AEROELASTICITY

4.1. INTRODUCTION

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AEROELASTICITY

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4.1.1. AEROELASTIC PHENOMENA
- A HISTORICAL REVIEW

The subject and domain of aeroelasticity

Aeroelastic or ***hydroelastic phenomena***

Phenomena in which deformable objects are deflected or driven to motion by moving medium (air or water).

Aerohydroelasticity

A domain of mechanics that concerns the analysis of phenomena in which a mutual interaction of fluid and deformable bodies occur.

Aviation aeroelasticity deals with the analysis of the phenomena that occur during flights of flexible aircraft or rockets in the air.

Examples:

- swing of trees, waving of cereals, waving of banners,
- wind induced oscillations of towers, chimneys or bridges,
- oscillations of wires of the transmission lines.

Aeroelastic phenomena are sometimes rapid and they may cause destruction of the objects, e.g.:

- snapping of trees, destructions of chimneys or bridges,
- rupture of wires of the transmission lines,
- destruction of wings or stabilizers of aircraft, turbine blades or helicopter rotor's blades.

In aeronautics the aeroelastic phenomena manifest as deflections or moving of the elements of aircraft structure caused by aerodynamic forces induced by the flow.

Examples:

- deflections and vibrations of wings and stabilators,
- vibrations of controls,
- vibrations of helicopter’s rotor blades,
- vibrations of blades of jet engines turbines.

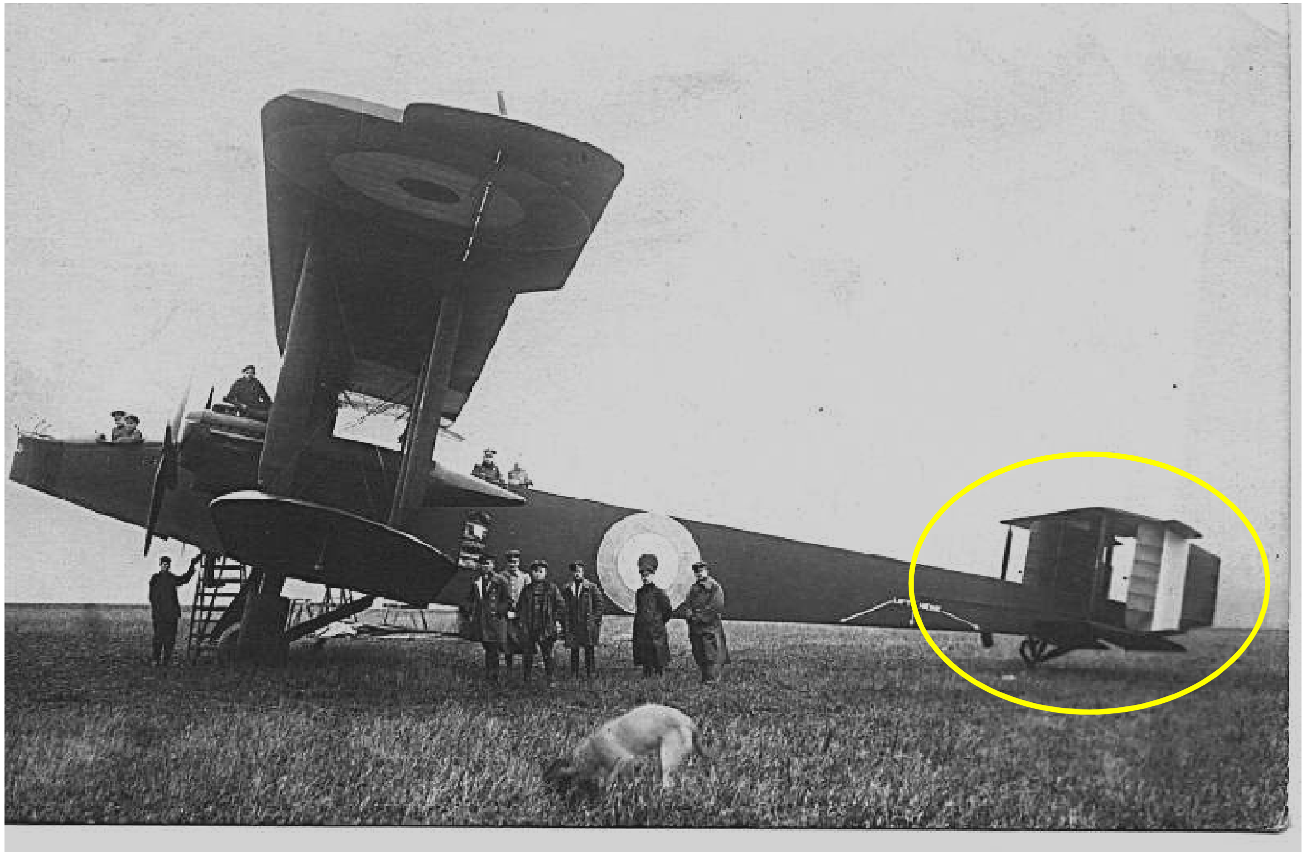
The most important, famous and dangerous aeroelastic phenomenon in aviation is **flutter**.

Flutter is the quick oscillations of the airplane (e.g., the wing) that occur during the flight with sufficiently high speed, called **the critical velocity**.

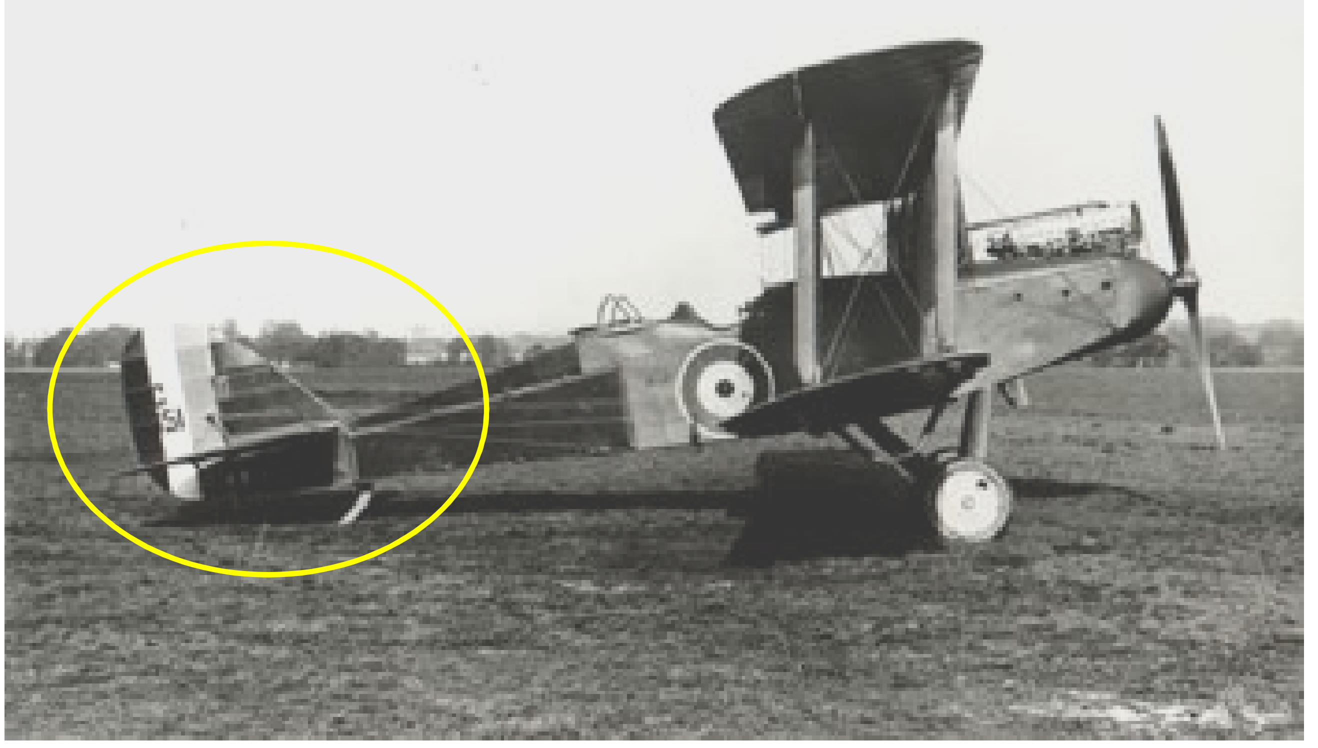
Flutter is usually a rapid phenomenon.

Flutter often destroys the wing structure.

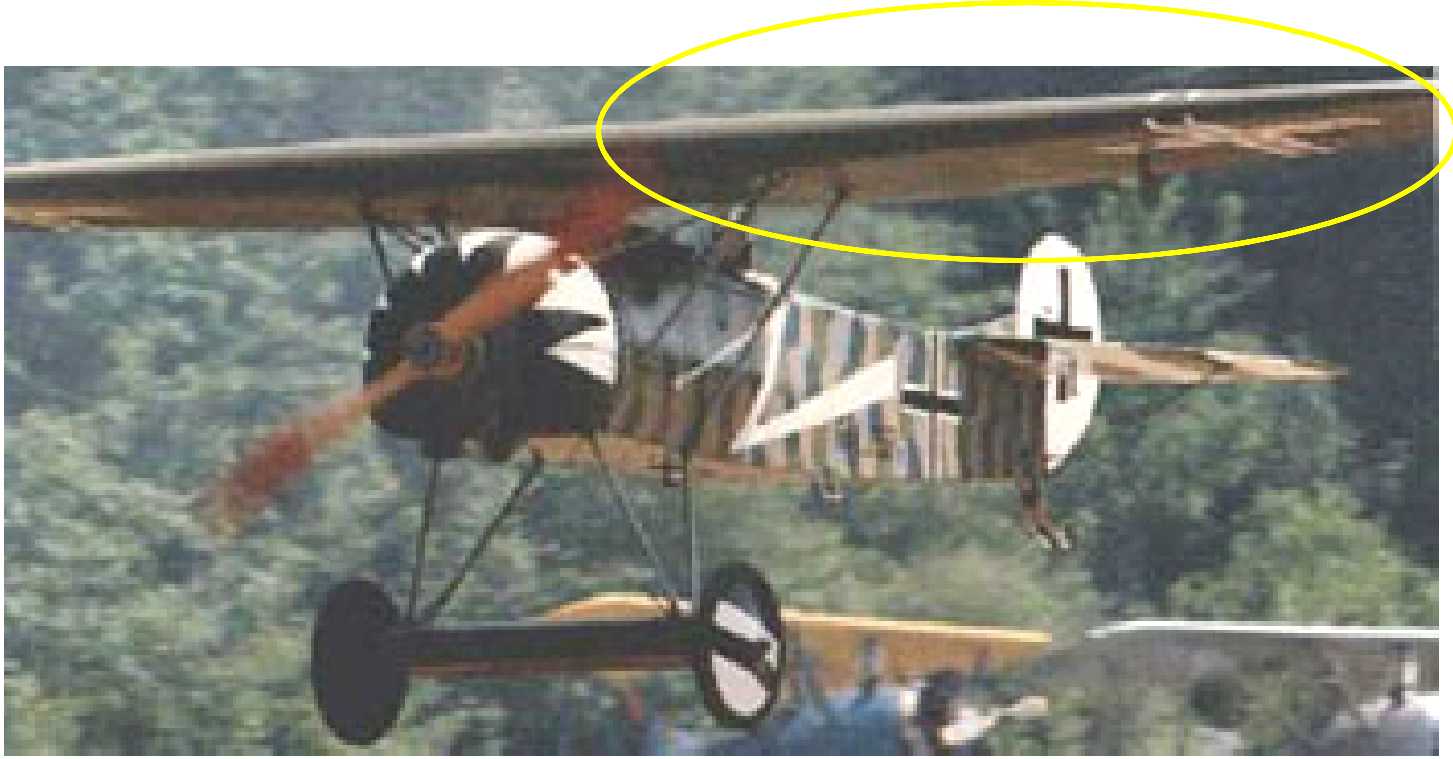
Almost a hundred years ago ...



The Handley Page 0/100 bomber – the first aircraft that was a victim of the flutter of stabilator (1914)



The De Havilland DH-9 bomber – the next victim of the stabilator flutter (1914)



The Fokker D-VIII fighter – the aircraft on which the divergence of the wing occured during the diving (1916)

The characteristic feature of the bomber's disasters were vibrations of fuselage’s tail and stabilators.

It was then the dynamic aeroelastic phenomenon - **the flutter**.

In cases of the bomber's disasters the intuition told the engineers, that they had to stiffen the aircraft’s tail and stabilators.

The Fokker’s disasters were quite different – there were no vibrations before the wing’s fracture.

It was the static aeroelastic phenomena – **the divergence**.

After a long analysis Anthony Fokker understood, that the reason of those disasters was the aerodynamic twisting of the wings.

Also in this case the solution was the stiffening the wing’s structure.

The speeds of the aircraft quickly increased that times, however, that enhanced occurring of flutter on the newly built machines.

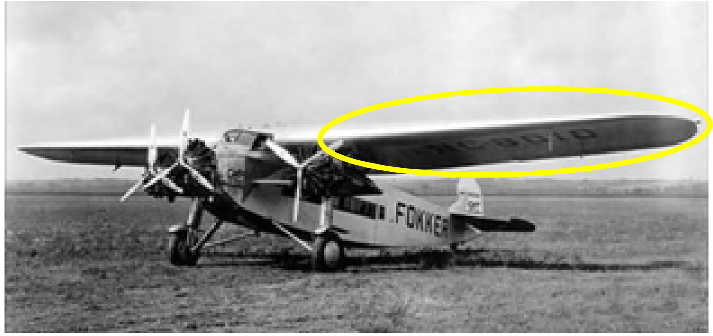
Reasons of disaster:

– too low siffness of the structures,

– lack of elementary aeroelastic knowledge.

Flight 599 Kansas City – Los Angeles, USA, Mach 31, 1931, Cottonwood Falls.

The Fokker F10 Trimotor passenger's aircraft disaster.



There were nine victims in this disaster, the famous football coach among others.

The reason was the flutter that caused fracture of the wing.

The flutter occurred due to weakening of the wing structure caused by softening of the glued joints by a fuel.

The disaster followed important consequences:

- the airlines had to withdraw Fokker's F10 from duty,
- it caused establishing the Federal Aviation Administration (FAA)

Reason of disaster – improper operation.

The Gee Bee R2 – the racing aircraft on which the wing flutter and the flutter of ailerons occured (1930)

It had been established experimentally, that one could prevent the aileron's vibrations by the forward mass balancing, that is – shifting forward the mass center of the aileron.

Also, the other undesirable aeroelastic phenomena occurred that times, e.g., the reverse action of the controls (especially the ailerons).

Reason of disaster – wrong mass balance of controls.

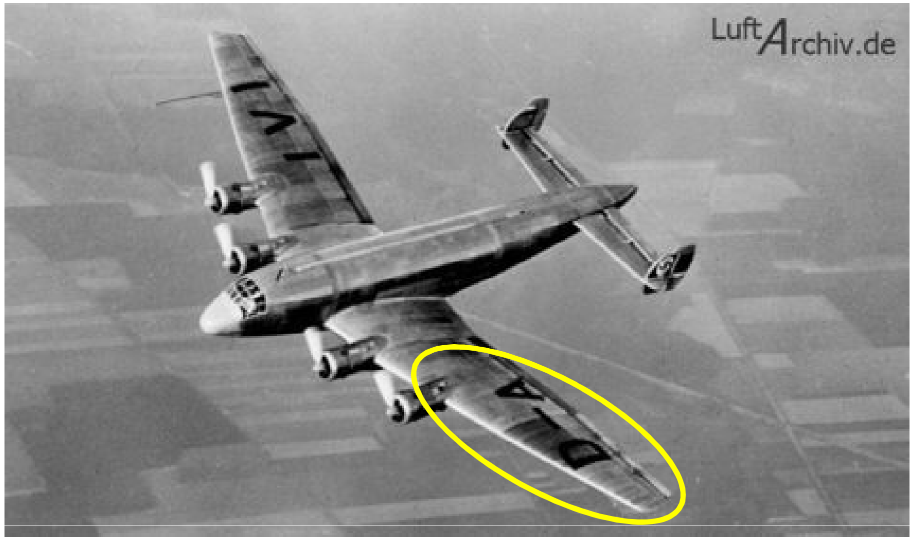
Disaster during the airborne flutter tests, Ju-90 VI - prototype

February 6, 1938, Germany

The aircraft crashed during the airborne flutter tests.

The tests were planned very carefully.

All the crew were killed, including the engineers – the flutter experts.



This disaster visualized a great danger of the airborne flutter tests.

It had been realized, that the flutter tests had ultimately to be preceded by exceptionally careful theoretical analysis.

It seemed evident, that the theoretical analysis had to predict the critical velocities of all the possible aeroelastic phenomena with sufficient likelihood and accuracy – that assures the safety during the flutter tests.

Reasons of disaster:

– inaccurate determination of the flutter speed,

– lack of accurate methods of aeroelastic analysis.

One then learned gradually - by bloody trials and errors - how to prevent the aeroelastic disasters.

Before the 30. of the XX. Century there was not a theory, however, that enabled one to predict these disasters in a systematic manner.

The urgent necessity of developing the adequate models of the aeroelastic phenomena has then emerged.

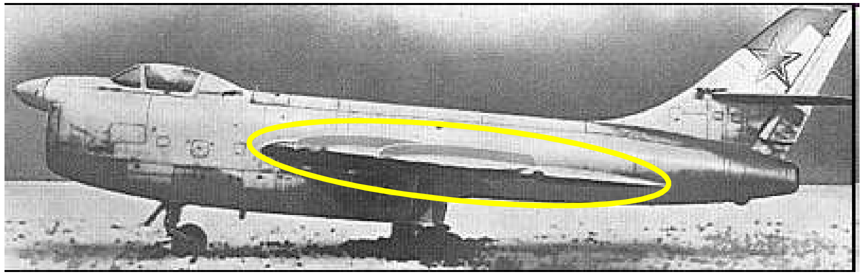
These models were required to be able to determine the so called critical velocity, at which the aeroelastic phenomena might occur.

The very first models were developed at 30. of the XX Century by:

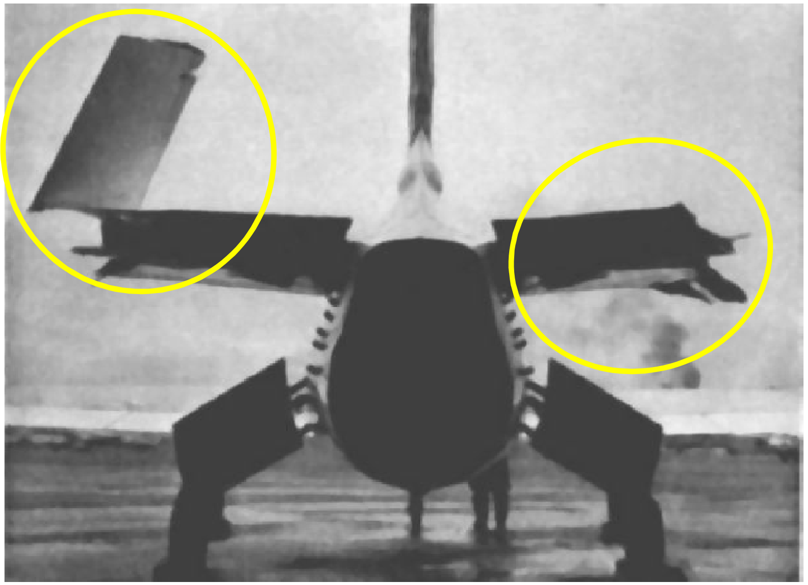
- Theodorsen, Garrick (USA),
- Küssner, Schwarz (Germany),
- R.T. Jones (GB),
- Nekrasov, Keldysh (USSR).

A quick progress of the aviation during the II World War and after it caused the occurrence the brand new aeroelastic problems – especially when aircraft and rockets had broken the sonic barrier.

In 3 July 1949, during the 39. test flight of the Su-15 (P) prototype aircraft, the wing flutter occured. Pilot had ejected and survived.



The F-86 „Sabre” fighter after successful landing despite damaging of the horizontal stabilator caused by flutter (Korea, 1950)

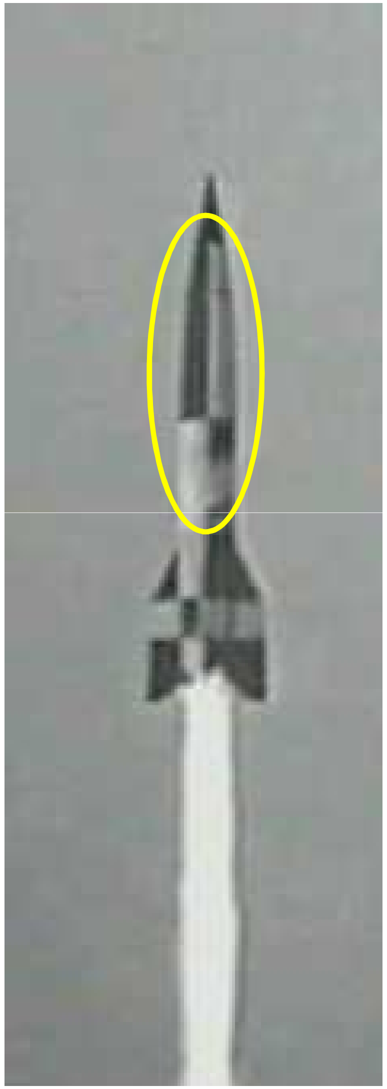


A brand new aeroelastic phenomena had appeared…

In the years 1943-1944 German rockets V-2, that were able to achieve a high supersonic speed (Ma > 2), underwent mysterious disasters during the high speed phase of the flight.

They simply bursted apart at high altitudes.

At least 70 rocket was destroyed.



Reason of disaster – the panel flutter.

A brand new aeroelastic phenomena had appeared…

The Lockheed L-188
„Electra” passenger aircraft

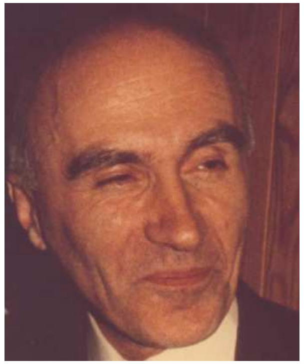
...after the disaster
caused by the whirl flutter
(1960)

Reason of disaster – the whirl flutter

Famous aircraft having problems with flutter...

- PZL P-23 „Karaś”
- Messerschmitt Bf-109 B
- RWD-6 (1936)
- Focke Wulf Fw 191
- Supermarine „Spitfire” Mk.III
- Avro „Lancaster”
- De Havilland DH-98 „Mosquito”
- Lockheed P-38 „Lightning”
- Mitsubishi A6M „Zero”
- Hawker „Typhoon”
- Chance Vought „Corsair”
- Boeing B-29 „Superfortress”
- Su-15
- North American F-86 „Sabre”
- Mucha 100 (1953)
- Lockheed L-188 „Super Electra”
- SZD-21 „Kobuz” (1960)

⇦



Prof. Władysław Fiszdon

(1912-2004)

In 50. and 60. of the XX Century he was Head of the Department of Mechanics of the Faculty of Power and Aeronautics

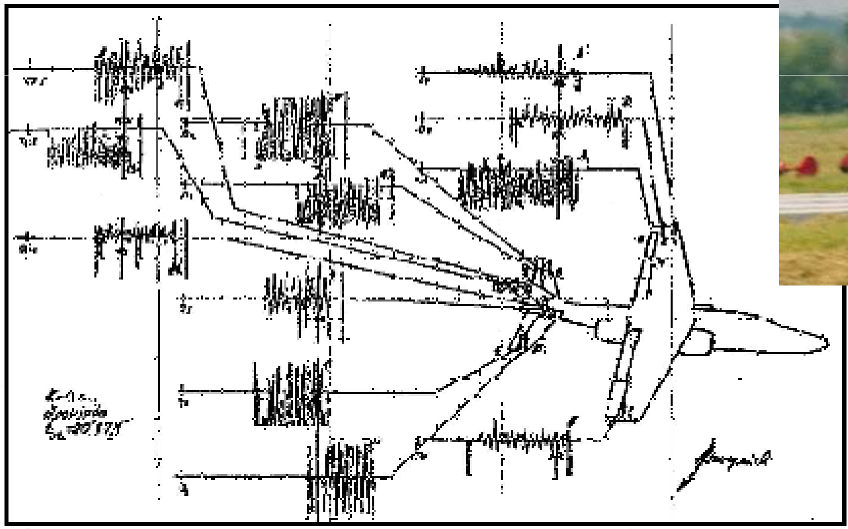
Before the Sixties of the XX. Century the adequate models of majority of aeroelastic phenomena were developed.

It enabled then to include the aeroelastic analysis to the designing process of aircraft…

…but it does not eliminate completely the danger of flutter occurrence!

Even the modern aircraft undergo disasters caused by flutter…

The Polish I-22 „Iryda" aircraft underwent disaster January 30, 1987 in course of airborne flutter tests – the stabilator flutter had occurred.



Reasons of disaster:

– contravene the regulations,

– improper operation.

Even the modern aircraft undergo disasters caused by flutter…

The F 117 „Nighthawk" stealth aircraft – underwent the disaster in September 14, 1997, in a consequence of the aileron's flutter caused by incorrect assembling of the control system after the technical inspection.

Flutter of the F-117 stealth aircraft

Baltimore, USA, September 14, 1997, air show.

It was the first flight of this airplane after inspection and reparation of the system of aileron control.

The velocity of the aircraft was about 750 km/h, that is much less than the critical velocity of flutter of the F-117.

During the climbing the vibrations of the external part of the left wing occurred, caused by the four quick vibrations of the aileron.



The reason of the vibrations were the plays in the aileron control system.

After the disaster all the 33 F-117 aircraft were inspected and none of them exhibited vibrations, even at higher velocities.

Despite this, in all aircraft manufactured after the disaster the system of aileron control (its actuators) had been stiffened.

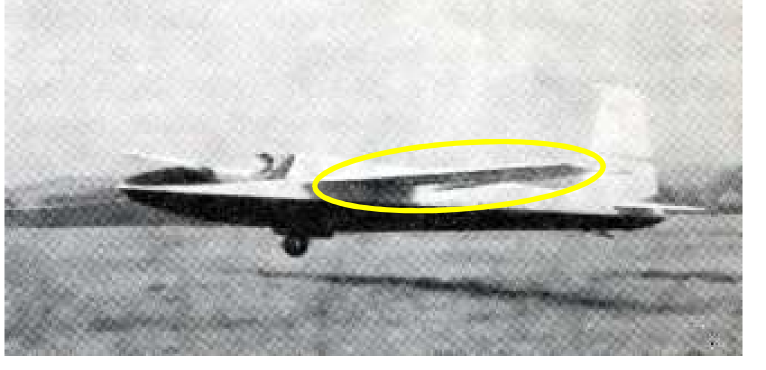
Reason of disaster – improper operation.

Flutter may also occur on gliders and light airplanes

The SZD-12A „Mucha 100 A" glider disaster (November 1953)
In course of the maximal speed flight test the aileron flutter occured. The glider underwent a partial destruction.
Pilot survived due to a parachute jump.

The SZD-21 „Kobuz" 2A glider disaster (20 April 1963)
In course of the flutter test flight the bending-torsion wing flutter occured.
Reasons:

- poor flutter knowledge,
- flight was not prepared properly,
- flutter speed was not evaluated (!!!)



Reason of disaster – improperly performed flight tests.

Flutter of the JK-05L aircraft

Krosno, April 26, 2004.

The first flight of the aircraft after modification to the version JK-05L.

The aim was checking the handling qualities of the aircraft and accelerating to the velocity >200 km/h.

At the instrumental velocity that exceeded 200 km/h, on altitude 450 m, the wing flutter occurred.

Flutter's vibrations caused fracture of the left wing and flaperon on the right wing at 2/3 of its span.

Another similar disaster – the Sky Cruiser aircraft (2006), Poznań

Reasons of disaster: – contravene the regulations,
– improper operation.

Flutter of the JK-05L aircraft – some details

The Komisja Badania Wypadków Lotniczych (Polish counterpart of Federal Aviation Administration) has ruled that:

- The flutter analysis of the balancing of mass of the flaperons for the maximal speed greater than 200 km/h was not carried out.
- The calibration of speedometer did not meet the requirements of the tests programme and was insufficient for the safety of flight - pilot was not able to precisely evaluate the flight speed.
- The (ignored!) information about the same aircraft obtained from France suggested, that the velocity indications in the upper range of the speedometer might differ from the real ones even by 40 km/h (20%) towards the unsafe values.
- Weather conditions (especially high turbulence) did not fulfill the required conditions for such types of tests flights and might also be the reason of the disaster.

The disaster has been classified as „contravene the regulations”.

Flutter is thus still very dangerous!

Regardless a great progress in understanding the flutter phenomenon it is still dangerous for several reasons:

- Ignorance: amateur designers frequently do not know on flutter at all!
- The manufacture or assembly errors may lead to decrease of the stiffness of the structure.
- The amateur aircraft often do not undergo of the complete cycle of the ground vibration tests and airborne flutter tests.
- Instrumental errors (especially the speedometer) in connection with (not uncommon) recklessness of pilots may lead to the exceeding of the critical velocity of flutter.
- Even the modern military aircraft are exposed to the occurrence of flutter, mainly because of incorrect exploitation.

Primary reasons of aeroelastic disasters

- **Ignorance**: lack of knowledge on aeroelastic phenomena and their danger.
- **Errors in developing and manufacturing**: too low stiffness of structures, aileron's mass unbalancing, …
- **Improper operations**: weakening or softening of structures, backlashes in control systems, improperly performed overhauls, bad instrument calibration,…
- **Human errors**: hazardeous operations, contravene the regulations and handling procedures, hurry at testing.

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4.1. INTRODUCTION

4.1.2. GENERAL CHARACTERISTIC OF AEROELASTIC PHENOMENA

Main types of aeroelastic phenomena

Static aeroelastic phenomena

Phenomena in which the inertia of the structure is not important

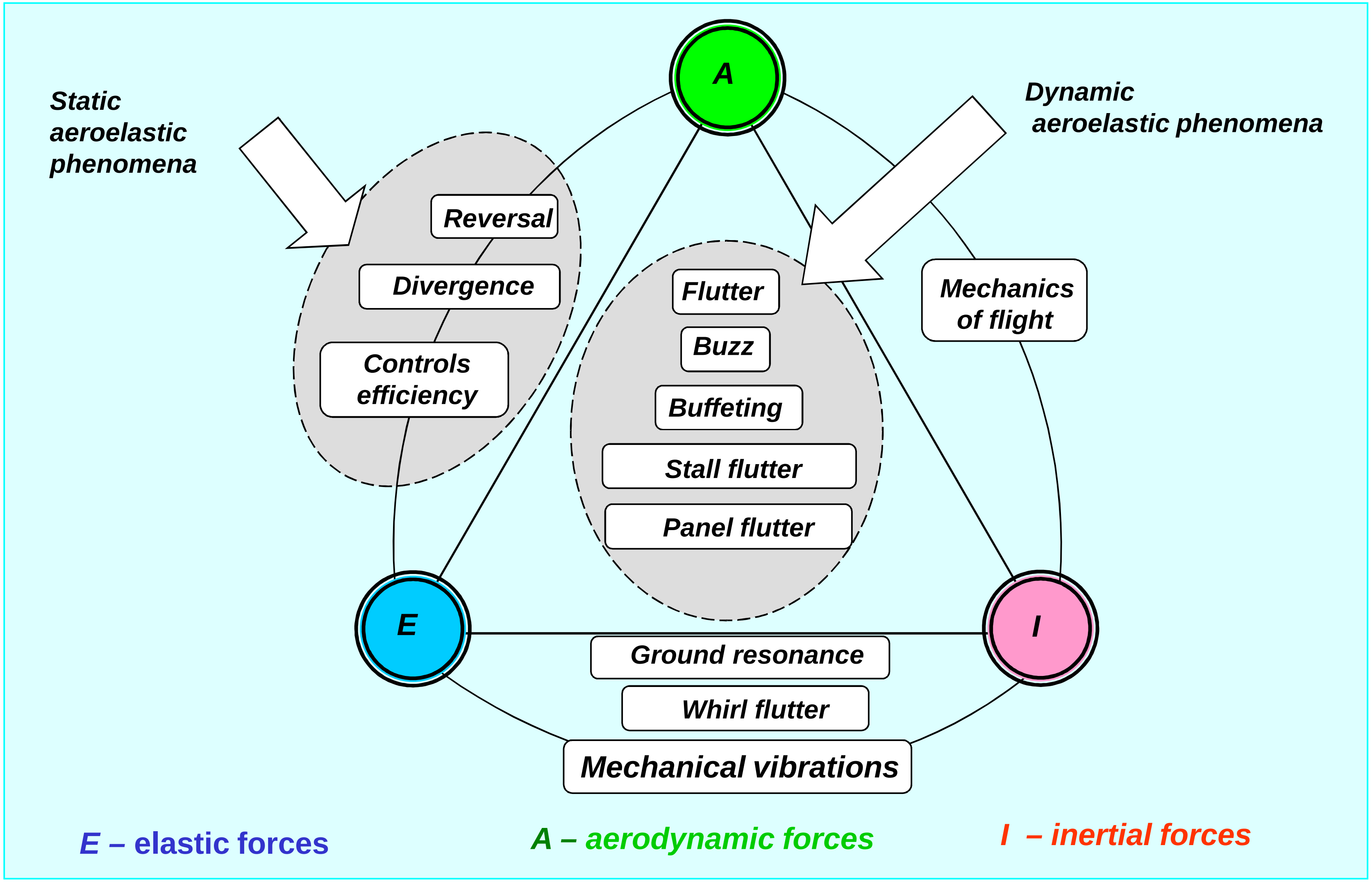
- divergence of wings,
- reversal of ailerons.

Dynamic aeroelastic phenomena

Phenomena in which the inertia of the structure is essential

- flutter of wings,
- flutter of stabilators,
- flutter of controls,
- stall flutter,
- whirl flutter,
- panel flutter,
- transonic flutter („buzz”),
- buffeting.

Types of aeroelastic phenomena



The classic Collar's triangle

Other aeroelastic problems

Aerothermoelasticity

The aeroelastic phenomena in which the temperature plays an important role:

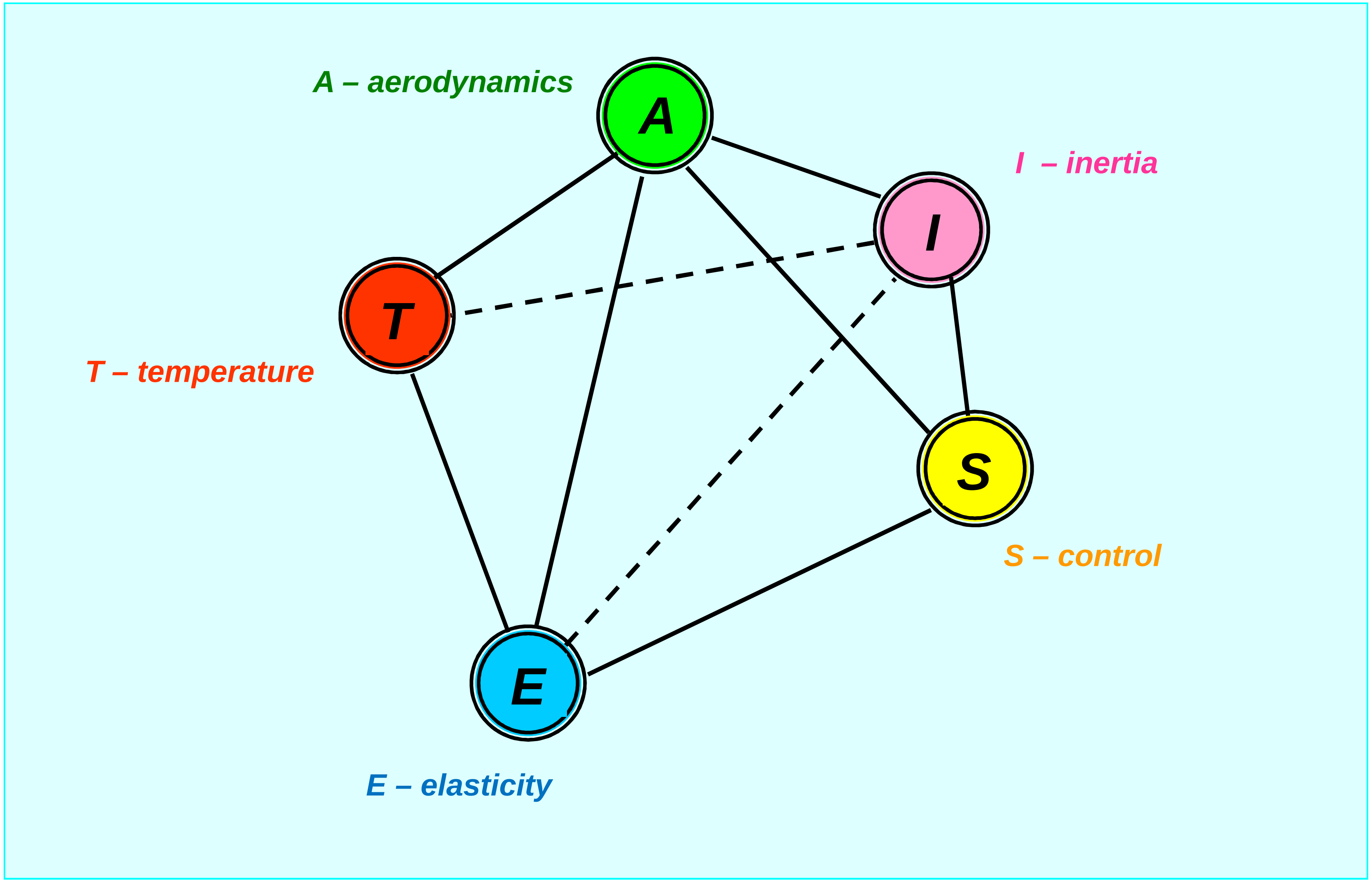
- hypersonic and space flights,
- aeroelasticity of jet engine turbine blades.

Aeroservoelasticity

Active control of the aeroelastic phenomena:

- active flutter suppression,
- active control of the wing section geometry.

Types of aeroelastic phenomena



The Aeroelastic Diamond

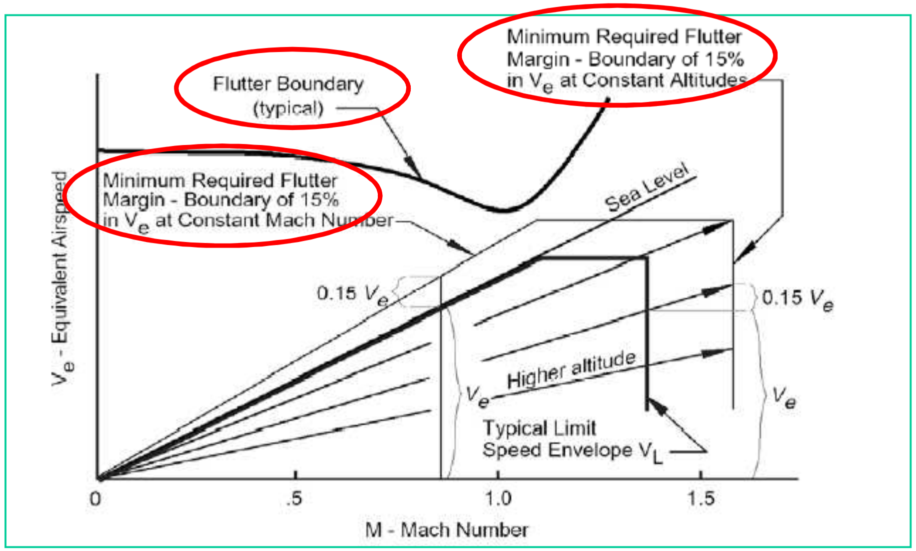
The critical velocity

The critical velocity of the aeroelastic phenomenon is **the least** velocity of flow (which is the velocity of the object relative to the medium at rest) at which the aeroelastic phenomenon may occur.

Importance of the critical velocity in aeronautics

The critical velocity restricts the permissible exploitation velocity of the aircraft.

A necessity of determination of the critical velocity of an aircraft are regulated by the appropriate aviation regulations: MIL, FAR, JAR, CS.



Determination of the critical velocity has the essential importance in proper designing of an aircraft and for its safe exploitation.

AEROELASTICITY

4.1. INTRODUCTION

4.1.3. METHODS OF AEROELASTIC ANALYSIS

Analysis of aeroelastic phenomena

The danger of flutter (and other aeroelastic phenomena) forces one to carry out the theoretical and experimental investigations of aircraft before the prototype is allowed to fly at higher speeds.

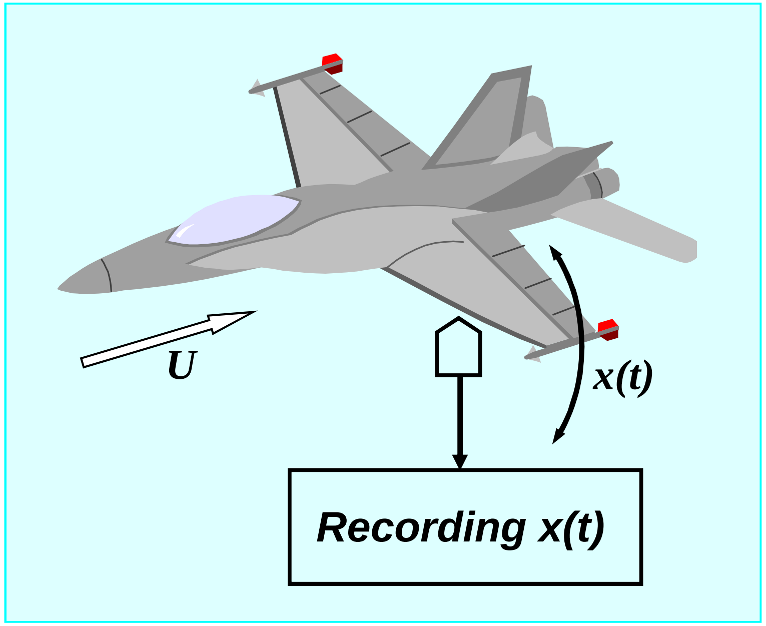
The airborne flutter tests are extremely dangerous – both in the past (Junkers Ju-90) and quite recently (PZL Iryda) there were disasters in course of these tests.

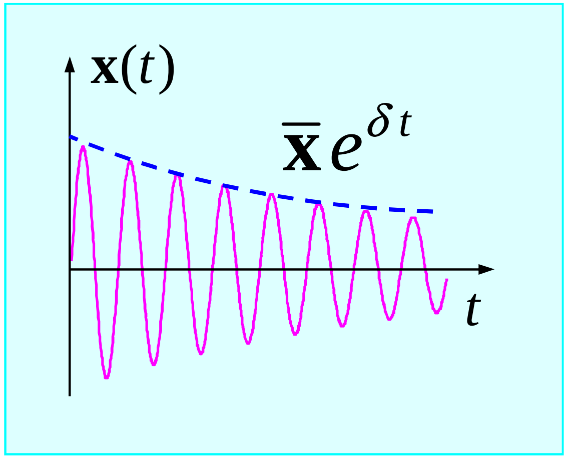
The theoretical investigation of the aeroelastic phenomena, that will precisely determine the critical velocities for various flight conditions, have to be thus performed.

It follows that there is a need for reliable methods of aeroelastic analysis.

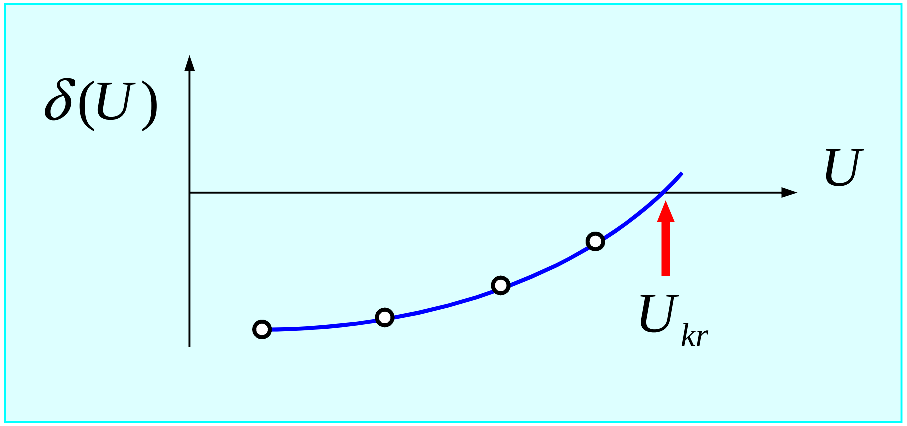
Their reliability determines the safety of pilots that perform the airborne flutter tests.

Experimental methods





δ - logarytmic decrement of vibrations



The laboratory experimental methods are performed in similar manner.

Analytical methods

Classical aeroelastic analysis

$$\mathbf{M}(U)\ddot{\mathbf{x}} + \mathbf{C}(U)\dot{\mathbf{x}} + \mathbf{K}(U)\mathbf{x} = \mathbf{0}$$

$$\Downarrow$$

$$\mathbf{x}(t) = \overline{\mathbf{x}}\, e^{\lambda t}$$

$$\Downarrow$$

$$(\lambda^2\mathbf{M} + \lambda\mathbf{C} + \mathbf{K})\overline{\mathbf{x}} = \mathbf{0}$$

The roots $\lambda = \alpha + i\omega$ depend on the velocity *U*, $\lambda = \lambda(U)$

$\omega(U)$ - frequency of the vibrations,

$\alpha(U)$ - damping coefficient of the vibrations.

The stability of motion $\mathbf{x}(t)$

$\alpha < 0$ - vibrations disappear

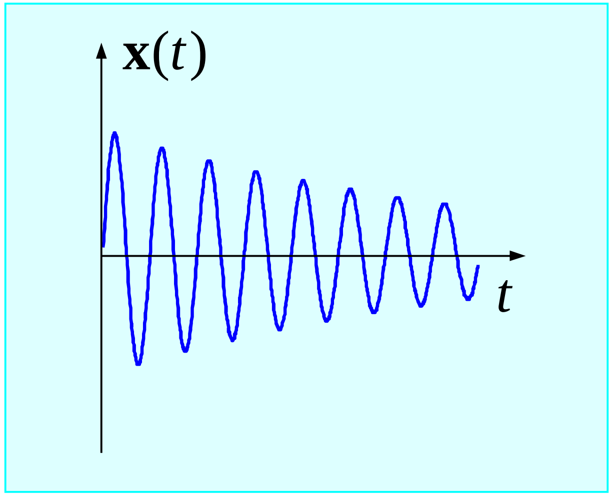
$\alpha = 0$ - steady vibrations ➡ The critical velocity U_{kr}

$\alpha > 0$ - vibrations increase.

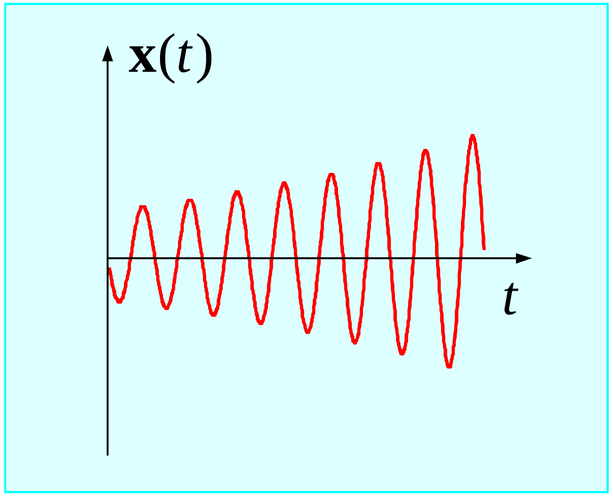
Analytical methods

Simulation aeroelastic analysis

U ➡ $\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{0}$ ➡ numerical integration ➡ $\mathbf{x}(t;U)$



U_1 – vibrations dissapear



U_2 – vibrations increase

$$U_1 < U_{kr} < U_2$$

This is the numerical equivalence of the airborne flutter tests.

Conclusions

1. The aeroelastic phenomena are those in which the flexible structure are deflected or started to move as a result of aerodynamic loadings induced by the air flow.

2. The critical velocity is the least velocity of flight at which the aeroelastic phenomenon may occur.

3. The most important aeroelastic phenomenon in aviation is the flutter.

4. Flutter is extremely dangerous, because it often causes the damage of the structure.