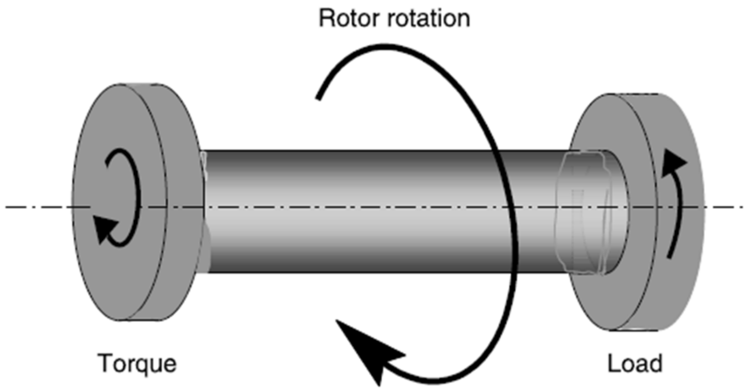
Rotordynamics

By S Ziaei-Rad, R. Tikani

Mechanical Engineering Department
Isfahan University of Technology

Basic Rotordynamics

- Since the invention of the wheel, rotors have been the most commonly used parts of machines and mechanisms.
- In this course the word "rotor" is used to describe the assembly of rotating parts in a rotating machine, including the shaft, bladed disks, impellers, bearing journals, gears, couplings, and all other elements, which are attached to the shaft.

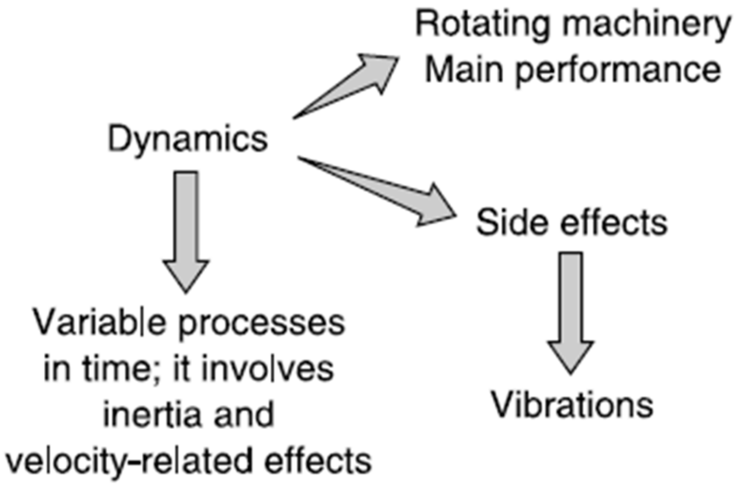


Why rotational motion?

- Rotational motion is employed
  - to achieve translation, as from the wheel to the axle
  - to store energy, as in the ancient sling or modern flywheels
  - to transfer power from one point to another by using belts, cogwheels, or gear trains
  - to obtain kinetic energy from other kinds of energy, such as thermal, chemical, nuclear, or wind energy

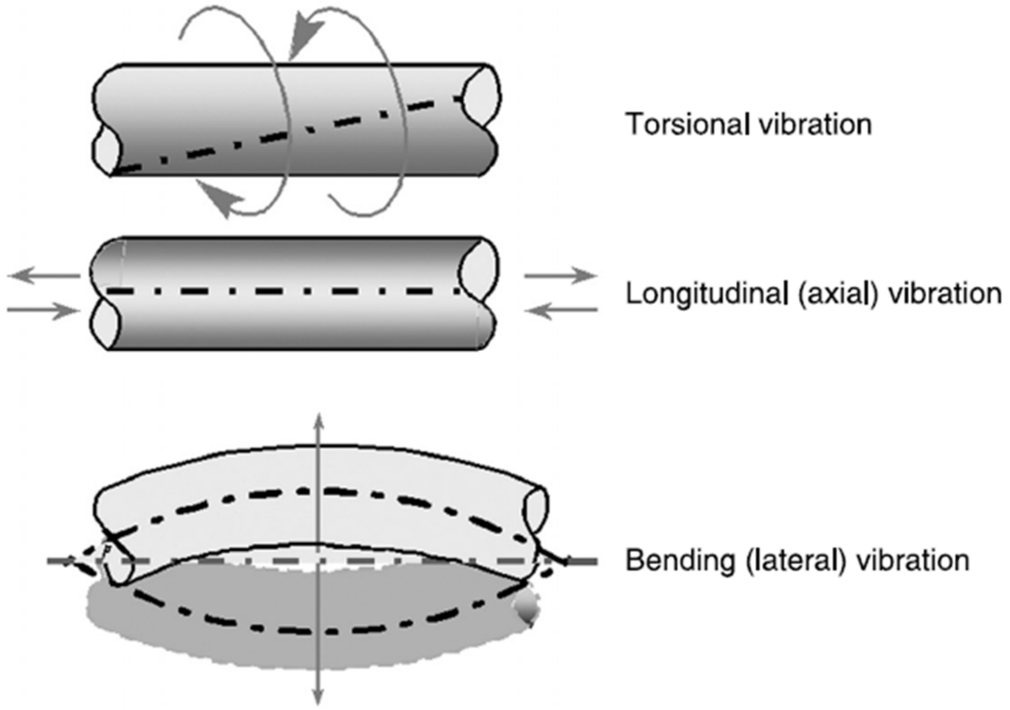
Energy flow in rotors

- The rotational energy has a potential for serious leaks and can easily be transformed into other forms of energy such as heat.
- In addition, in rotors there exist additional sources of energy leaks, transforming the rotor rotational energy into other forms of mechanical energy.



Various mode of vibration

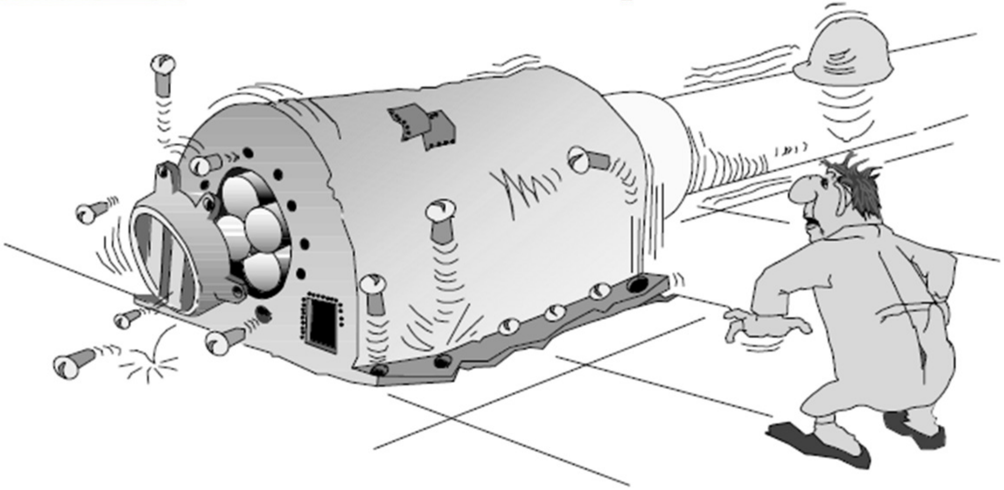
- Due to several factors, which contribute to the energy transfer - from rotation to other forms of motion - the rotor rotation may be accompanied by various modes of vibrations

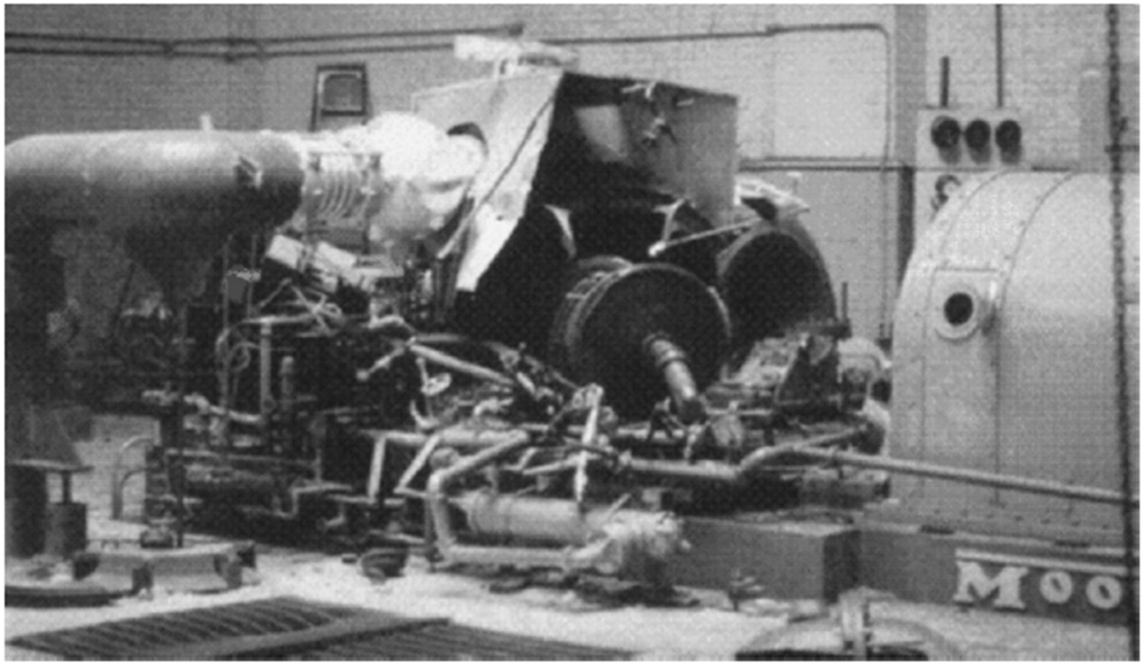


Various mode of vibration

- Among these modes, the lateral modes of the rotor are of the greatest concern.
- Most often, they represent the lowest modes of the entire machine structure.
- Next, through the supporting bearings and through the fluid encircling the rotor (unless the rotor operates in vacuum), the rotor lateral vibrations are transmitted to the nonrotating parts of the machine.
- Eventually, the vibrations spread to the machine foundation, to adjacent equipment, building walls, and to the surrounding air in the form of acoustic waves.

Severity of the rotor vibration



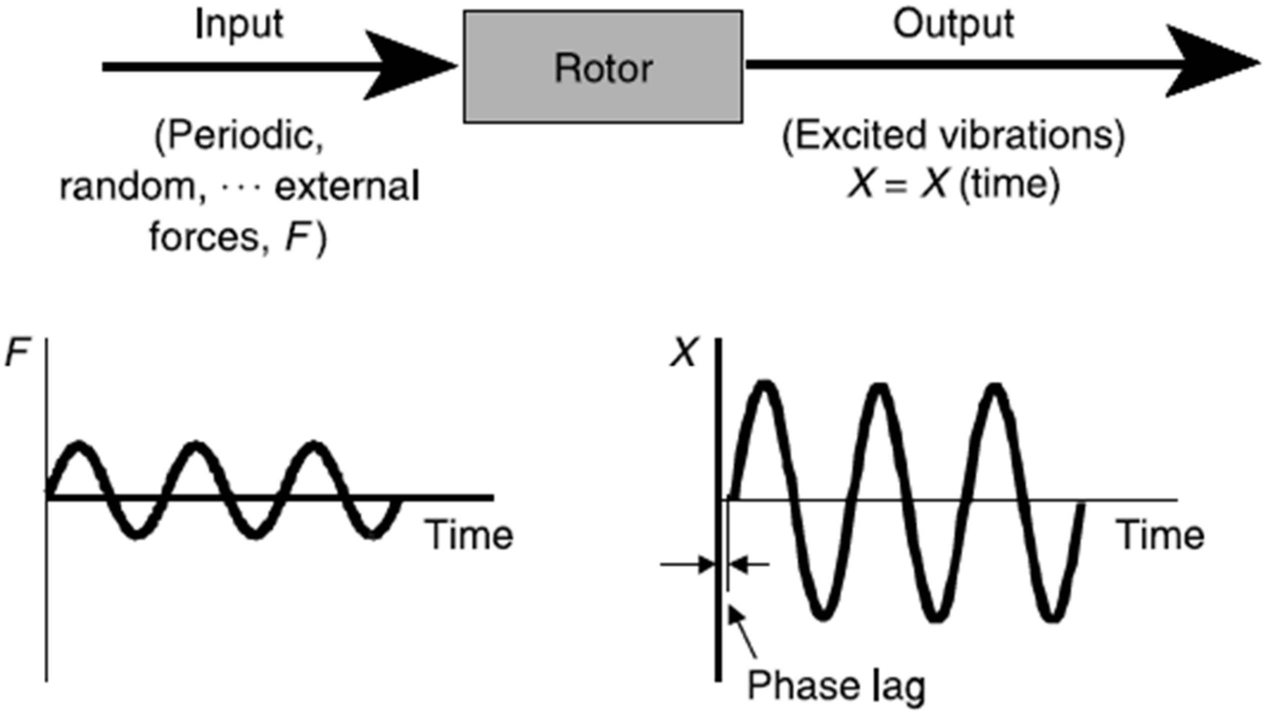


Rotating machine catastrophic failure due to excessive vibrations
Bently Nevada Corporation

Forced Excitation

- There is a long list of factors which contribute to the energy transfer from rotation to these “side-effect” vibrations.
- The first and best known among them is rotor unbalance.
- When the rotor mass centerline does not coincide with its rotational axis, then mass unbalanced inertia-related rotating forces occur.
- The rotor unbalance acts, therefore, in the lateral vibration mode, like an external exciting centrifugal force.
- As a result, the rotor responds with lateral vibrations with frequency, synchronous to rotational speed.

Forced Excitation


Input

Rotor

Output

(Periodic, random, ··· external forces, F)

(Excited vibrations) $X = X$ (time)

F: unbalance, torque pulsation, fluid forces, etc.

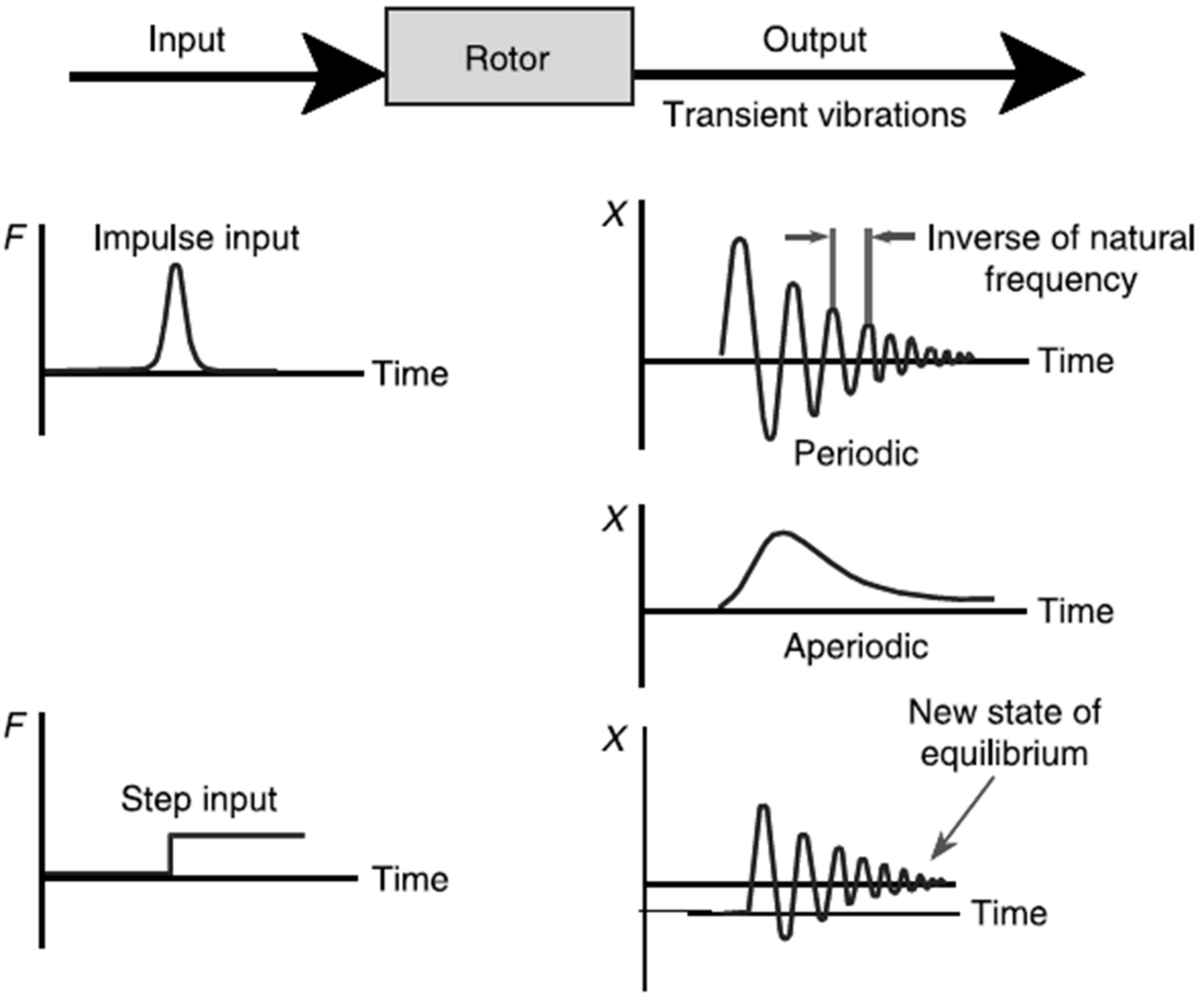
Forced Excitation

- The frequency of the rotor lateral vibrations due to unbalance will be the same as the rotational speed.
- In industry, the frequency of vibrations is usually related as ratios of the rotational speed; thus, the unbalance-related synchronous lateral vibrations are referred to as (1X) vibrations.
- If the rotor system is nonlinear, which is usually the case to a certain degree, then, in the system, more frequency components can be generated in response to an exciting force of a single frequency.
- The corresponding frequencies usually represent multiples of the excitation frequency. A nonlinear rotor synchronous (1X) response to unbalance will then be accompanied by higher harmonic components 2X, 3X, ...
- Additionally, often a single-frequency force can excite rotor responses with fractional 1/2X, 1/3X,…

Free vibrations or transient vibrations

- “free vibrations” or “transient vibrations”, which occur when the system is excited by a short-lasting impact, causing instantaneous changes in system acceleration, velocity, and/or position.
- The system responds to the impact with free vibrations, with “natural” frequencies, characteristic for the system.

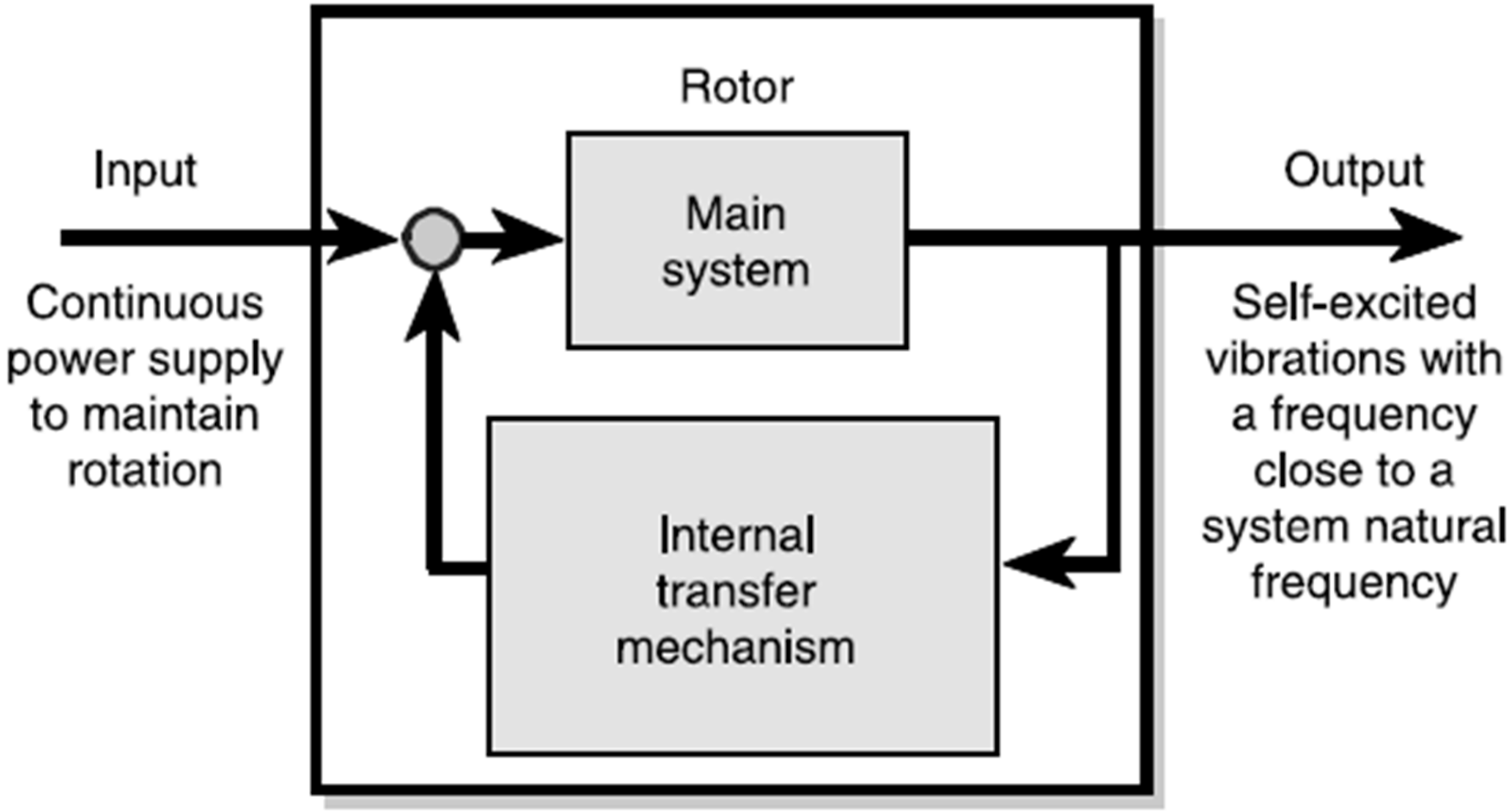
Free vibrations or transient vibrations



Self Excited Vibration

- There exists also a third category of vibrations in physical systems, known as self-excited vibrations.
- These vibrations are steady, usually with constant amplitude, phase, and frequency.
- They are sustained by a constant source of energy, which may be external, or is a part of the system. In this type of vibrations, through the feedback mechanism, the constant energy is "portioned" by the oscillatory motion .
- The frequency of self-excited vibrations is close to one of the system natural frequencies.
- Well known are aerodynamic flutter vibrations of wings or blades, or transmission lines sustained by unidirectional wind.

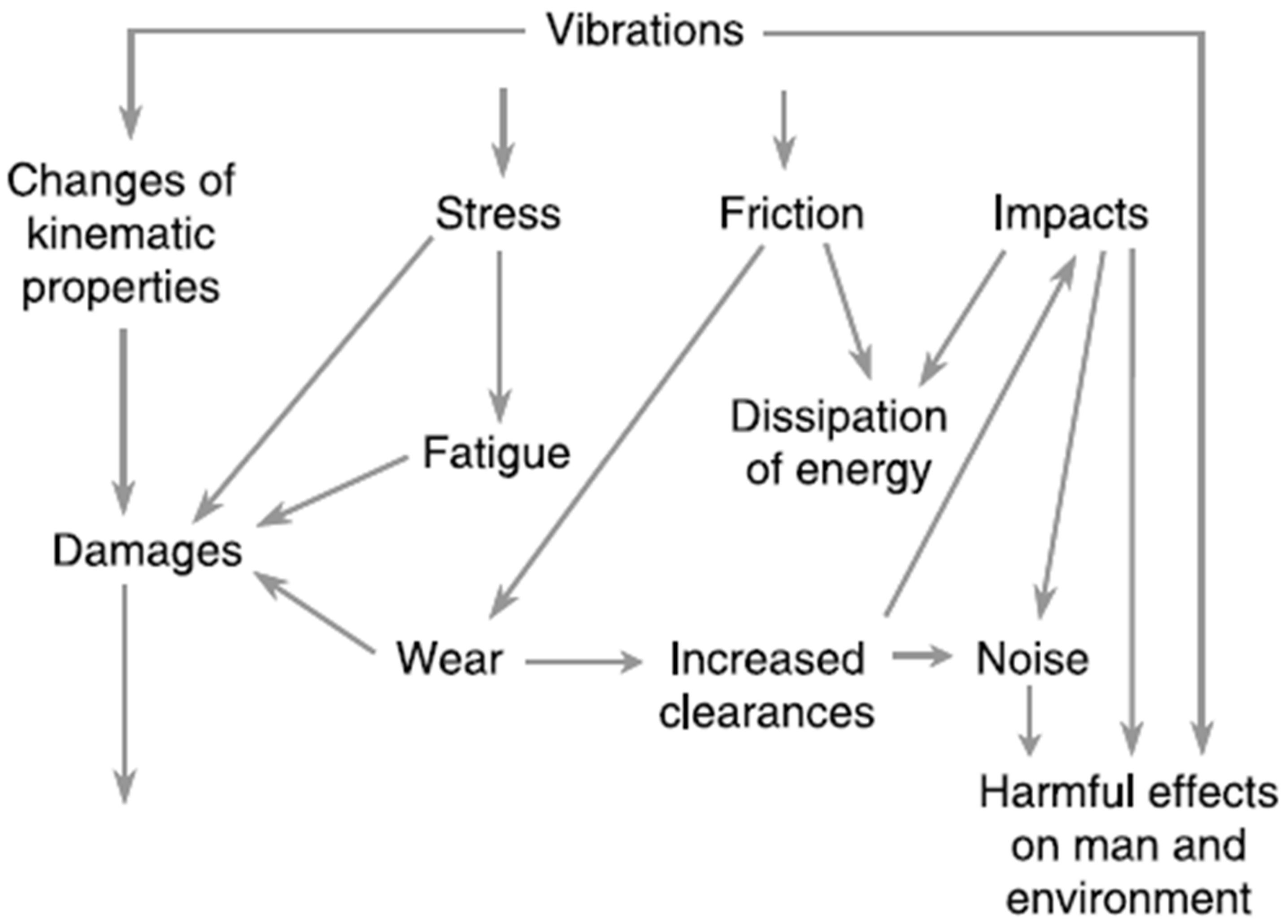
Self Excited Vibration



Types of self excited vibrations

- Internal friction in the rotor material
- the rotor-surrounding fluid
- rotor-to-stationary part rubbing

Vibration in mechanical systems



Vibrations

Changes of kinematic properties

Stress

Friction

Impacts

Fatigue

Dissipation of energy

Damages

Wear

Increased clearances

Noise

Harmful effects on man and environment

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Evolution of rotating machinery - Steam turbines

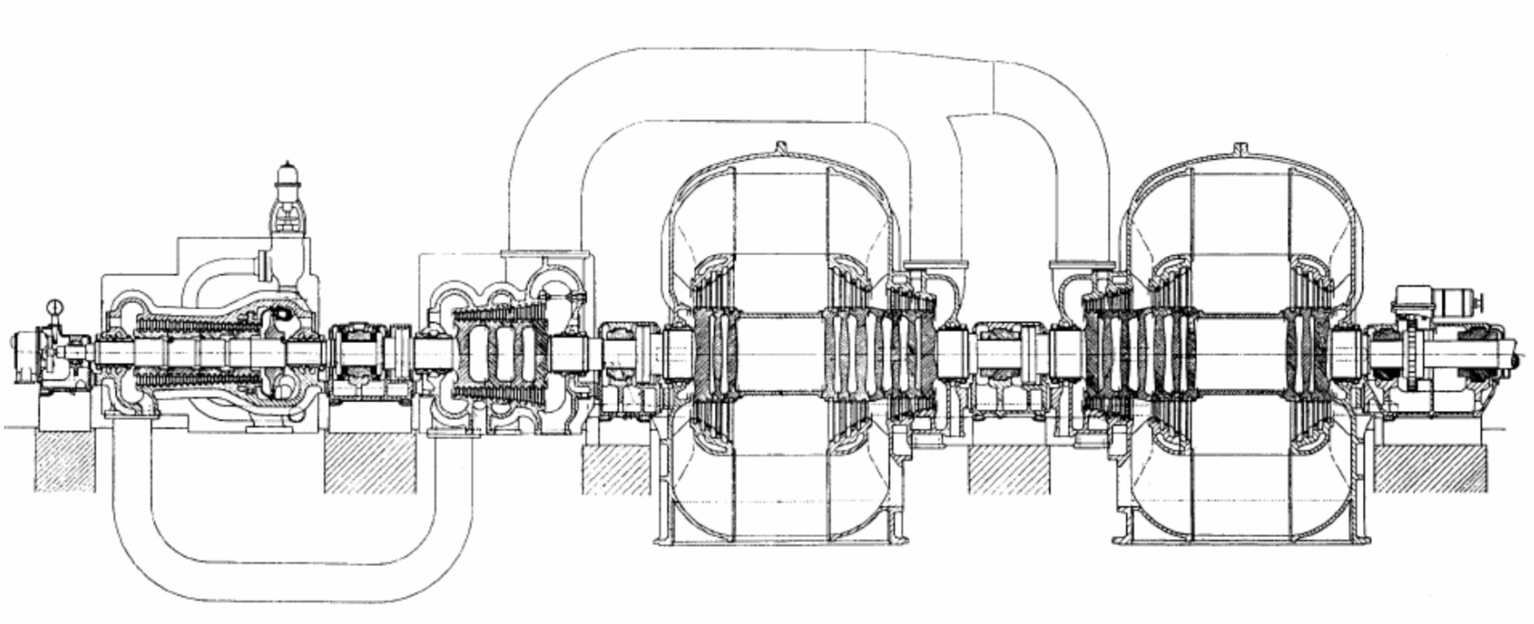
- The first single stage impulse turbine built in 1883 by the Swedish engineer Gustaf de Laval (with a speed of 30000 rpm reduced to 3000 rpm by gearing)
- The first multistage reaction turbine built in 1884 by Charles Parsons (having a speed of 18000 rpm and an output of 10 HP)
- Early in 1901 the Brown Boveri Company built a steam turbine of 250 kW at 3000 rpm, coupled directly to an a.c. generator.
- In 1914, a turbine of 25 MW at 1000 rpm was the largest single-cylinder steam turbine in the world.

Evolution of rotating machinery - Steam turbines

- After 1920, the high price of coal imposed the increase of steam turbine efficiency.
- The first super-pressure three-cylinder (high, intermediate and low pressure) turbine was built by BBC in 1929, and had an output of 36 MW at 3000 rpm.
- The increased efficiency of steam turbines lowered the amount of coal required for producing 1kWh of electrical energy from 0.75 kg during the war to 0.45 kg in 1927.
- The output of the largest turbines in Europe had reached 50 to 60 MW by the mid twenties, when, for large units, turbines of 1500 rpm were coupled to four-pole generators.

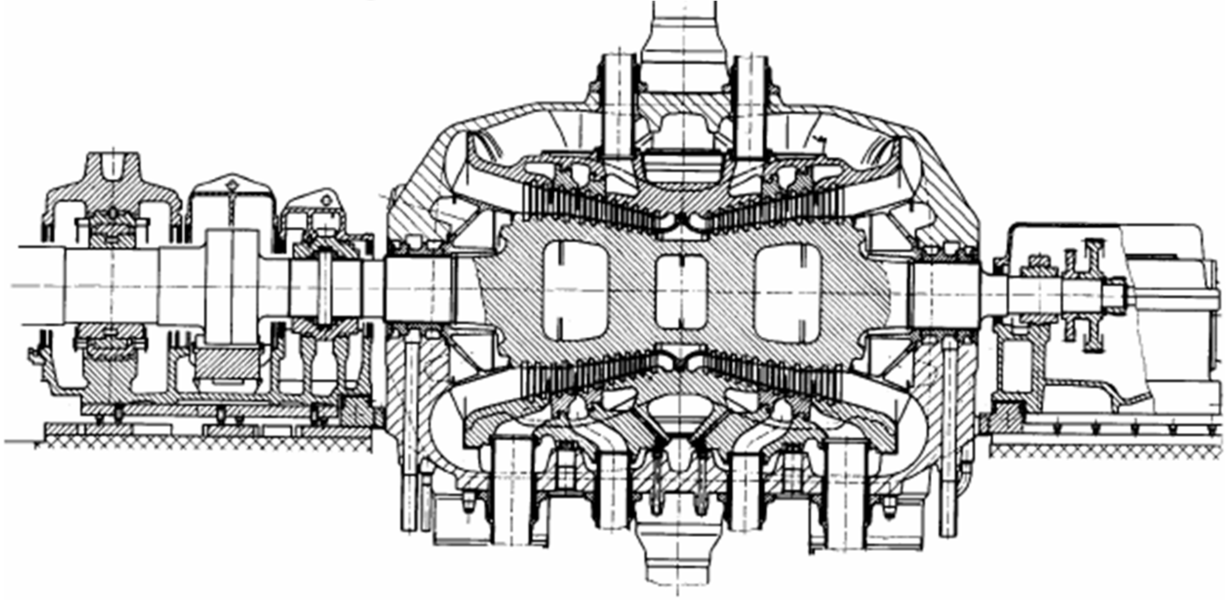
Evolution of rotating machinery - Steam turbines

- A 165 MW two-shaft turboset was built in 1926-1928, with the highpressure shaft rotating at 1800 rpm, and the low-pressure shaft at 1200 rpm.
- In 1948, the largest steam turboset of single-shaft design had four cylinders, a length of 27 m (without the station service generator), an output of 110 MW and speed of 3000 rpm.



Evolution of rotating machinery - Steam turbines

- In 1950, turbosets of 125 MW were built in Europe and of 230 MW in the U.S.A., then, in 1956 - with ratings of 175 MW, and in 1964 - with ratings of 550 MW and two shafts.
- In 1972, the first 1300 MW cross-compound turboset was built at 3600 rpm, provided with two shaft lines for two 722 MVA generators.



Evolution of rotating machinery - Steam turbines

- Current designs have generators of 1635 MVA at 1500 rpm, and of 1447 MVA at 3000 rpm.
- At present time, turbosets of 1700-2000 MW at 1500 or 1800 rpm, and of 1500-1700 MW at 3000 or 3600 rpm are currently built.

Evolution of rotating mach

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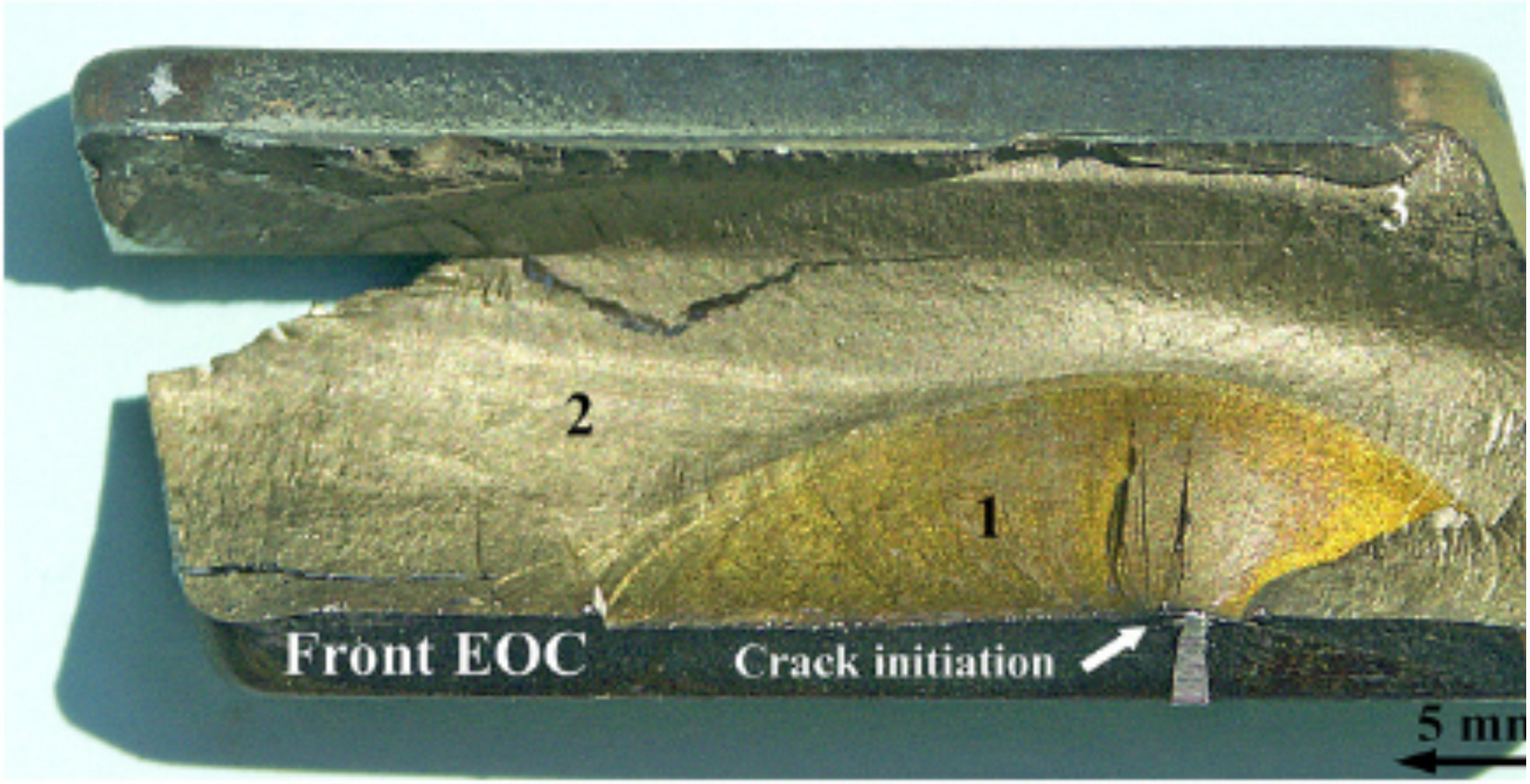
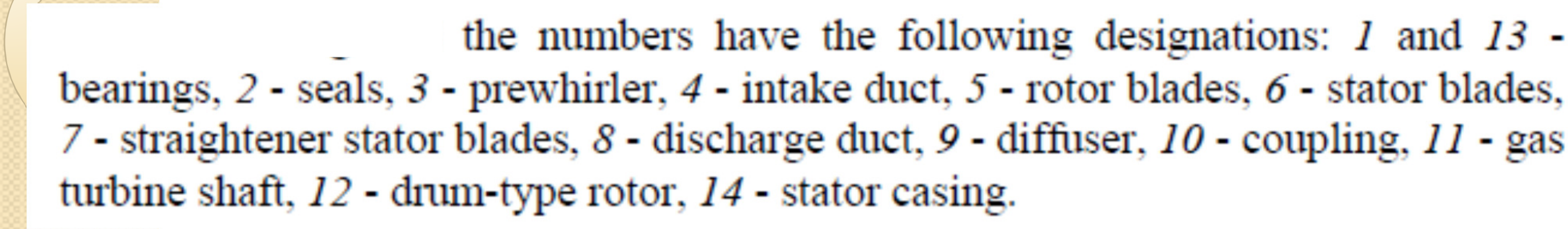
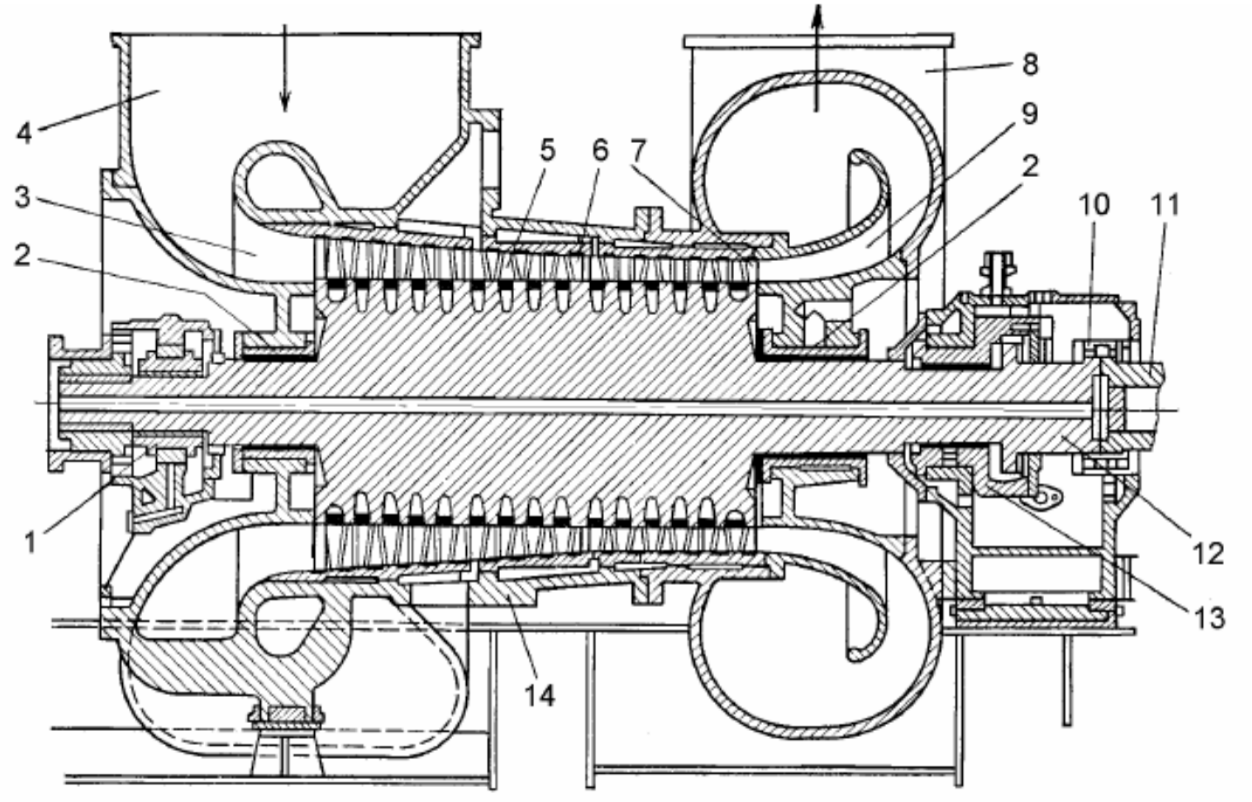


Evolution of rotating machinery - Axial compressors



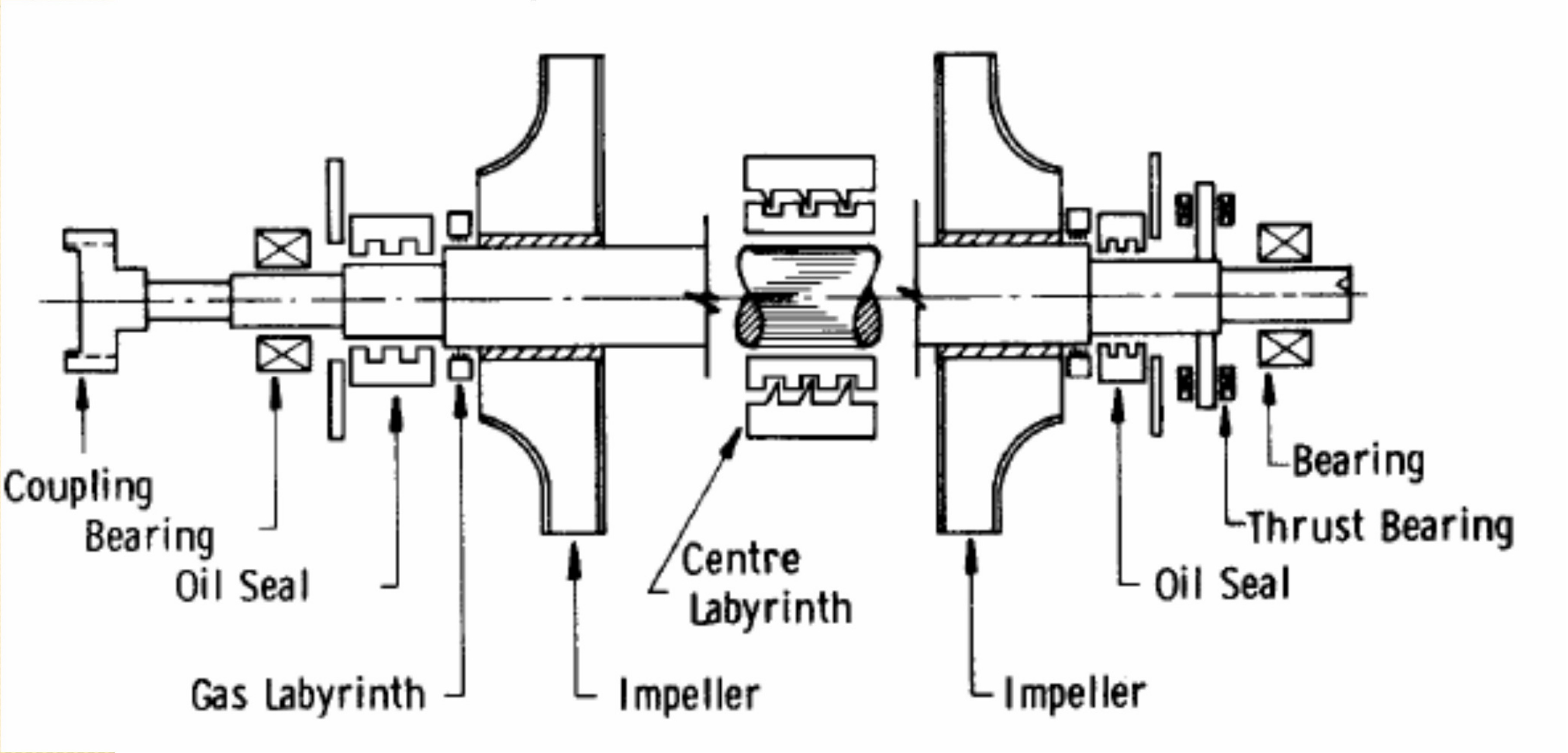
the numbers have the following designations: *1* and *13* - bearings, *2* - seals, *3* - prewhirler, *4* - intake duct, *5* - rotor blades, *6* - stator blades, *7* - straightener stator blades, *8* - discharge duct, *9* - diffuser, *10* - coupling, *11* - gas turbine shaft, *12* - drum-type rotor, *14* - stator casing.

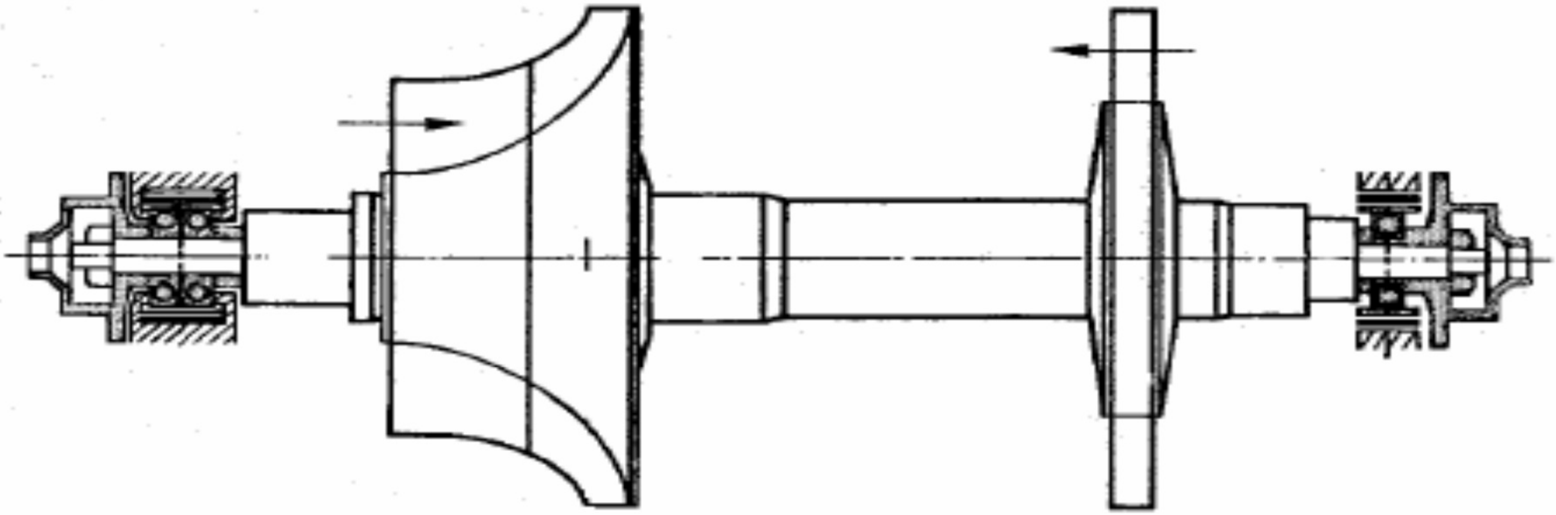
work.



Evolution of rotating machinery - Centrifugal compressors

- Centrifugal compressors are slightly less efficient than axialflow compressors.





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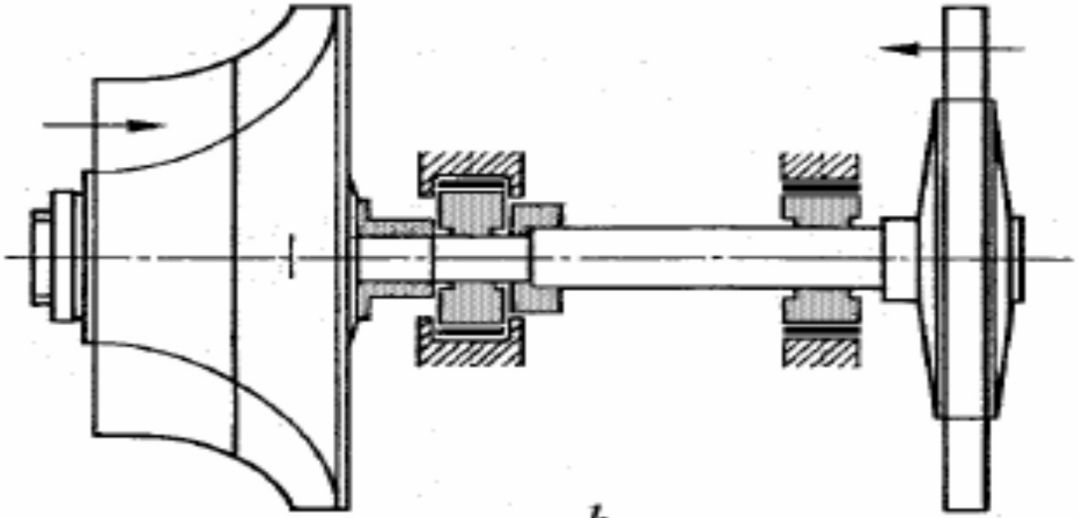

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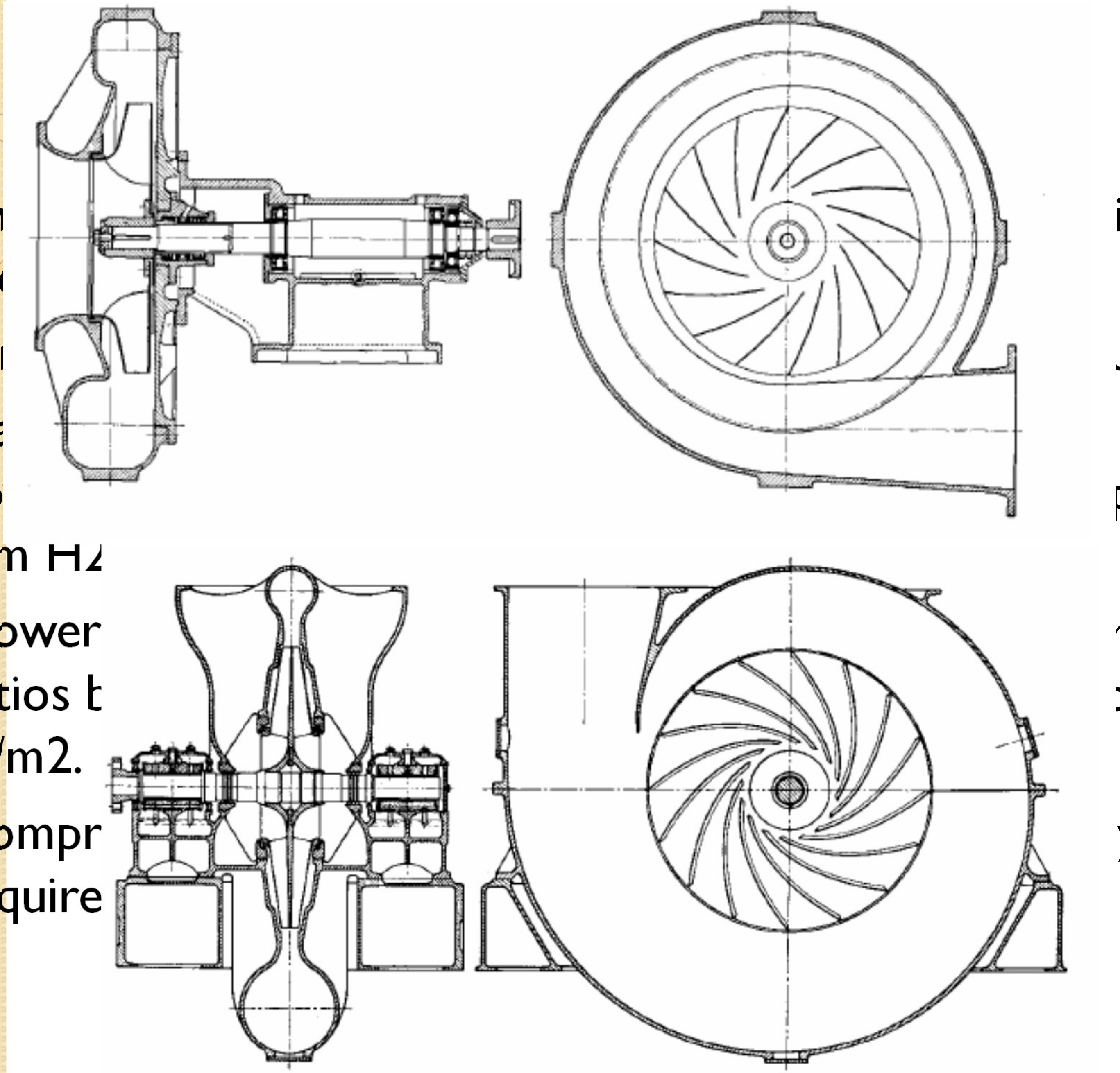

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- Compr y usually
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Centrifugal pumps

- Centrifugal pumps are used in services involving boiler feed,
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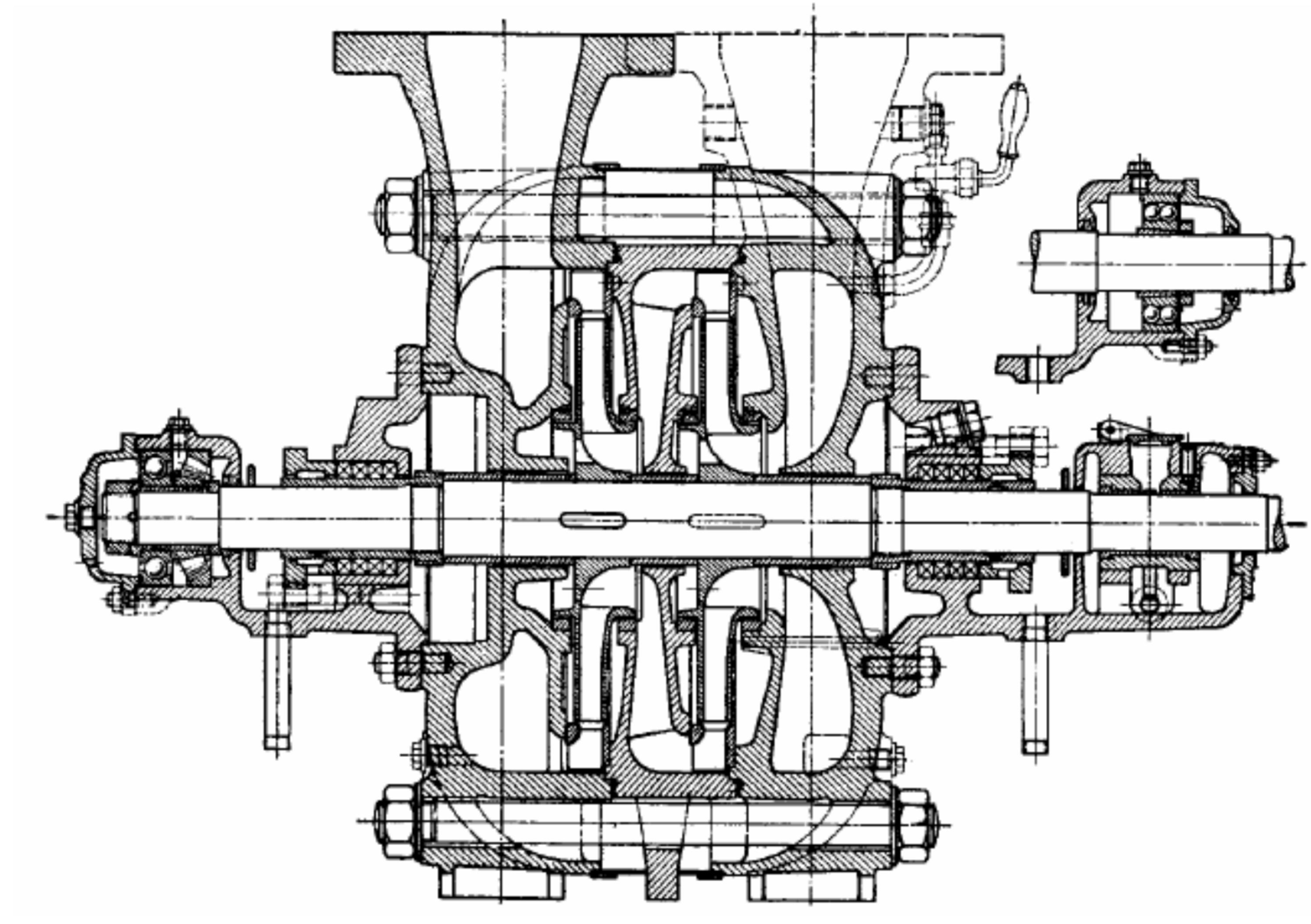


Centrifugal pumps

- major problem with fans is unbalance caused by
- 1) uneven buildup or loss of deposited material;
- and 2) misalignment.

- Both are characterized by changes in vibration at or near the rotational frequency.

Centrifugal pumps

- It is now recognized that turbulent flow annular seals in multi-stage pumps have a dramatic effect on the dynamics of the machine.
- Stiffness and damping properties provided by seals represent the dominant forces exerted on pump shafts, excluding the fluid forces of flow through the impellers, particularly at part-flow operating conditions.
- For these systems, the hydrodynamics of oil-lubricated journal bearings is dominated by seal properties.

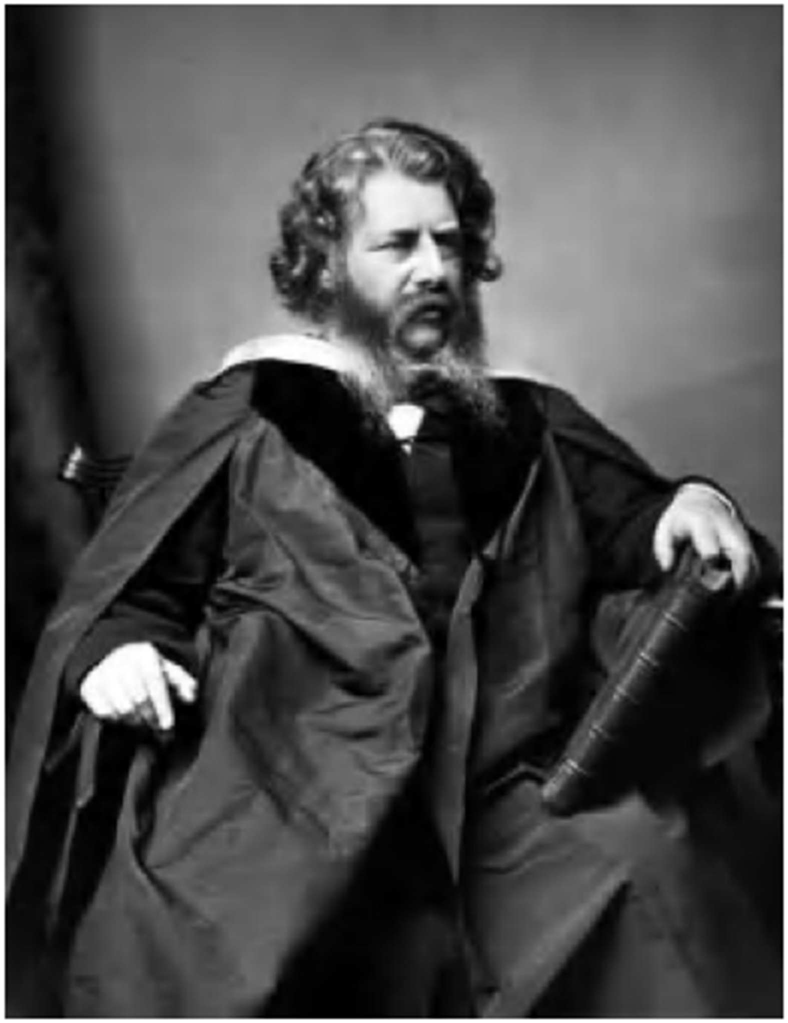
Historical Perspective

- Research on rotordynamics spans at least a 140-year history, starting with Rankine's paper on whirling motions of a rotor in 1869.
- Rankine discussed the relationship between centrifugal and restoring forces and concluded that operation above a certain rotational speed is impossible.
- Although this conclusion was wrong, his paper is important as the first publication on rotordynamics.

APRIL 9, 1869. THE ENGINEER.

ON THE CENTRIFUGAL FORCE OF ROTATING SHAFTS.

THE IRON TRADE OF MONMOUTHSHIRE AND SOUTH WALES.



Historical Perspective

- De Laval, an engineer in Sweden, invented a one-stage steam turbine and succeeded in its operation.
- He showed that it was possible to operate above the critical speed by operating at a rotational speed about seven times the critical speed

Historical Perspective

- In the early days, the major concern for researchers and designers was to predict the critical speed, because the first thing that had to be done in designing rotating machinery was to avoid resonance.
- Dunkerley (1894) derived an empirical formula that gave the lowest critical speed for a multirotor system.
- He was the first to use the term "*critical speed*" for the resonance rotational speed.

Historical Perspective

- Holzer (1921) proposed an approximate method to calculate the natural frequencies and mode shapes of torsional vibrations.
- The first recorded fundamental theory of rotordynamics can be found in a paper written by Jeffcott (1919) .
- A shaft with a disk at the midspan is called the *Jeffcott rotor.*
- It is also called the *Laval rotor*, named after de Laval.

Historical Perspective

- The developments made in rotordynamics in the masterpiece written by Stodola (1924).
- This superb book explains nearly the entire field related to steam turbines.
    - the dynamics of elastic shafts with disks,
    - the dynamics of continuous rotors without considering the gyroscopic moment,
    - the balancing of rigid rotors, and
    - methods for determining approximate values of critical speeds of rotors with variable cross sections.

Historical Perspective

- Thereafter, the center of research shifted from Europe to the United States.
- Campbell (1924) at General Electric investigated vibrations of steam turbines in detail.
- His diagram, representing critical speed in relation to the cross points of natural frequency curves and the straight lines proportional to the rotational speed, is now widely used and referred to as the *Campbell diagram*.

Historical Perspective

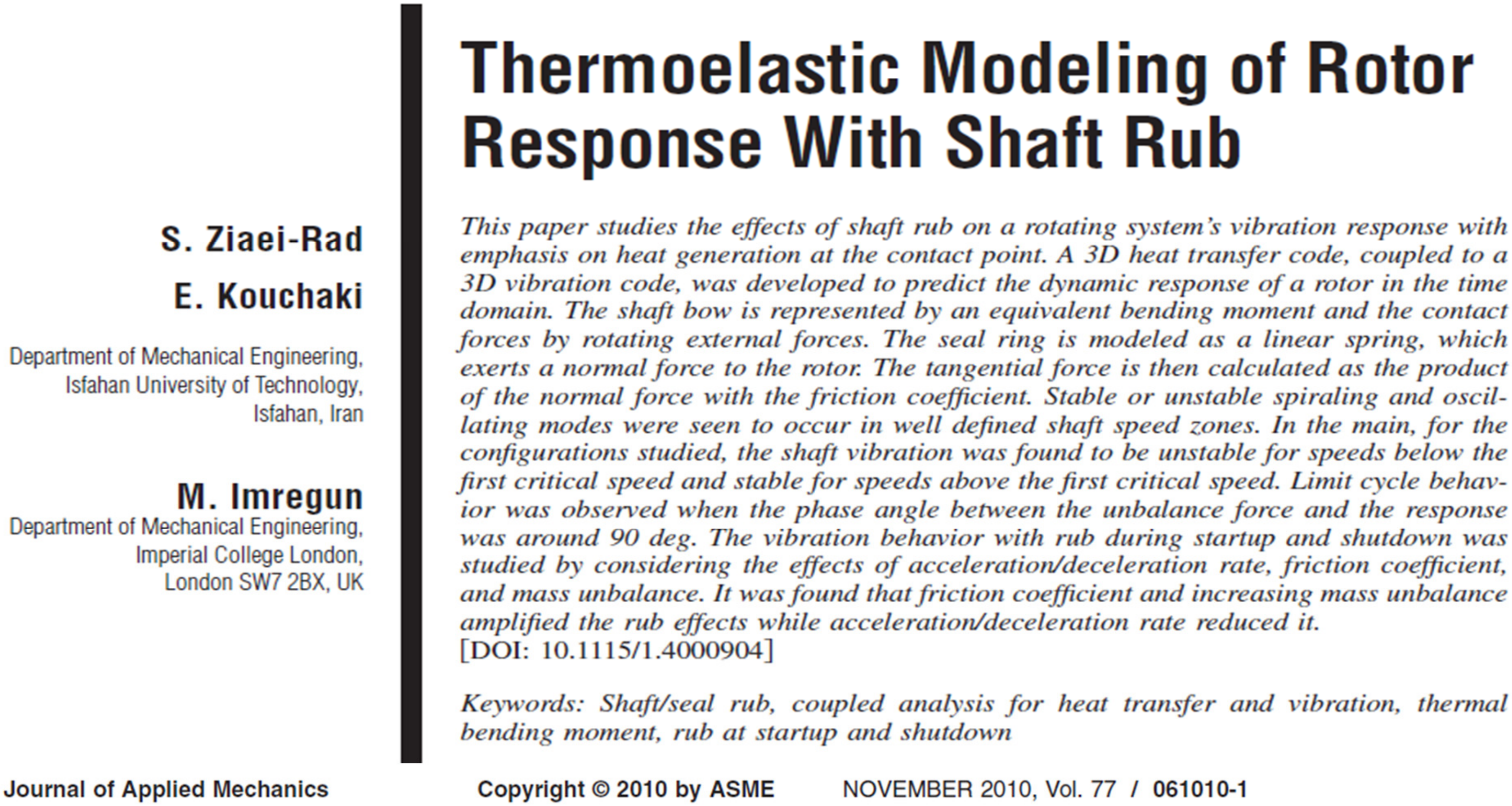
- As the rotational speed increased above the first critical speed, the occurrence of self-excited vibrations became a serious problem.
- In the 1920s, Newkirk (1924) and Kimball (1924) first recognized that internal friction of shaft materials could cause an unstable whirling motion.

Historical Perspective

- These phenomena, in which friction that ordinarily dampens vibration causes self-excited vibration, attracted the attention of many researchers.
- Newkirk and Taylor (1925) investigated an unstable vibration called *oil whip*, which was due to an oil film in the journal bearings.

Historical Perspective

- Newkirk (1926) showed a forward whirl induced by a hot spot on the rotor surface, which was generated by the contact of the rotor and the surroundings.
- This hot spot instability is called the *Newkirk effect.*



Thermoelastic Modeling of Rotor Response With Shaft Rub

S. Ziaei-Rad

E. Kouchaki

Department of Mechanical Engineering,
Isfahan University of Technology,
Isfahan, Iran

M. Imregun
Department of Mechanical Engineering,
Imperial College London,
London SW7 2BX, UK

This paper studies the effects of shaft rub on a rotating system's vibration response with emphasis on heat generation at the contact point. A 3D heat transfer code, coupled to a 3D vibration code, was developed to predict the dynamic response of a rotor in the time domain. The shaft bow is represented by an equivalent bending moment and the contact forces by rotating external forces. The seal ring is modeled as a linear spring, which exerts a normal force to the rotor. The tangential force is then calculated as the product of the normal force with the friction coefficient. Stable or unstable spiraling and oscillating modes were seen to occur in well defined shaft speed zones. In the main, for the configurations studied, the shaft vibration was found to be unstable for speeds below the first critical speed and stable for speeds above the first critical speed. Limit cycle behavior was observed when the phase angle between the unbalance force and the response was around 90 deg. The vibration behavior with rub during startup and shutdown was studied by considering the effects of acceleration/deceleration rate, friction coefficient, and mass unbalance. It was found that friction coefficient and increasing mass unbalance amplified the rub effects while acceleration/deceleration rate reduced it.

[DOI: 10.1115/1.4000904]

Keywords: Shaft/seal rub, coupled analysis for heat transfer and vibration, thermal bending moment, rub at startup and shutdown

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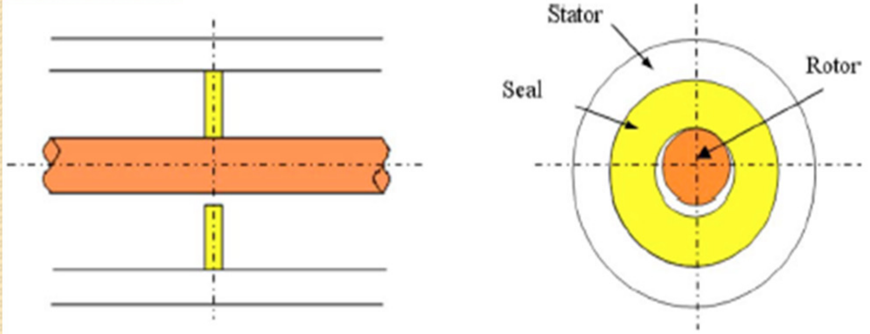
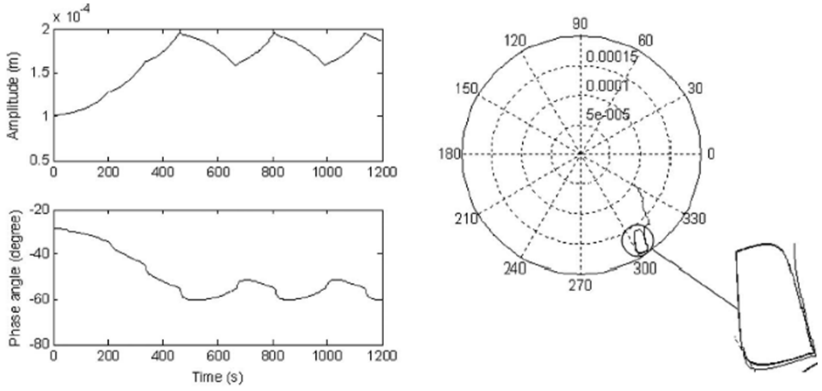


Fig. 1 The contact between shaft and seal

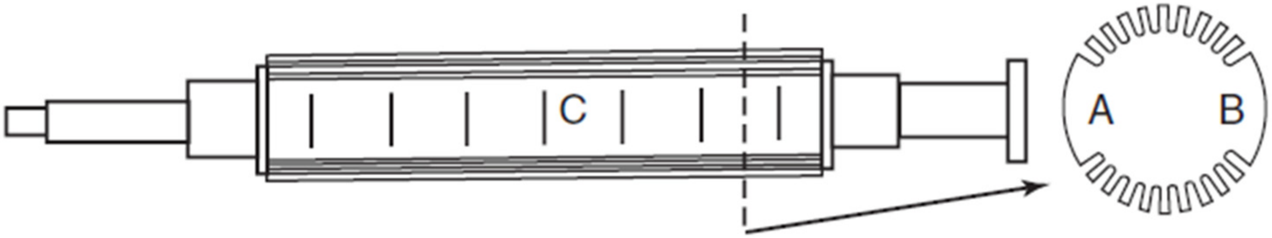


(a) Amplitude and phase versus time

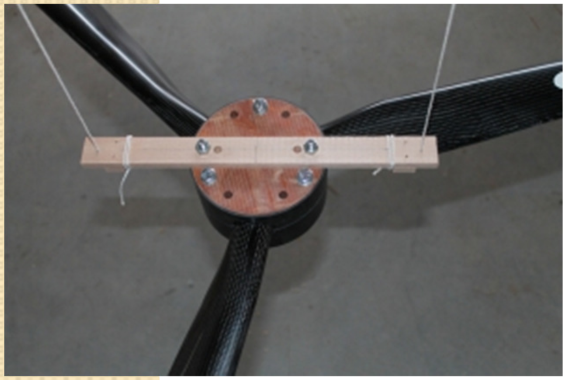
(b) Amplitude in polar plot

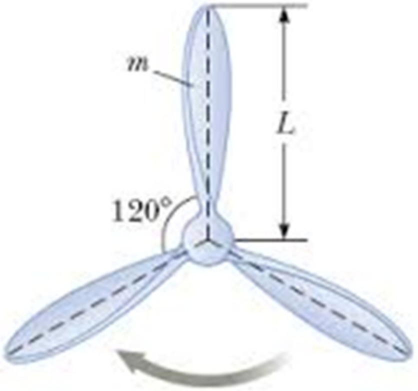
Historical Perspective

- About a decade later, the study of asymmetrical shaft systems and asymmetrical rotor systems began.



Two-pole generator rotor. asymmetrical shaft systems





In the case of a propeller, its moment of inertia has a directional difference.

Historical Perspective

- As these directional differences rotate with the shaft, terms with time-varying coefficients appear in the governing equations.
- These systems therefore fall into the category of parametrically excited systems.
- The most characteristic property of asymmetrical systems is the appearance of unstable vibrations in some rotational speed ranges.
- Smith (1933)'s report is a pioneering work on this topic.

Historical Perspective

- Various phenomena related to the asymmetries of rotors were investigated actively in the middle of the twentieth century by Taylor (1940) and Foote, Poritsky, and Slade (1943), Brosen and Crandall (1961), and Yamamoto and Ota (1963a, 1963b, 1964).

Historical Perspective

- Nonstationary phenomena in passage through critical speeds have been studied since Lewis reported his investigation on the Jeffcott rotor in 1932.
- reports on this topic are classified into two groups.
    - with a constant acceleration and
    - with a limited driving torque.
- Due to complexity of the problem numerical integrations was used.
- The asymptotic method developed by the Russian school of Krylov and Bogoliubov (1947) and Bogoliubov and Mitropol'skii (1958) considerably boosted the research on this subject.

Historical Perspective

- The vibrations of rotors with continuously distributed mass were also studied.
- The simplest continuous rotor model corresponding to the Euler beam was first studied in the book by Stodola (1924).
- In the 1950s and 1960s, Bishop (1959), Bishop and Gladwell (1959), and Bishop and Parkinson (1965) reported a series of papers on the unbalance response and the balancing of a continuous rotor.
- Eshleman and Eubanks (1969) derived more general equations of motion considering the effects of rotary inertia, shear deformation, and gyroscopic moment.

Historical Perspective

- The most important and fundamental procedure to reduce unfavorable vibrations is to eliminate geometric imbalance in the rotor. The balancing technique for a rigid rotor was established relatively early.
- A practical balancing machine based on this technique was invented by Lawaczeck in 1907.
- In 1925, Suehiro invented a balancing machine that conducts balancing at a speed in the postcritical speed range.
- In 1934, Thearle developed the two-plane balancing

Historical Perspective

- The arrival of high-speed rotating machines made it necessary to develop a balancing technique for flexible rotors.
- Two representative theories were proposed.
- One was *the modal balancing method* proposed in the 1950s by Federn (1957) and Bishop and Gladwell (1959).
- The other was *the influence coefficient method* proposed in the early 1960s and developed mainly in the United States alone with the progress of computers.
- Goodman (1964) improved this method by taking into the least square methods.

Historical Perspective

- In the latter half of the twentieth century, various vibrations due to fluid were studied.
- Hori (1959) succeeded in explaining various fundamental characteristics of oil whip by investigating the stability of shaft motion and considering pressure forces due to oil films.
- In 1964, Alford reported accidents due to labyrinth seals.
- Another one was a self-excited vibration called *the steam whirl.* The mechanism of this vibration in turbines was explained by Thomas (1958) and that in compressors was explained by Alford (1965).

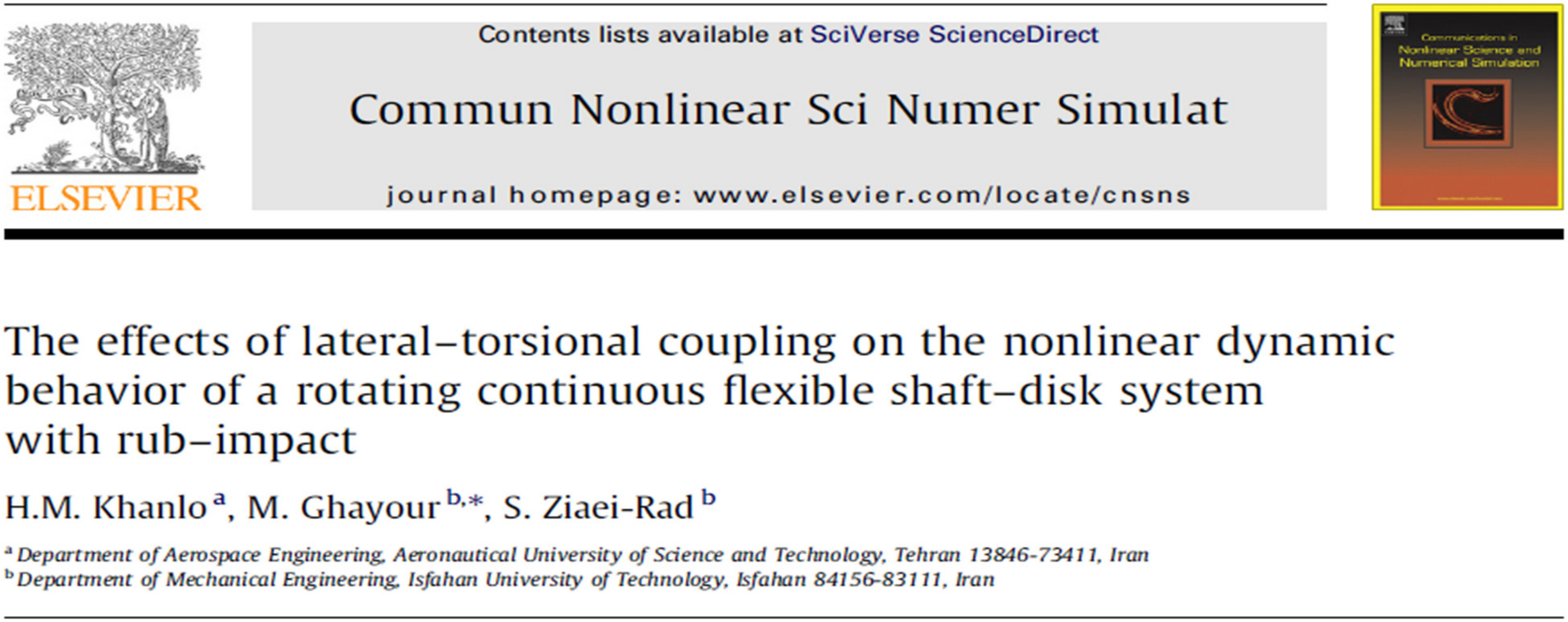
Historical Perspective

- As rotors became lighter and their operational speeds higher, the occurrence of nonlinear resonances such as subharmonic resonances became a serious problem.
- Yamamoto (1955, 1957a) studied various kinds of nonlinear resonances after he reported on subharmonic resonances due to ball bearings, in 1955.
- In the 1960s, Tondl (1965) studied nonlinear resonances due to oil films in journal bearings.

Historical Perspective

- Ehrich (1966) reported subharmonic resonances observed in an aircraft gas turbine with squeeze-film damper bearings.
- The cause of strong nonlinearity in aircraft gas turbines is the radial clearance of squeeze-film damper bearings.
- Later, Ehrich (1988, 1991) reported the occurrence of various types of subharmonic resonances up to a very high order and also chaotic vibrations in practical engines.

Historical Perspective



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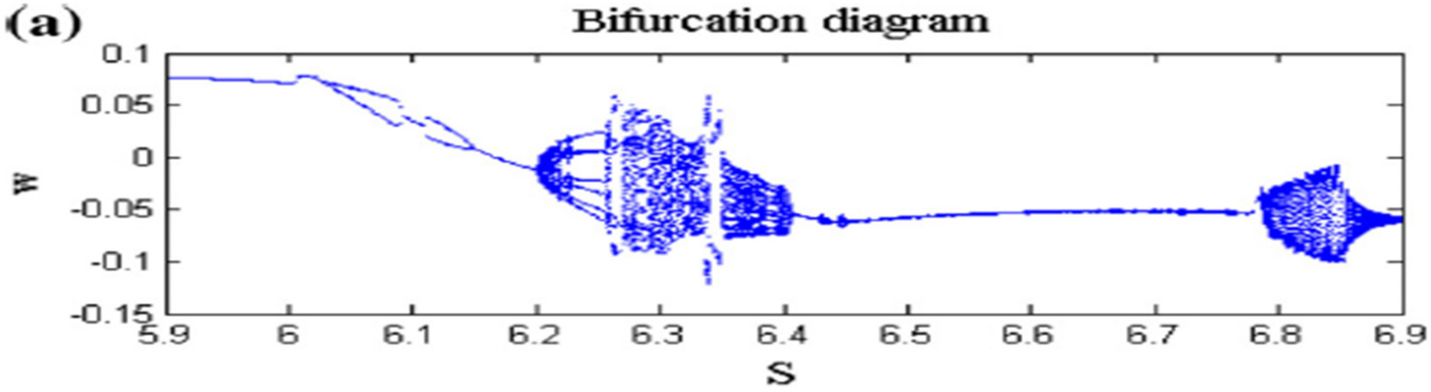
The effects of lateral–torsional coupling on the nonlinear dynamic behavior of a rotating continuous flexible shaft–disk system with rub–impact

H.M. Khanlo[a], M. Ghayour[b,*], S. Ziaei-Rad[b]

[a] Department of Aerospace Engineering, Aeronautical University of Science and Technology, Tehran 13846-73411, Iran
[b] Department of Mechanical Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran



Historical Perspective

- In the practical design of rotating machinery, it is necessary to know accurately the natural frequencies, modes, and forced responses to unbalances in complex-shaped rotor systems.
- Prohl (1945) used the transfer matrix method in the analysis of a rotor system by expanding the method originally developed by Myklestad (1944).
- This analytical method is particularly useful for multirotor-bearing systems and has develop rapidly since the 1960s by the contribution of many researchers such as Lund and Orcutt (1967) and Lund (1974).

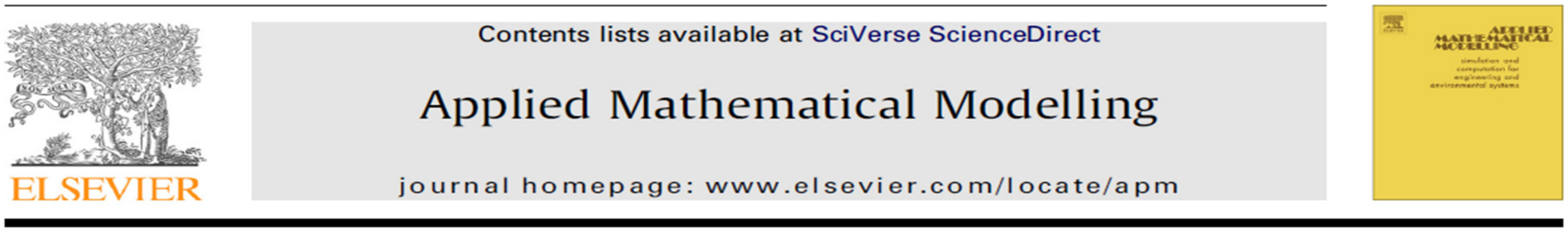
Historical Perspective

- The finite-element method was first developed in structural dynamics and then used in various technological fields.
- The first application of the finite-element method to a rotor system was made by Ruhl and Booker (1972).
- Then, Nelson and McVaugh (1976) generalized it by considering rotating inertia, gyroscopic moment, and axial force.

Historical Perspective

- From the 1950s, cracks were found in rotors of some steam turbines .
- To prevent serious accidents and to develop a vibration diagnosis system for detecting cracks, research on vibrations of cracked shafts began.
- In the 1970s, Gasch (1976) and Henry and Okah-Avae (1976) investigated vibrations, giving consideration to nonlinearity in stiffness due to open–close mechanisms.
- They showed that an unstable region appeared or disappeared at the major critical speed, depending on the direction of the unbalance. The research is still being developed and various monitoring systems have been proposed.

Historical Perspective



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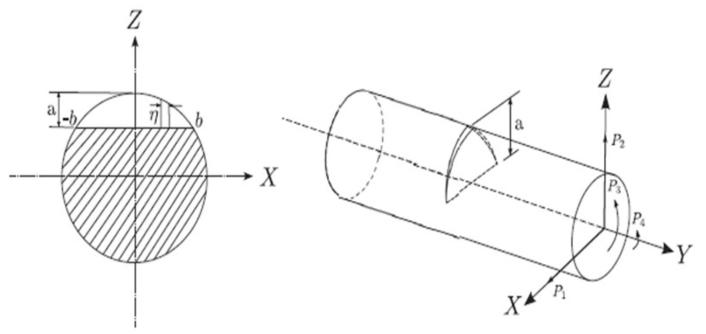
Vibration analysis of rotating systems with open and breathing cracks

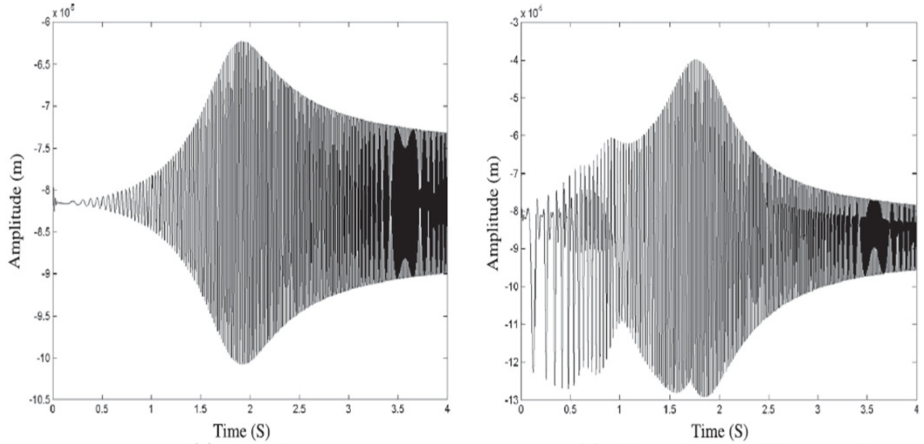
M. Silani [a,*], S. Ziaei-Rad [a], H. Talebi [b]

[a] *Department of Mechanical Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran*
[b] *Graduiertenkolleg 1462, Bauhaus-Universität Weimar, 99423 Weimar, Germany*



(a) Cross section of cracked element

(b) Nodal forces on the element

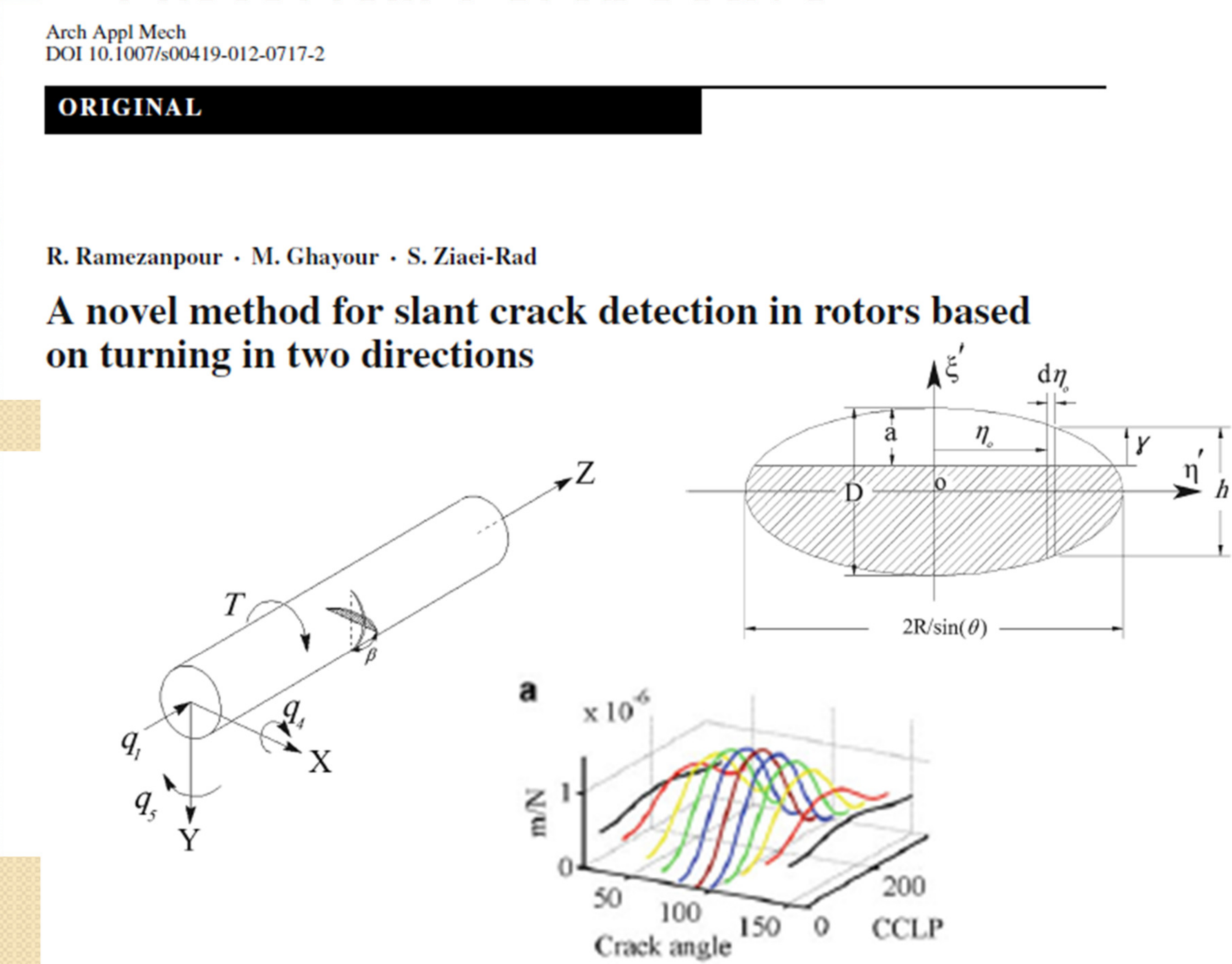


(a) no crack

(b) with crack, phase difference =0

x 10⁻⁵

Historical Perspective



Arch Appl Mech
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ORIGINAL

R. Ramezanpour · M. Ghayour · S. Ziaei-Rad

A novel method for slant crack detection in rotors based on turning in two directions

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Failure analysis of Ti6Al4V gas turbine compressor blades

A. Kermanpur [a,*], H. Sepehri Amin [a], S. Ziaei-Rad [b], N. Nourbakhshnia [b],
M. Mosaddeghfar [c]

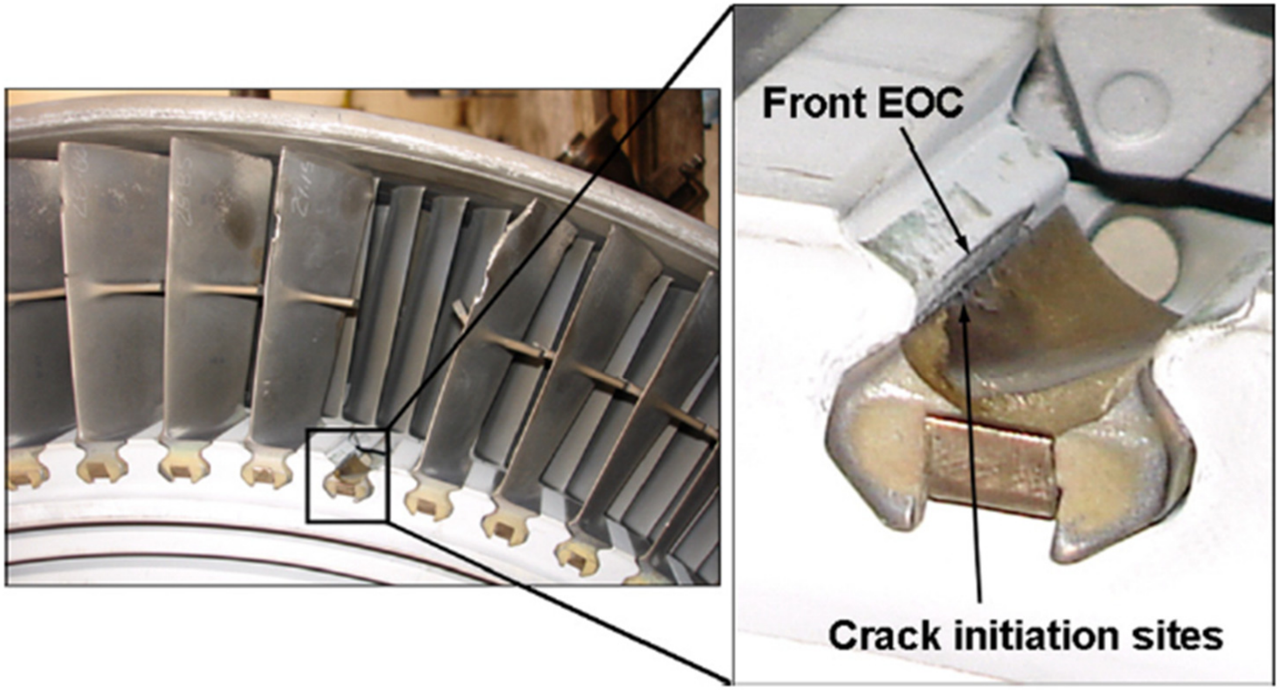
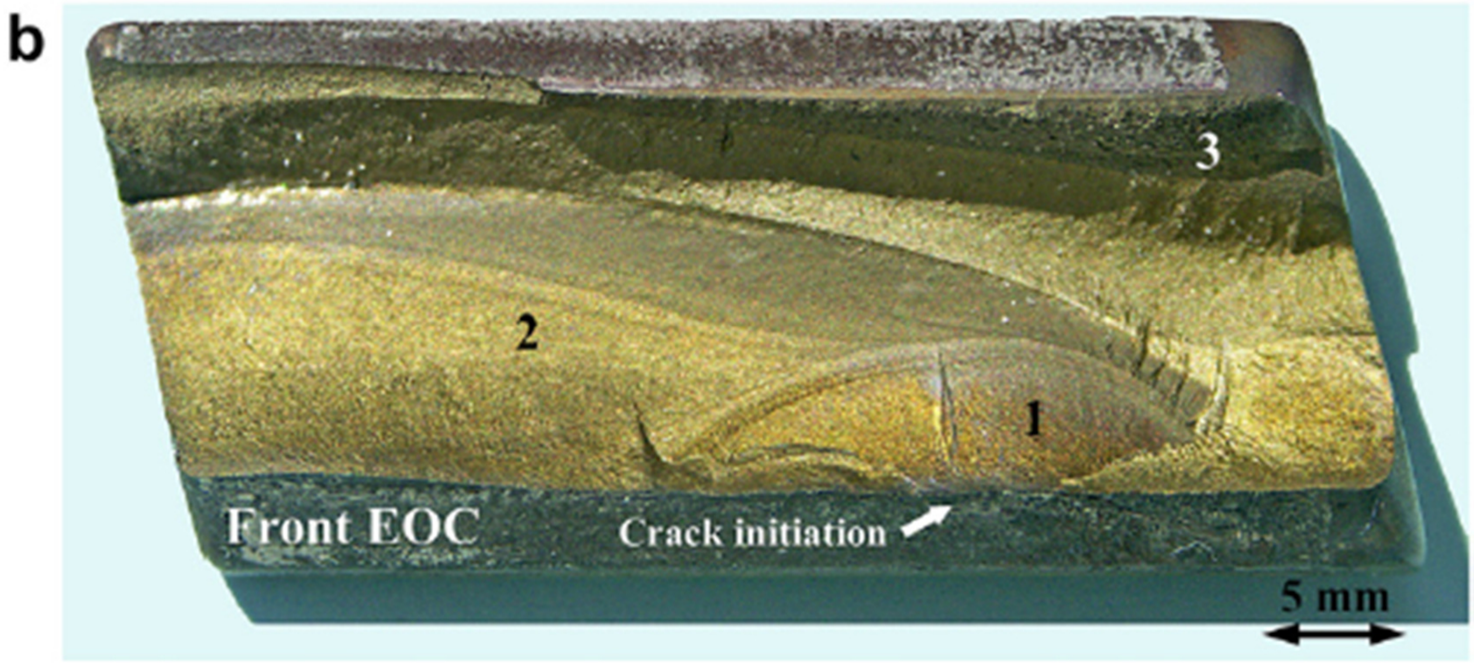
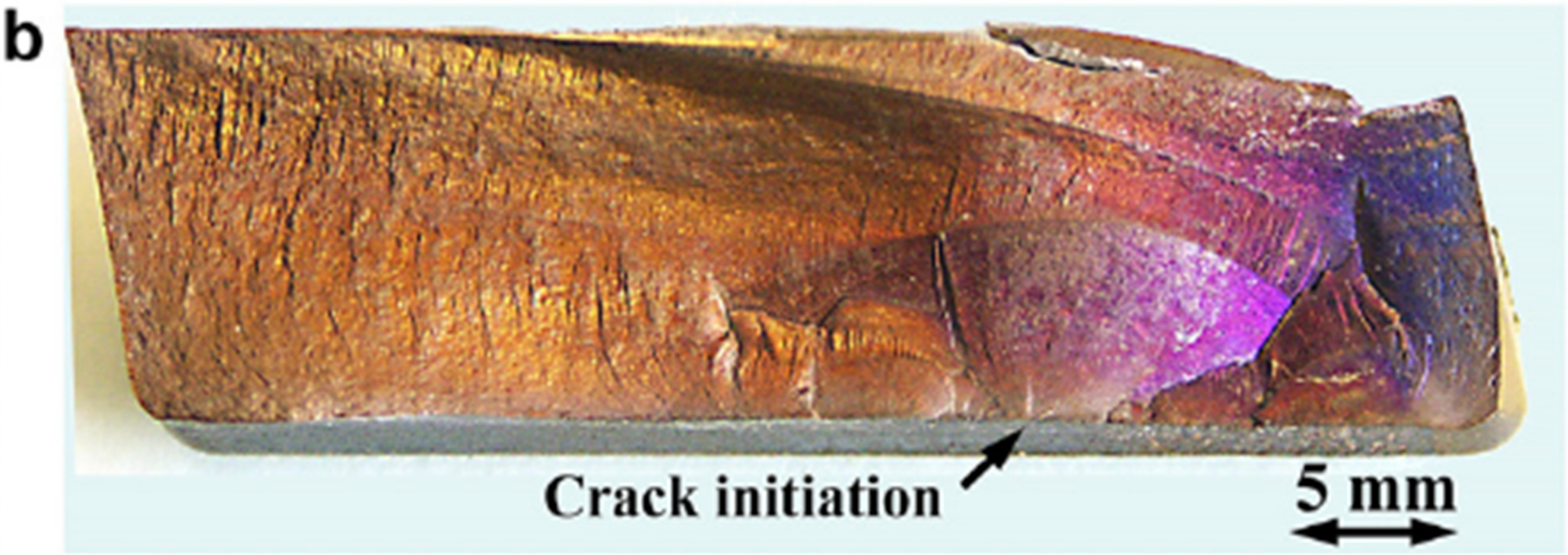


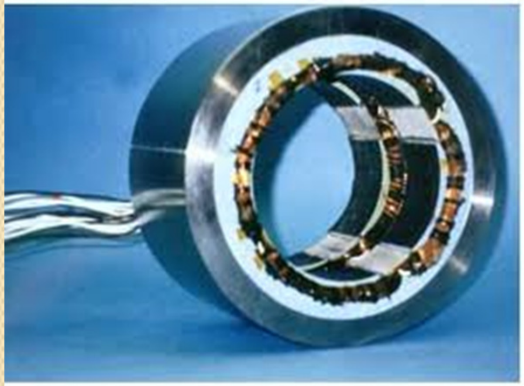
Fig. 12. Part of the 1st stage of the HP compressor including the remained blade root in the dovetail region. Note that the crack initiation sites on the root surface and the wear appearance on the counterpart disk dovetail are shown by arrows.

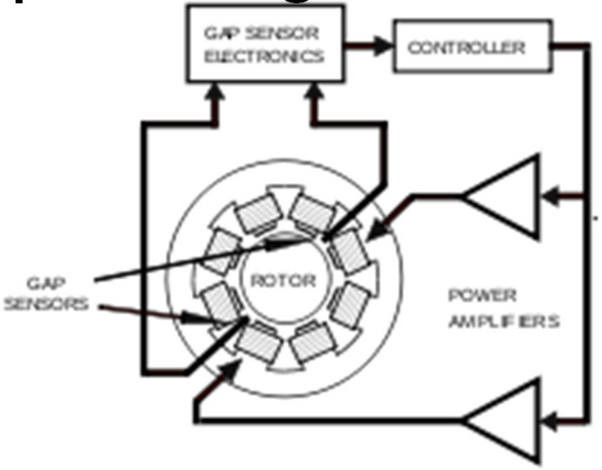

b
3
2
1
Front EOC
Crack initiation
5 mm

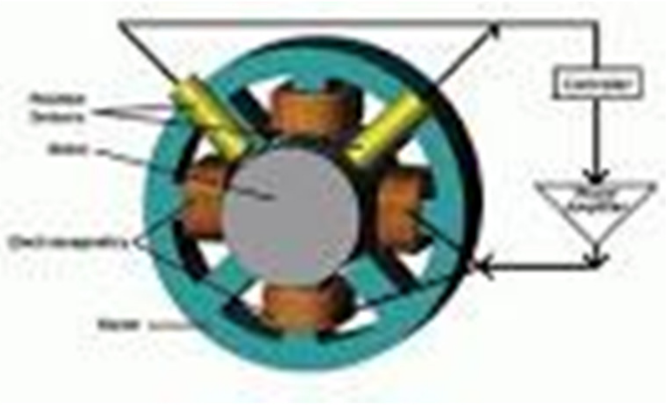

b
Crack initiation
5 mm

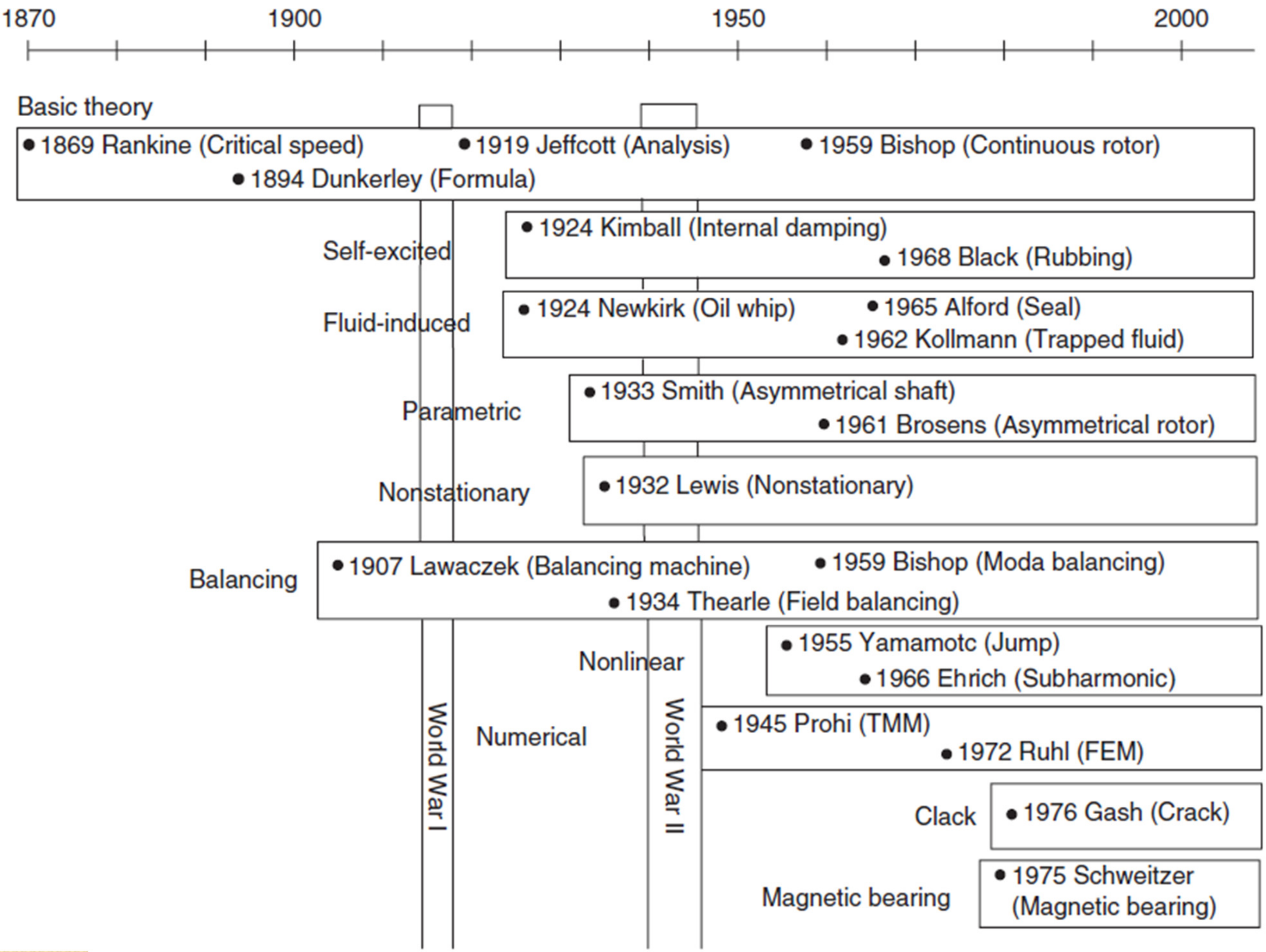
Historical Perspective

- The latest topics in rotordynamics are magnetic bearings that support a rotor without contacting it and active control.
- This study has received considerable attention since Schweitzer (1975) reported his work in 1975.
- Nonami (1985) suppressed an unbalance response of a rotor controlling the bearing support actively using the optimal regulator theory.









1870 1900 1950 2000

Basic theory
- 1869 Rankine (Critical speed)
- 1894 Dunkerley (Formula)
- 1919 Jeffcott (Analysis)
- 1959 Bishop (Continuous rotor)

Self-excited
- 1924 Kimball (Internal damping)
- 1968 Black (Rubbing)

Fluid-induced
- 1924 Newkirk (Oil whip)
- 1965 Alford (Seal)
- 1962 Kollmann (Trapped fluid)

Parametric
- 1933 Smith (Asymmetrical shaft)
- 1961 Brosens (Asymmetrical rotor)

Nonstationary
- 1932 Lewis (Nonstationary)

Balancing
- 1907 Lawaczek (Balancing machine)
- 1959 Bishop (Moda balancing)
- 1934 Thearle (Field balancing)

Nonlinear
- 1955 Yamamotc (Jump)
- 1966 Ehrich (Subharmonic)

Numerical
- 1945 Prohi (TMM)
- 1972 Ruhl (FEM)

Clack
- 1976 Gash (Crack)

Magnetic bearing
- 1975 Schweitzer (Magnetic bearing)

World War I

World War II