AEROELASTICITY IN AXIAL-FLOW TURBOMACHINES

Torsten H. Fransson

Book 1: INTRODUCTION

Chapter 1:

Basic Introduction to Aeroelasticity

SUMMARY

This introductory section gives an overview, from an historical perspective, of various types of aeroelastic problems that have appeared in a few engineering fields. It describes some failures that have appeared and what the research has indicated as possible causes. The basic definitions of static and dynamic aeroelasticity are introduced. Some references to basic text books on the subject of aeroelasticity are given.

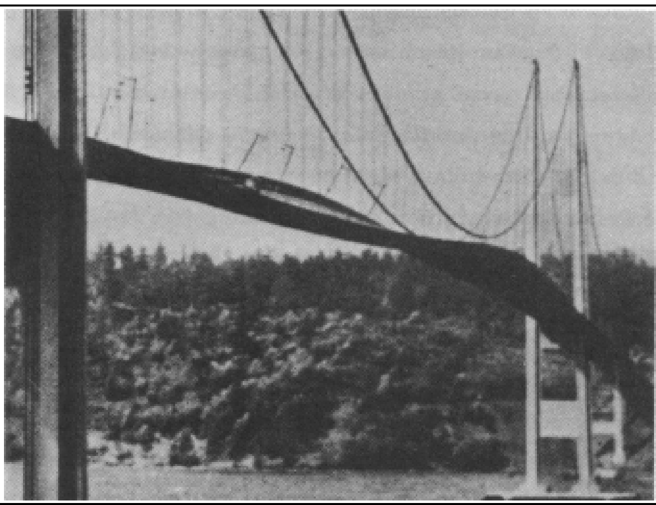
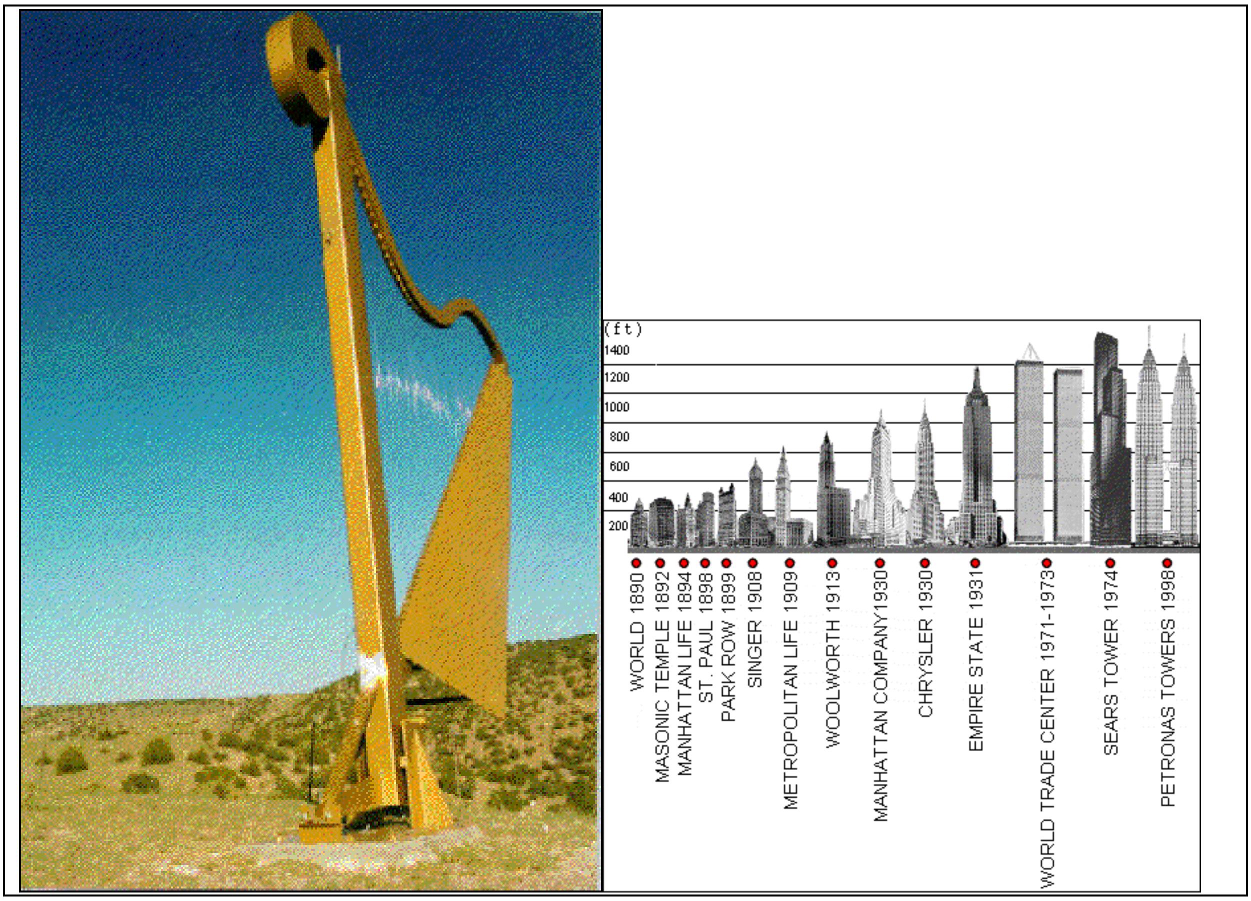


Fig. B1C1.1: *Failure of the Tacoma Narrows Bridge in 1940 [Försching, 1974, p. 5].*

THE PROBLEM AND THE HISTORY

Vibration-related failures of structures are of a large importance in many aspects of mechanical engineering. Problems may appear as a sudden destruction or can be related to longer-term fatigue of the structure, and they may be related to an eventual flow of fluid around the structure (called for example "flow induced vibrations", "flow-structure interaction" or "fluid-elasticity") or be purely structural. It is widely recognized that flow induced vibrations are of major concern in the design of modern engineering structures, as the continuous interaction between a vibrating structure and the changing flow characteristics can cause high stresses leading to short-term fatigue failure. A non-optimal development of a structure can, especially in aeronautics, where development costs are extremely high, have a significant influence on the viability of the final product.

Flow induced vibrations appear in many circumstances in nature and in different engineering concepts. Trees and flowers move in the wind, and flags flutter. Wind harps (Fig. B1C1.2a) give an enjoyable sound and is an example of "positive" flow induced effects. Civil engineering structures, such as bridges and tall buildings, are typical constructions where flow induced vibrations must be taken into account (Figs. B1C1.1, B1C1.2b-d). Flow induced vibrations are of major concern in the design of modern tube and shell heat exchangers (the problem is especially critical in nuclear steam generators that often are designed to last 30 years or more). Fluid flow through a flexible pipe, submarine periscopes, oil pipe lines, television antennas and telephone wires often encounter vibration troubles of aeroelastic origin [Fung, 1969, p. 61].



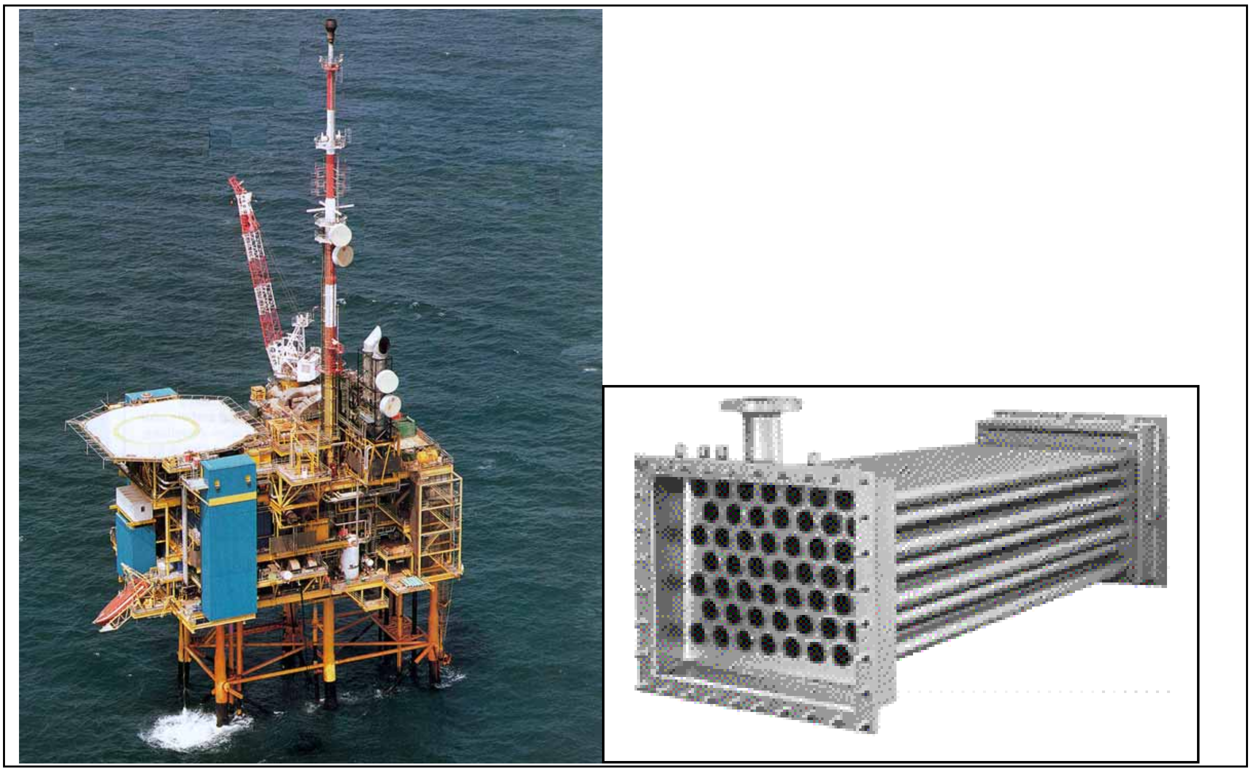


Fig. B1C1.2: *General example of fluid-structure interactions: Wind harp, tall buildings, oil platforms and boilers*

Sluices for the regulation of water flows in rivers and dams vibrate under some circumstances, and blades in hydraulic and thermal turbomachines (both axial and centrifugal flow machines) are subject to large time-dependent variations in the oncoming flow. Vibrations of measurement instruments or their supports, such as long tubes holding neutron flux and temperature sensors in nuclear power plants reactor cores, are of concern. Among other examples of structures where flow induced vibrations are of importance, harbor and marine piles, offshore drilling and production platforms, smoke stacks and chimneys, missiles on launch pads, heat shields in afterburners of jet engines, propellers of aircraft and rotor blades of helicopters, can be mentioned. In other cases unsteady flow effects and induced vibrations lead to high noise levels, which can today be of major environmental concern.

From the above it is clear that flow induced vibrations can appear in any sort of fluid (such as, for example, air, water, oil), but also in mixtures such as, for example, two-phase flows.

Apart from natural phenomena, it has been noted by Sisto [1987a, p. 1.1] that encounters with flow induced vibrations can be dated back to at least 1818 when empirical studies on "iron" bridges in England were reported. It was however in the aeronautical sciences where flow induced vibrations phenomena suddenly and abruptly showed the large importance the discipline has for the reliability and safety of structures, and especially for aviation (Fig. B1C1.3).

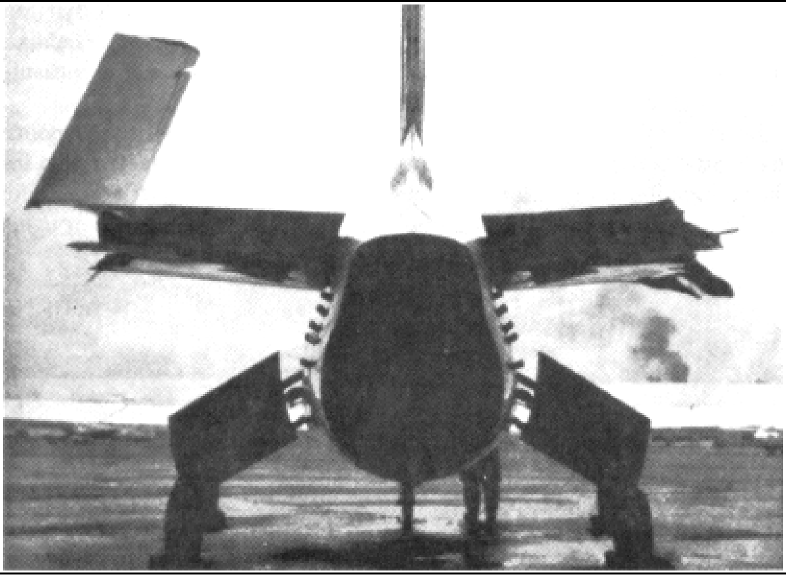
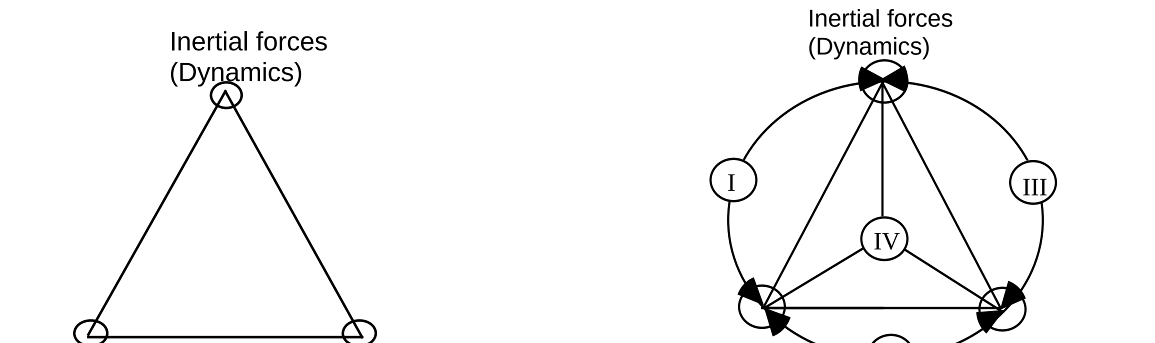


Fig. B1C1.3: *Rear view of empennage of jet fighter which was successfully landed after encountering flutter of the horizontal stabilizer in transonic flight [Ashley and Bisplinghoff, 1975, p. 6].*

"Aeroelasticity" is an engineering terminology that defines an interdisciplinary field which combines aerodynamic, inertia and elastic forces in such a way that the structure and the flow around it interacts with each other. Collar [1946] defines a triangle of forces in which the inertial, elastic and aerodynamic forces each occupies a vertex (Fig. B1C1.4a). In addition he notes that other forces, such as gravitational forces, may contribute to the stiffness of the structure, but that these generally are of



a: Forces considered [Collar, 1946, p. 62]. *b: Relations between the different forces*

I: Rigid-body aerodynamics; Stability; Control
II: "Static" aeroelasticity
III: Mechanical vibrations; Impact
IV: "Dynamic" aeroelasticity

Fig. B1C1.4: *Collar's triangle of forces .*

a negligible nature. In the case that only the aerodynamic and inertia forces act together the static aspects of the loading on the structure is considered (domain "I" in Fig. B1C1.4b). When the aerodynamic and elastic forces are taken into consideration, the resulting problem is defined as a "static aeroelasticity" (domain "II" in Fig. B1C1.4b) [Bisplinghoff, 1958, p. 99], whereas a third domain ("III"), mechanical vibrations, considers the relationship between the inertial and elastic forces. A fourth domain ("IV") takes into account all three forces (aerodynamic, inertia and elastic forces), and is usually called "dynamic" aeroelasticity [Bisplinghoff, 1958, p. 99]. In a general sense the term "aero-elasto-dynamics" [Platzer, 1990a, p. 1] would thus describe the phenomena involving all three forces more accurately, whereas the term "aero-elastic" should be reserved for what is generally today known as "static aeroelasticity". However, "aeroelasticity" is the generally acknowledged terminology today[1].

Försching [1974, p. 2] notes that aviation pioneers were confronted with aeroelastic problems already during their first flights and that the failure of the Langley monoplane in 1903 can be characterized as, in the present terminology, "static aeroelastic torsional divergence" of the wing. Brewer [1913] was among the first to report on this problem, although he did not use the terminology of today. He also notes that this incident, and the following success of the Wright brothers biplane, might have contributed to the preference of biplanes, with their higher torsional stiffness, in the beginning of the aviation era. Lanchaster [1916] and Barstow and Fage [1916] report, according to Fung [1969, p. 179], on an "antisymmetric fuselage torsion-elevator flutter" of a Handley Page 0/400 bomber during the First World War, and Blasius [1925] made calculations after the failure of the lower wing of an Albatross D3 biplane. Garrick [1976, p. 642] notes that the two basic remedies for flutter problems (that are still in use today), namely increased stiffness and mass balance, were already framed by 1922. Incompressible flow aeroelastic theories for oscillating wings were slowly developed during the 1920's and 1930's, simultaneously as a whole series of failures appeared during the development of monoplanes during the 1920's and the development of different types of airplanes during the arms race in 1934-1937 [Försching, 1974, p. 3; Fung, 1969, p. 180]. In 1930 a Junkers F13 airplane crashed in England, with the most likely diagnoses of "buffeting" of the tail, brought about by the airplane flying into a region of strong, rising gusts that exposed the tail to the stalled wing wake [Platzer, 1990, p. 4]. In 1938 a Junkers 90 VI crashed during flutter tests, killing all scientists aboard [Fung, 1969, p. 181]. This lead to the recognition of the dangers of "flight-flutter" tests[2] and to the conclusion that it was not possible to rely on these alone to determine the "flutter-speed" of the airplane.

A spectacular demonstration of aeroelastic phenomena in the non-aeronautical field appeared in 1940. In the mid-year a new suspension bridge, Tacoma Narrows Bridge, was opened over Puget Sound in Washington (Fig. B1C1.1). This bridge was

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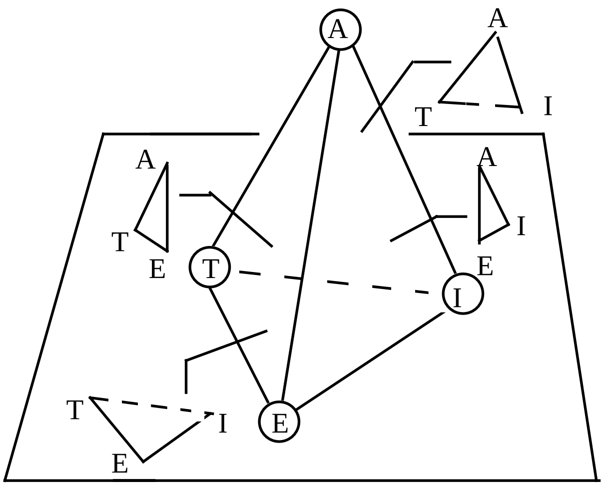
1 A discipline close to this field, although perhaps not as widely described, is the "hydro-elasticity" in which problems related to hydrodynamics and structures in water are comprised.

2 "Flight flutter tests" are performed by operating the aircraft closer and closer to the flutter limit and to measure the vibration response to different types of self-imposed excitations. As small changes in flight conditions can significantly change the aerodynamic stability of the structure, the procedure is not entirely safe (see for example Scanlan and Rosenbaum [1955, p. 338]). Such tests thus have to be carefully planned and cautiously pursued.

designed to be strong enough to withstand high wind velocities, but on November 7 the center span developed a torsional movement with a node at mid-span at a wind velocity of 67 km/h (18 m/s) [Ammann et al, 1941]. The frequency of vibration changed suddenly from 37 to 14 cycles per minute (0.62 and 0.23 Hz, resp.), the vibration grew violent, with amplitudes of 45^o, and failure occurred half an hour later. The failure is today generally attributed to the term "stall flutter" [Fung, 1969, p. 62].

As flight speeds went into transonic and supersonic velocity domains, with little or no increase in stiffness of the airframe, during and after World War II, entirely new aeroelastic problems were encountered. Collar [1946, p. 77] indicates that "German military aircraft suffered heavily at one period during the war as a result of the lack of attention paid to aeroelastic phenomena" and "early V-2 missiles were said to have been broken up by flutter of panels located near the nose of the missile" [Garrick, 1976, p. 642]. Platzer [1990a, p. 5] mentions the so-called P-38 troubles ("transonic control surface buzz") and "panel flutter" on the X-15 rocket plane is mentioned by Runyan and Morgan [1961]. Two specially tragic incidents took place on the commercial Electra airplane in the late 1950’s [xx, 1961a, 1961b]. One of the reports from these two accidents indicate that the "outboard powerplants and engine support structures, the complete right wing, and the outer portions of the left wing and aileron separated from the rest of the airplane in flight during such a short time interval that the sequence of these separations was not apparent" [xx, 1961a, p. 6]. Initial flight tests had proven the aircraft to be flutter-free, and the probable cause for these accidents was considered to be "whirl flutter" that likely was caused by a weakened structure (which drastically reduced the original stiffness of the supporting system [xx, 1961a, p. 21], although the aircraft was recently put into operation), together with the aircraft entering an area of severe clear air turbulence. Garrick [1976, p. 643] mentions that "panel flutter was also quite bothersome for the Saturn V-Apollo launch vehicle and required much detailed consideration". Försching [1974, p. 5] notes that the NASA Subcommittee on Vibration and Flutter concluded that between 1951 and 1956 three times as many flutter occurrences were found on military aircraft as during the previous five year period. Similarly, Garrick [1976, p. 643] points out that "in the decade 1947-1957 more than 100 different flutter incidents occurred in the U.S. for civil and military aircraft, mostly of control surfaces and tabs, some wings carrying external stores, and one case of a T-tail airplane". At this time and in the context of high-speed flight, thermal effects became of importance for aeroelasticity and a more correct terminology describing these phenomena would be "aero-elasto-thermo-dynamics" (Fig. B1C1.5). As an example thereof in modern day life can be mentioned "that because of aerothermoelastic effects in accelerated flights to altitude, the Concorde may exhibit in different flights a two-degree elevator rim-angle change, an effect that is monitored, computed and adjusted continuously in flight" [Garrick, 1976, p. 654]. Garrick [1963, p. 133] notes that thermal gradients can lessen the stiffness of the structure to both static airloads and to inertia loadings associated with vibrations. The natural frequency of the structure may thus decrease.



A:	Aerodynamic forces	E:	Elastic forces
I:	Inertial forces	T:	Thermal forces

E+I:	Mechanical vibration
A+I:	Stability (Rigid-body aerodynamics; Stability, Control)
A+T:	Aerothermodynamics
E+T:	Thermoelasticity
A+E:	Static aeroelasticity
I+T:	Thermal molecular processes
A+E+I:	Collar's original triangle of forces
A+I+T:	Stability modified by thermal effects
A+E+T:	Static aerothermoelasticity (Static aeroelasticity, modified by heat)
E+I+T:	Mechanical vibration and thermal effects
A+E+I+T:	Aero-thermo-elasticity

Fig. B1C1.5: *Tetrahedron of aerodynamic, inertia, elastic and thermal forces [Garrick, 1963, p. 130].*

Furthermore, as the dynamic of modern-day flight vehicles automatic guidance and control systems can influence the aeroelastic behavior of the structure, the domain "aero-servo-elasto-thermo-dynamics" becomes a field of importance [Försching, 1974, p. 6; Platzer, 1990b]. However, this field still goes under the terminology of "aeroelasticity".

Among the first indications (as far as the author is aware of) of blade vibration problems in turbomachines from the open literature can be mentioned the problems related to blade and disk vibrations encountered in the 1910's on marine turbines[3]. The pioneering work by Campbell [1924, 1925] resulted in one of the, still today, most important aeroelastic design tools, namely the Campbell diagram[4]. One of the first

3 Ljung [1979] calls the period 1917 to 1922 the 'Great Disk-Flutter'. He indicates that this 'illness certainly shook Generel Electric. For Brown-Curtis, the consequences were so grave, that combined with their gearing problems, the company was forced to give up marine turbine manufacturing. Zoelly, Rateau, AEG and de Laval managed to recover from the sickness without too severe consequences'.

4 Ljung [1979] gives a summary of Campbell's design philosophy for marine turbines something like:

'a: To avoid vibrations in discs having short blades, the discs should be made so stiff that all the disc vibrations occur outside the operation range.

early overview-discussion about turbine troubles and their causes was given by Mellanby and Kerr [1923]. They discussed vibration problems due to distortion effects and blade passing to a great length (as well as lacing wires on end blades of large reaction turbines), but (obviously) no mention of self-excited aeroelastic effects were at that time given. The importance of the position of the lacing wires was already then discussed [for ex. on p. 36].

Towards the mid- and end 1940's the first indications (as far as the author is aware of) about the possibility of 'self-excited' (or 'flutter') problems on blades in axial-flow turbomachines appeared in the open technical literature [Shannon, 1945; Owens and Trumpler, 1949; Bellenot and d'Epinay, 1950; Lilley, 1952; Sisto, 1953; Söhngen and Quick, 19xx; Wang et al, 1956; Lane, 1956]. These reports show that blade failures in these early days often were due to one degree-of-freedom bending rather than torsional vibrations [Schnittger, 1958, p. 152] (not a flutter coalescence mode as on an airfoil), and efforts to solve the problems were concentrated on close-to-stall operating conditions. The most general remedy at the time was to stiffen the blades sufficiently to build in enough mechanical (or aerodynamic) damping or to use tip shrouding [Schnittger, 1958, p. 154] or lacing wires [Bellenot and d'Epinay, 1950, p. 369][5]. Armstrong and Stevenson [1960] gave an empirical rule stating that the reduced frequency of the blade ($k=2\pi fc/U_1$) should not be less than 0.33 for the bending frequency and 1.6 for the torsion frequency in order to avoid blade stall flutter, and they point out that in the early days of compressor aeroelasticity the flutter appeared exclusively in the fundamental bending or torsion modes. Such empirical factors are today still used for a "safe" design of a turbomachine blade. As an example can be mentioned a recent report by O'Neill [1989, p. 5] who reports cracks on the third row of turbine blades, that were thought to come from flutter, on a 42.5MW gas turbine. The experience from this machine indicated that a reduced frequency (based on outlet flow velocity for the turbine) of $k>0.328$ defined a safe limit, in considerable agreement with the empirical criteria established by Armstrong and Stevenson 30 years earlier.

As the turbomachine environment is very complex (much more so than the external flow in aeronautical applications) it is today impossible to define which problems in those early days appeared because of interaction between neighboring blade rows (forced response problems) and which should be attributed to self-excited vibrations (flutter). Although these two problems are today distinguished as different disciplines it is still now not always easy to separate them from each other and to define the exact reason for why a blade failure occurs (as the analysis has to be done after the failure has occurred and as, obviously, large efforts are made not to repeat the experience). Whitehead [1980, p. 6.3] points out that "many cases of blade failure

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b: For discs having long blades, where the combined blade and disc vibrations cannot be avoided within the operating range, the blades and discs should be made so stiff that resonance can first occur at frequencies higher than the natural frequency for four nodal diameters. This generally gives adequate security

c: To avoid tangential blade vibrations, none of the natural frequencies of the blades can be allowed to coincide with steam impulses from the guide vanes within the operation range. Downstream from each guide vane a turbulent path occurs, and the excitation frequency of these disturbances is therefore the number of guide vanes multiplied by the rotating speed. The natural frequency of the blade must lie at an adequate distance from this impulse frequency.'

[5] Fan-stages in modern jet-engines encounters rather coupled bending/torsion flutter, largely because of the use of part-span shrouds [Carta and Platzer, 1987, Vol. 2, p. 18.6]

which have been put down as forced vibration have in fact been due to a near approach to a flutter situation, in which the aerodynamic damping of the vibration has become very small".

Although enormous progresses have been made in the field of aeroelasticity in axial-flow turbomachines during the last four decennia, it is likely that aeroelastic problems will remain of importance for years to come, both in aeroengines and industrial turbomachines (as well as in many other fields, for example in aeronautical and civil engineering), as modern turbomachines are pushed towards higher fuel efficiency and higher performances, with increasing temperatures and velocities of the flow, higher aerodynamic efficiencies and lighter materials of the structures. These advances in technology forces the designer to predict vibration-free (flutter and forced response, as well as any other vibration problem) operating ranges for conditions beyond regions of available empirical data. Forced response problems may appear in any part of the multistage machine, whereas most flutter problems that appear in axial-flow turbomachines are related to the blades with the lowest eigen-frequencies. High aspect ratio fan blades, steam and gas turbine blades, accompanied with transonic flow conditions, are most susceptible to come into flutter. Although problems appear regularly, it is seldom that major discussions appear in the open literature. Aeroelastic problems that lead to failures are today mostly (and rightly) regarded as negative publicity and are not widely advertised, especially in domains where the competition between different companies is fierce, such as turbomachinery. Most analysis, descriptions and expertise of aeroelastic problems in turbomachines thus stay within the companies, or are sometimes mentioned just in a short sentence of a commercial publication. Every now and then a technical article treats a specific problem, but most scientific information has to be taken from brief notes in "User’s" magazines (such as "Aviation Week", "Electricity International" or "International Power Generation", to mention a few), from articles treating cascade flow, and from specialized technical conferences. A few examples of turbomachine blade failures under true operating conditions, mentioned in the open literature during the three last decennia are given below:

- Cavaillé stated in 1972 [p. 2] that aeroelastic phenomena are "quite important for low-pressure steam turbine blades when they are 1 m high and simply cantilevered".
- Sears et al [1976, p. 316]: "Steam people will agree that their last stages are fluttering, whether it is stall flutter or negative incidence flutter is not entirely clear, but they are probably getting both types at different times"
- A short note in Electricity International [1989, p. 10] indicates that a 160MW gas turbine in the Netherlands was taken out of service in 1988 because of shaft vibrations. The increased shaft vibration was found to appear because of a breakage of a blade of the fifth (last) row of stationary blades of the gas turbine, as these were overstressed by vibrations occurring during transients on startup and shutdown.
- Pigott and Abel [1974, p. 206] reports that a third mode oscillation could be self-excited for long low pressure steam turbine blades (laced together in groups of four) at low flow rates, provided the back pressure was sufficiently high. Silvestri [1981, p. 67] states that “instances of blade flutter and resulting blade failure occurred on some units operating at low exhaust volumetric flows in the early 1970's".

- Extended flutter studies have been performed on the F100 engine developed for the F-15 fighter aircraft [Jeffers and Meece, 1975; Nieberding and Pollack, 1977; Chi, 1980]. It is stated [Jeffers and Meece, 1975, p. 3] that "in the failure region of the flight envelope the outer portion of the airfoil experiences subsonic relative Mach numbers and stalled incidences".
- In January 1989 a (almost new) Boeing 737-400 crashed near East Midlands Airport in Great Britain, killing 47 passengers. One of the engines was on fire but the wrong one was shut down, causing the crash (the electrical connections for the indications from the two engines were inversed). The "Air Accidents Investigation Branch" in Great Britain attributed the failure of a fan blade of the engine to "fatigue of one of the engines fan blades which caused the blade's outer panel to detach" [Shifrin, 1990], and the engine to catch fire.
- Cracks were found in the third compressor stage in the engine presently being developed for the new Swedish fighter "JAS" [Svenska Dagbladet, 1990].
- Blade cracking problems on the fourth-stage turbine limited the flying life of F100-229 engines to 100 tactical cycles [xx, 1991a].
- Two in-flight F101 engine failures grounded the B-1B US fleet in December 1990. The failures appeared to have been caused by loss of a first-stage fan blade followed by failure of the retaining ring that helps hold the blades in place in the case of a failure. The modification effort centered on installing a strengthened first-stage blade retaining ring [xx, 1991b].

During the design of the turbomachine large care is taken to accurately determine flutter limits:

- Kadoya et al [1979, p.184] and Hirota et al [1978, p. 179] indicate that extended flutter investigations were performed during the development phase of a 1'016 mm 3'000 rpm last stage steam turbine blade (with three spanwise snubber dampers) to avoid flutter at low load and high back pressure.
- Maddaus et al [1982, p. 9] indicate that "design solutions dealing with flutter are primarily empirical in nature and specific to the application".

It should finally be stated that a sign of when an aeroelastic problem appears in a company is the research performed. During "good" (="flutter-free") years the designer is generally not very interested in the problem, and when a failure does arrive it is necessary to have the solution "yesterday". At this time a considerable project is usually started, but it gradually gets a lower priority if the failure does not repeat itself on another machine. Garrick [1976, p. 643] stated that "systematic aeroelastic research in compressors, fans and turbines is difficult and mostly lacking so that the problems arise anew with each new design". Although the situation has considerably improved the last decennia, the statement still holds. The field is however continuously of large technical, scientific and commercial interest: EL-Aini et al [1997] indicate that although over 90% of the potential High Cycle Fatigue (HCF) problems are uncovered during development testing, the remaining few problems account for nearly 30% of the total development cost and are responsible for over 25% of all engine distress events. It is also mentioned [Kielb, 1998] that every new development program for jet engines have about 2.5 serious high cycle fatigue problems. Estimates indicate that billions of $US will be spent on HCF problems in the US Air Force only up to year 2020 [Kielb, 1998].

As aeroelasticity is a very special and interdisciplinary subject only a few text books giving the basics of the discipline are available. Most of these are related to aeroelasticity from a general perspective, and the information available related to turbomachines is scarce. The works by Scanlan and Rosenbaum [1951], Fung [1955 and 1969], Bisplinghoff, Ashley and Halfman [1955], Bisplinghoff and Ashley [1962 and 1975], Försching [1974] and Dowell et al [1980, 1989] should be mentioned in this context (a few more text books are mentioned in these works). The four first are devoted exclusively to the aeronautical field, whereas the fifth also treats some aspects from civil engineering and turbomachines. Obviously, more text books treating either the elastic or the unsteady aerodynamic aspects of aeroelasticity exist. The material for understanding of aeroelastic phenomena in axial-flow turbomachines, to the extent that this basic understanding exists, must thus instead today be looked for in the specialized technical literature on the subject. The most comprehensive information till today is probably collected in the two volume AGARD manual on "Aeroelasticity in Axial-Flow Turbomachines" [Platzer and Carta, 1987]. This is the first extended description of turbomachine-aeroelasticity but it is not a textbook in the usual sense.

For the interested reader to get acquainted with the field of aeroelasticity in turbomachines, the conferences "Unsteady Aerodynamics and Aeroelasticity of Turbomachines and Propellers" (held every 3-4 years in different countries) and the specialized sessions at the ASME Gas Turbine Conference (held every year) can be recommended.

It should be pointed out that two problems close to aeroelasticity in axial-flow turbomachines are helicopter rotor and propfan (ducted and unducted) aeroelasticity. To some extent these can be consider to be even more complicated than the phenomena in the turbomachine because of the large variation in relative flow velocity on the helicopter rotor during one rotation and the high sweep together with the large spacing of the propfan blades. Dowell et al [1980, Section 7] and Kielb and Kaza [1985] are two examples of information in these areas.

Finally, although the present introduction and historical background has been centered on giving the reader a comprehensive overview of all the different problems that can arise from aeroelastic effects in engineering concepts, it should not be forgotten that the machines discussed are of excellent quality, reliability and safety. Of the thousands of turbomachines (as well as aircraft and other structures) operating every day only a very limited number fail during their predicted life-time. However, this is thanks to the engineering knowledge and research and development consistently performed in the turbomachine fields, among these the aeroelasticity. As stated above, because of the competitive continuous push towards more extreme operating conditions of turbomachines, as well as the necessary monitoring of older machines, aeroelastic research in axial-flow turbomachines will be around for quite some time in the future.

The design problem of the aeroelastician is thus to, once the "steady-state" geometrical and aerodynamic configuration is established, make the structure satisfactory from an aeroelastic standpoint (based on mechanical strength and other operational considerations), without adding mass above what was considered in the original design, and without destroying the optimal aerodynamic shape found

[Bisplinghoff, 1958, p. 102]. Such an ambitious goal will obviously not be attempted in these lectures. It is instead the purpose of the present introduction lectures to define some different terminology used in the field of aeroelasticity today, and to make an attempt to give an overview of important physical parameters as well as the present state of the knowledge of aeroelastic problems, together with a state-of-the-art view of computational models and experimental studies in the field. It is hoped that through this the reader will get a comprehensive overview of the aeroelastic blade problem in axial-flow turbomachines especially from an unsteady aerodynamic standpoint, and that the references will indicate further reading that will be of use for a designer.

Classification of Different Types of Aeroelastic Phenomena.

The flow through turbomachines is inherently time-dependent. This important fact is seen from the energy equation:

$$\frac{Dh_c}{Dt} = \frac{1}{\rho}\frac{\partial p}{\partial t} \qquad \text{(B1C1.1)}$$

which expresses that a local change of stagnation enthalpy can only be present in a fluctuating (in time) pressure field. This also indicates that any assumption from the fully time-dependent consideration of the flow through the machine must be a simplification. The fact that most turbomachine design methods, as well as experimental and theoretical research, is performed on a time-averaged bases just reflects the fact that the physical phenomena underlying the fully unsteady flow through the machine are not sufficiently well known.

Further to this fundamental fact, the flow through turbomachines are associated with many different time-dependent phenomena. Fig. B1C1.6, which shows some aspects of disturbances when the flow passes through a turbomachine blade row, serves to illustrate this. It is recognized that first of all the unsteady effects noted in the figure influence the flow through the blade row illustrated, and that also all the downstream blade rows will see a highly time-dependent approaching flow, especially as the different blade rows rotate relative to each other. Potential flow interactions between passing blade rows can create considerable pressure amplitudes, and distortions from the ideal uniform inlet flow are always present (for example from upstream struts or partial flow admissions). Flow passing over the tip of the blade as well as boundary layer effects at the hub will create vorticities that grow in the axial direction and wakes from upstream blade rows will be cut by the downstream blades and

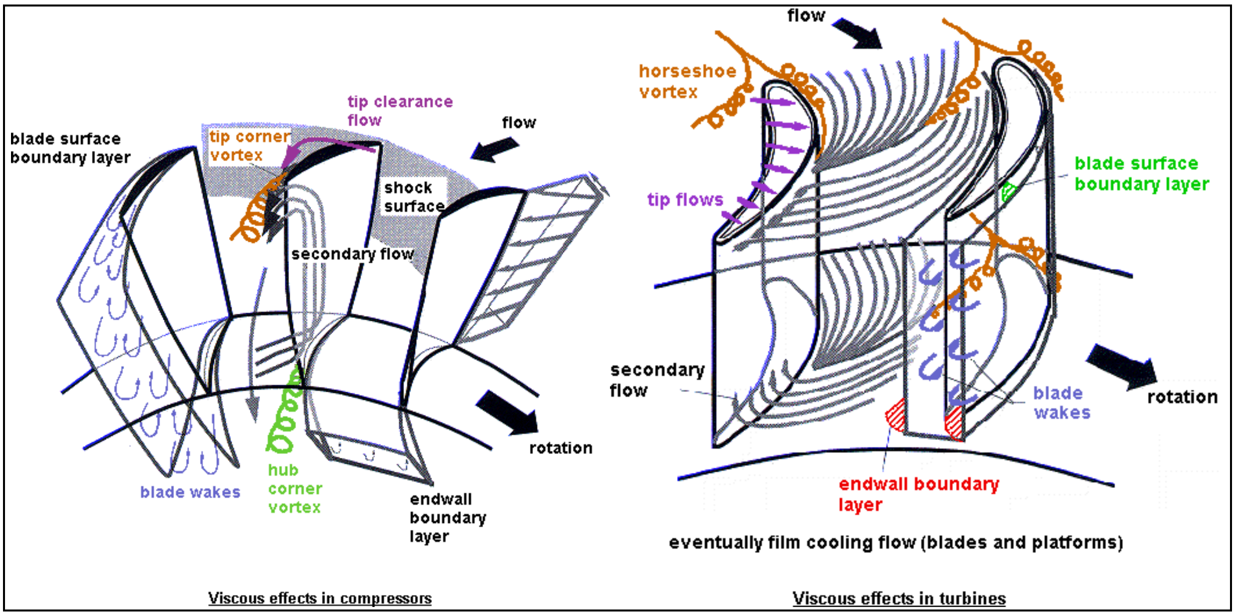

Fig. B1C1.6: *Rotor blade row phenomena [Compressor figure originally from McNally, 1977, p. 458]* create highly distorted flow effects. Radial aero- and thermodynamic gradients will push parts of the flow in certain directions and, in transonic and supersonic flow, highly three-dimensional shock structures will be reflected and interact with the blade (and casing) boundary layers to create unsteady effects on the blade surface. Flow instabilities can be caused by flow separations at large incidence angles (stall, surge).

All these time-dependent flow phenomena can interact with the blades to create vibrational patterns of different shape and magnitude. On top of all this, the phenomena of "self-excited" blade vibrations, i. e. the interaction of the flow (in principle uniform and steady incoming flow) and a structure vibrating out of one reason or another, can considerably complicate the comprehension of these complex flow interactions. Some of the phenomena mentioned are periodic in nature, whereas others can excite a blade stochastically. Others may be of a discrete nature, under which the blade has time to freely damp out the vibration before an eventual new force again forces the blade into vibration.

All the above phenomena appears with different magnitude at various operating points in a turbomachine. As an example, an operating map of a multistage compressor is schematically illustrated in Fig. B1C1.7. A few operating characteristics are shown, together with the surge and choke lines. If an attempt to operate the compressor above the surge line (i. e. at high positive incidence angles) is made, high pressure amplitudes of low-frequency will result as the compressor goes into surge. Decreasing the pressure level at a certain mass flow, on the other hand, will result in low positive or negative incidence angles with an associated choking of the flow. The compressor will then not accept, at a given mass flow, a further decrease of pressure ratio.

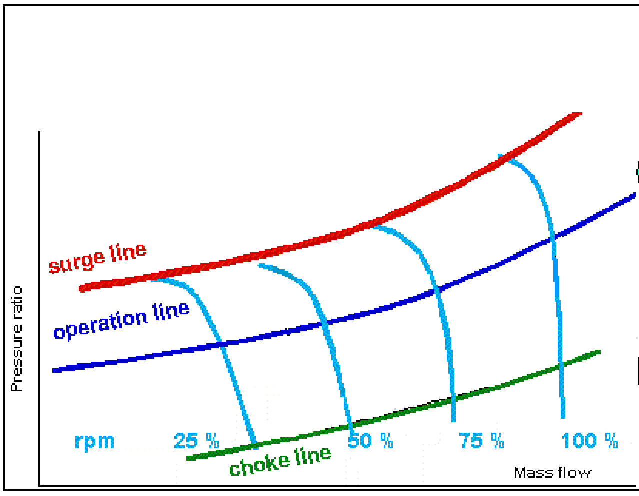

Fig. B1C1.7: *Schematic illustration of a compressor map*

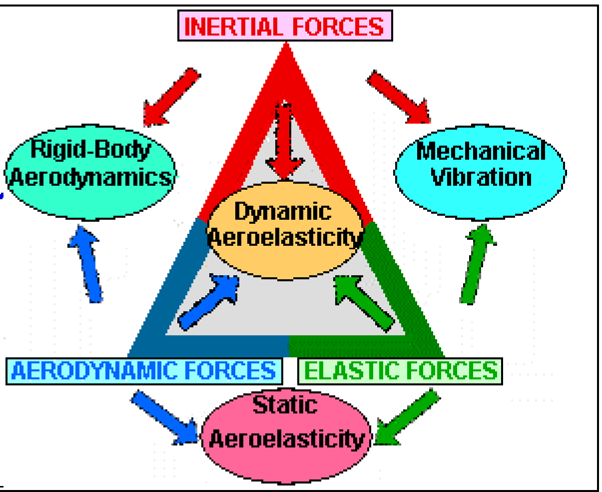

Fig. B1C1.8: *Collar's triangle of forces*

All of the above mentioned time-dependent flow phenomena can obviously, to a larger or smaller extent, affect the operation of the compressor. In most cases the short-term effect of performance is usually not related directly to the unsteadiness itself, but rather towards the time-averaged influence on the losses. Noticeable exceptions are cases of large vibrations, either of the rotor or of the blades. Such vibrations are often of aeroelastic origin.

In Collar’s triangle of forces (Fig. B1C1.8) it is possible to define four major axis, namely the interaction of:

I: Inertial and elastic forces
II: Inertial and aerodynamic forces
III: Elastic and aerodynamic forces
IV: Aerodynamic, inertial and elastic forces.

The first interdisiplinary technical field above gives an interaction between dynamics and solid mechanics and can be represented as structural vibrations in the absence of aerodynamic forces [Dowell et al, 1980, p. 1]. The second treats the connection between the dynamics and aerodynamics and can be represented by stability and control problems. The third and fourth are connected into "static" and "dynamic" aeroelasticity, respectively (see earlier discussion). As mentioned previously this triangle of forces can be extended to include also thermal forces and automatic guidance and control systems, with the corresponding increase of possible combinations.

In the next chapters an overview of the terminology used in the field of aeroelasticity is given. This is done as many terms appear in the literature, each with their distinct meaning, but as their clear definitions are often not given. It should be pointed out that this terminology is mostly taken from the field of aeronautics, but that also some phenomena from civil engineering are introduced. It is also important to realize that the separation lines between the different terms used are not distinct. The terms are instead often based on empirical ideas and given because of operating conditions in or close to a specific domain in the operating envelope. As an example the term "stall flutter" can be given. This term is used for flutter in or close to the stall line of a compressor, but strictly it is not necessary that the flow is stalled for this type of flutter to appear. Finally, some terms can have slightly different meanings for different applications.