircraft
- In low turbulence, tall buildings can produce a Kármán street so long as the structure is uniform along its height.

Karman Vortex Street



Karman Vortex Street

$$\frac{fd}{V} = 0.198\left(1 - \frac{19.7}{Re}\right)$$

- where:
- *f* = vortex shedding frequency.
- *d* = diameter of the cylinder
- *V* = flow velocity.
- The dimensionless parameter *fd/V* is known as the Strouhal number

Effect of Wind

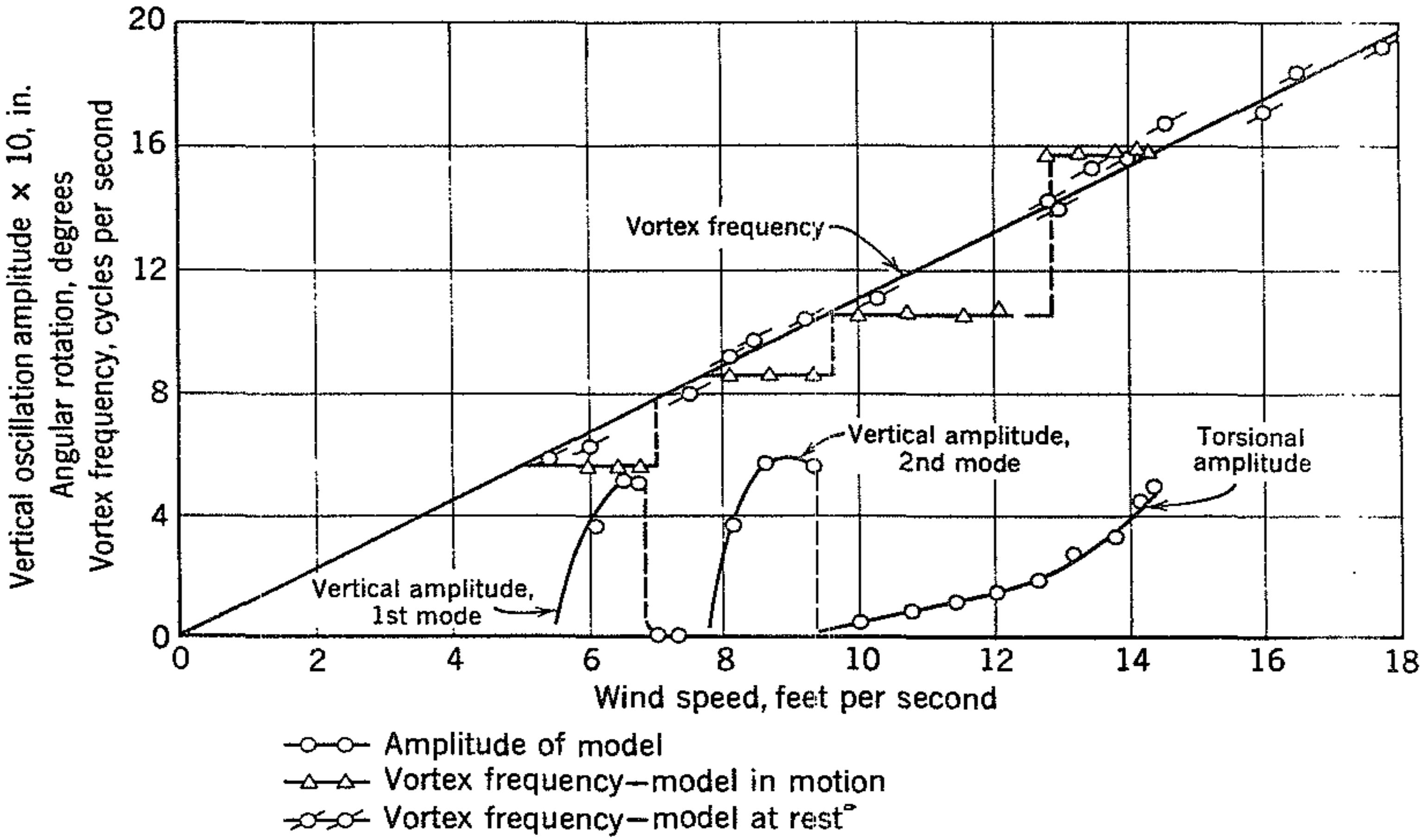


Fig. 2.8. Vortex frequency vs. wind speed. (Courtesy of Dr. L. Dunn of the Ramo-Wooldridge Corp. Formerly of the California Institute of Technology.)

Amplitude of Oscillations vs Wind

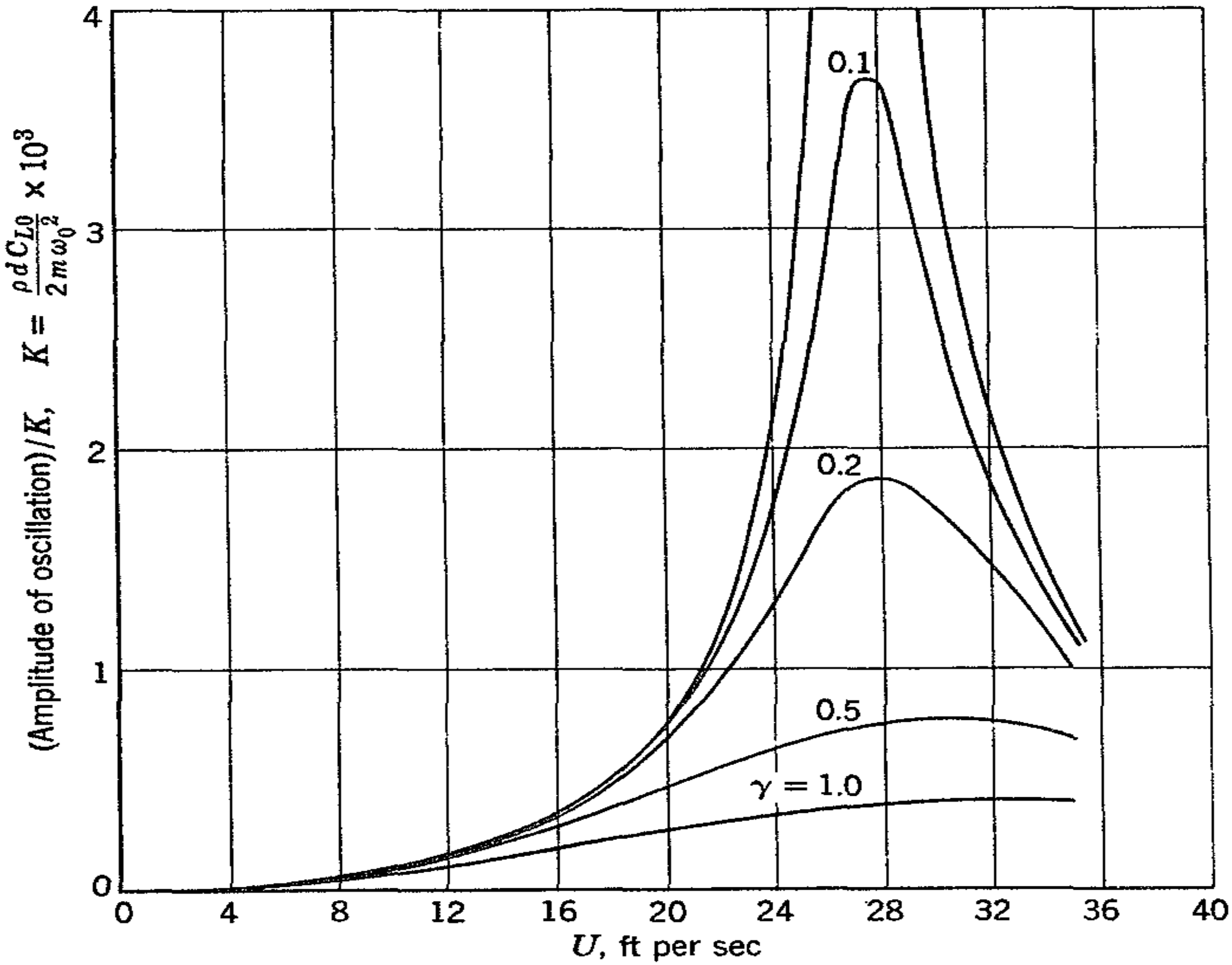


Fig. 2.6. The amplitude of oscillation as a function of wind speed. (d = 30 in., ω_0 = 2.5 cycles per second).

Prevention of Aeroelastic Instabilities

- Aeroelastic oscillations cannot be always prevented
- However, oscillations can be damped or the amplitude of the oscillations can be bounded for the entire range if flow speeds.
- Hence, different methods have been devised for reduced aerodynamic loads and vibration through strengthening the material or by changing the design shape

Prevention of Aeroelastic Instabilities

- For a cylindrical body, the resonance oscillation between the structure and the shedding vortices can be avoided by providing the structure with sufficient stiffness so that the natural frequency of the structure is much more higher then the frequency of the vortices.

Prevention of Aeroelastic Instabilities

- For an unstable aerodynamic section, the only way of preventing large amplitude oscillations is to provide sufficient damping of the system.
- However, this damping must be made in such a way that the overall stability of the flight vehicle must not be compromised
- Again using composite materials is usually a good idea as they can be built with semi damping capabilities

Prevention of Aeroelastic Instabilities

- In a civil engineering structure, aerodynamic forces are undesirable and an ideal section is one that produces no lift or drag.
- Usually many civil structures are designed in a streamlined manner so that flow separation will not occur and flutter can be predicted with good accuracy.
- In addition, decreasing the projected frontal area against the wind will decrease the magnitude of the aerodynamic forces

Prevention of Aeroelastic Instabilities

- Aerodynamic forces are proportional to the vorticity strength, which in turn is proportional to the profile drag.
- A reduction in projected frontal area reduces the profile drag and hence reduces the effective aerodynamic force

Prevention of Aeroelastic Instabilities

- Changing the configuration of the control surfaces would also work as you would be able to change the position of flow separation as well as you will be able to dampen the oscillations up to some degree.
- Nowadays, all major flights are flown purely on autopilot in which the flight computer evaluates the information from its sensors and adjusts the control surfaces as well as engine power and navigation systems constantly

Flow Separation

- Flow separation along with flutter is an important Aeroelastic phenomena.
- The flow in the boundary layer is pulled forward by the free stream, but is retarded by friction at the solid wall as well as by the adverse pressure gradient. (since pressure difference is an important part of flows)
- If the adverse pressure gradient is sufficiently large, the flow will reverse on itself and detach completely and become separated.

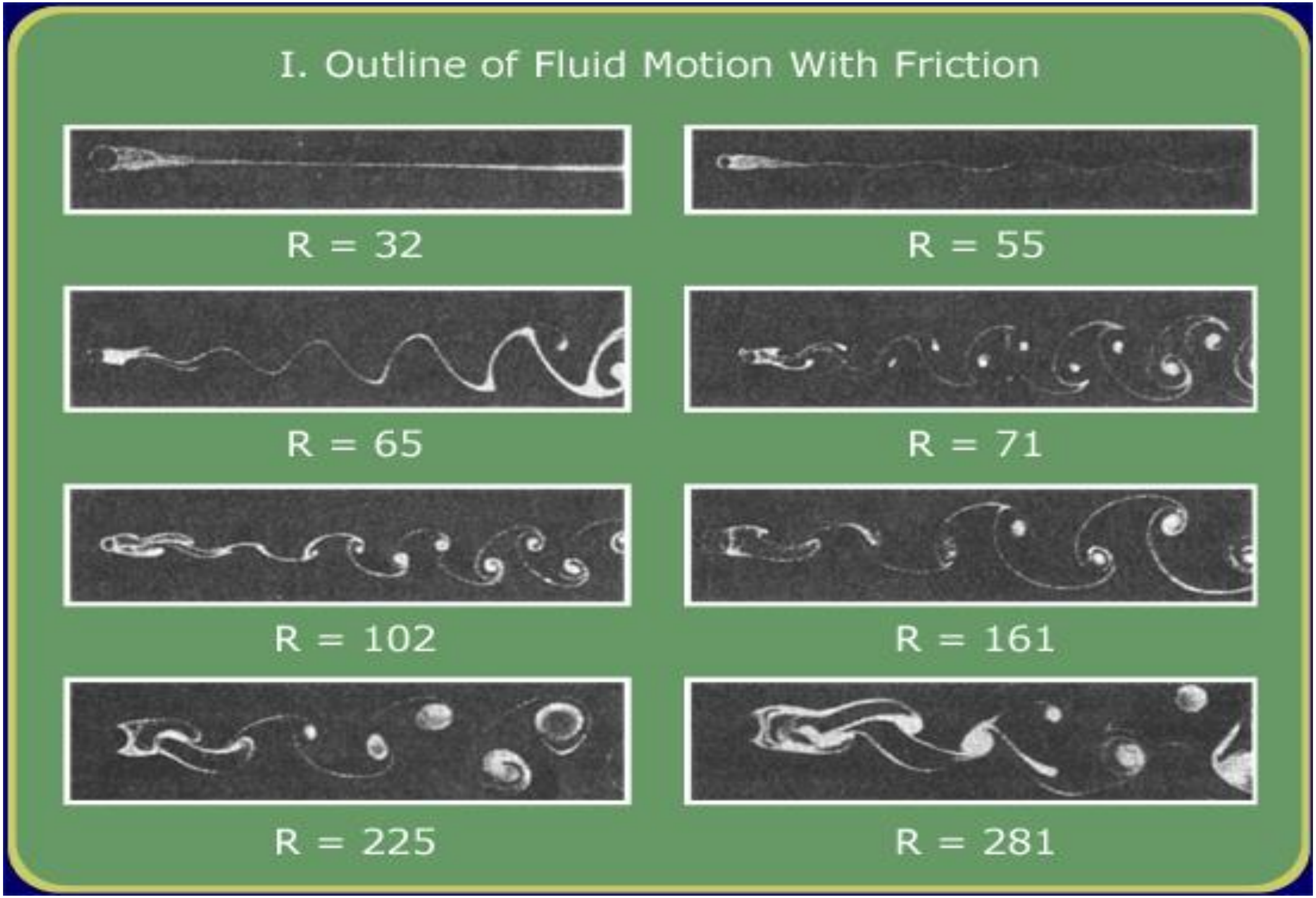
Flow Separation

- A streamlined body maintains a smooth flow when it is properly situated in the flow, but when the angle between the chord and the undisturbed stream is sufficiently large , separation may still occur.
- Hence, both the Reynolds number as well as the Strouhal number are very important in understanding the phenomena of separation

Importance of Reynolds Number in Aeroelasticity

- Reynolds number expresses a ratio between inertial forces and the friction force.
- A flow pattern is determined by the interplay amongst the pressure gradients, friction as well as inertia.
- A small value of the Reynolds number means friction forces predominate, while a large value means inertial forces dominate
- High Reynolds numbers will cause turbulent flow and as a result excite oscillations in an elastic structure

Reynolds Number Effect



Strouhal Number

- As defined before in the Karman Vortex Street, Strouhal number is also another important parameter in aeroelasticity.
- k = fd/V
- *Frequency is defined as radians per second*
- Strouhal number has a tendency to rise as the Reynolds number also rises. However, the relationship is not linear in nature and can depend upon the shape of the object as well too

Relationship Between Strouhal Number – Re - C_d

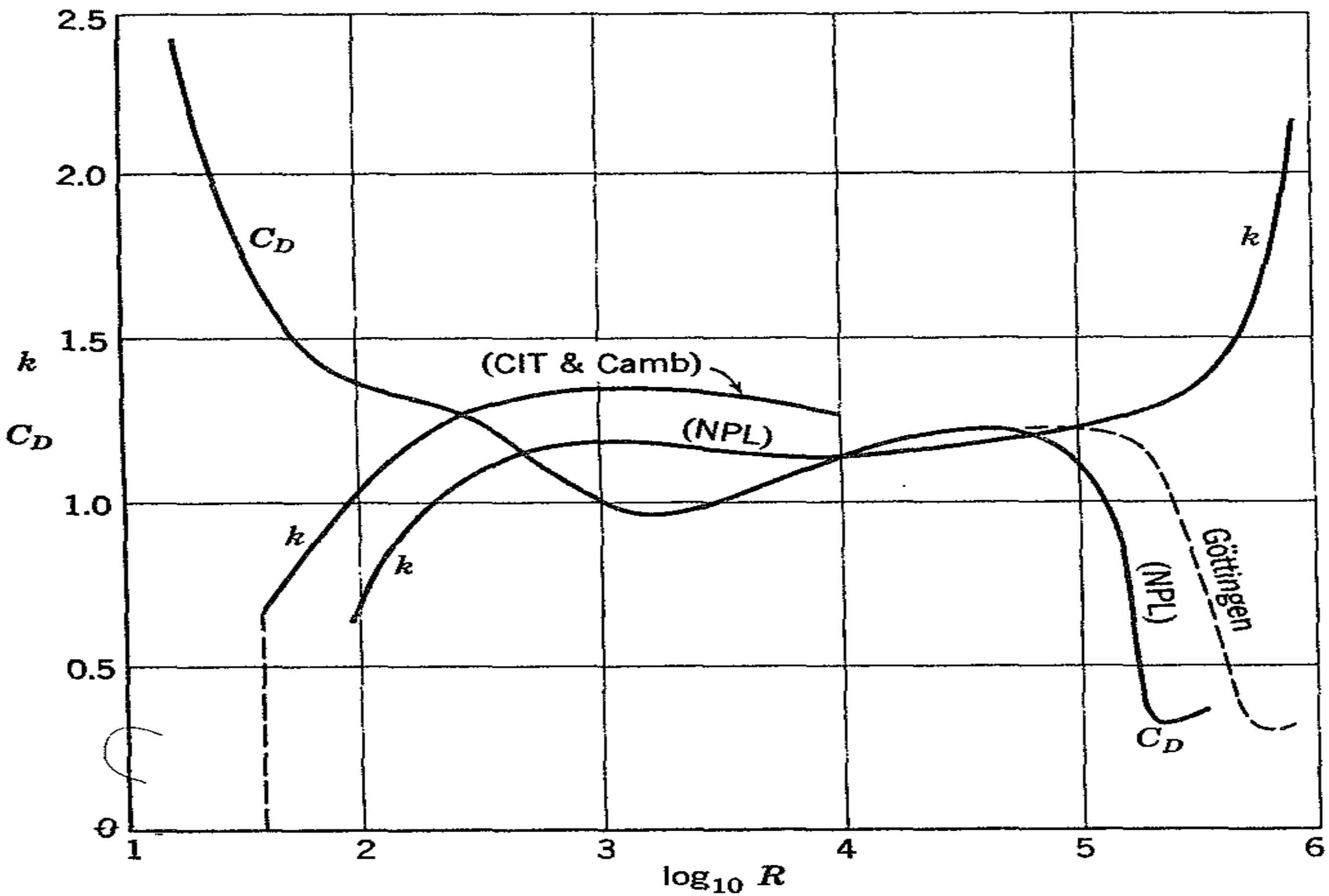
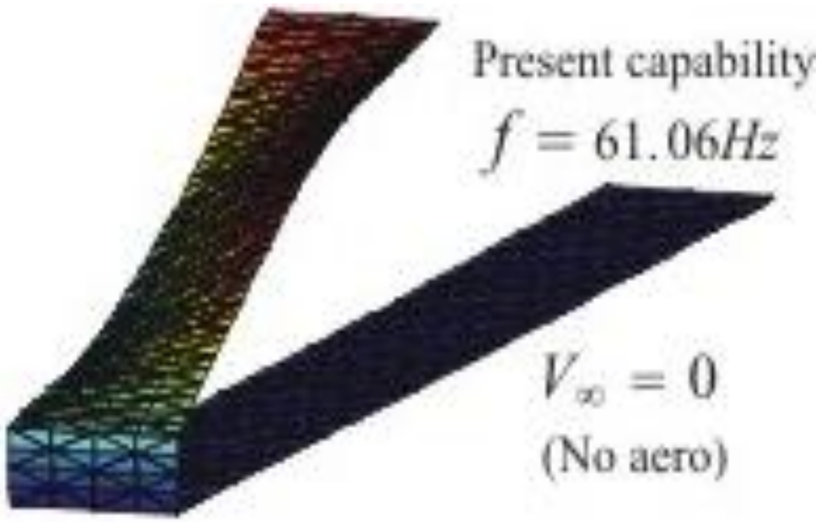
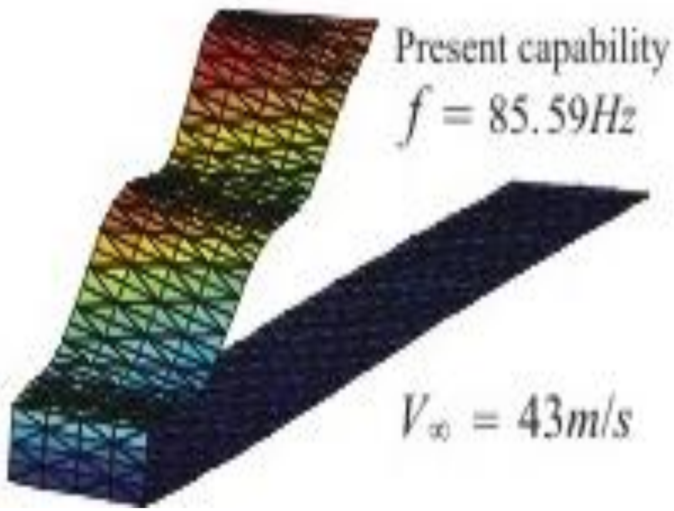


Fig. 2.4. Variation of the Strouhal number and drag coefficient against Reynolds number for a circular cylinder. C_D and R are based on the diameter of the cylinder. Sources of data are: NPL; Relf and Simmons, *Aeronaut.*

Effect of Frequency and Aeroelasticity





THANK YOU

Please refer to the following website for further lectures on Aeroelasticity

www.aerospacelectures.co.cc

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