# Mechatronics in Rotating Machinery

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## ABSTRACT

In this survey paper, we discuss the recent progress in researches on mechatronics in rotating machinery. Even before 'mechatronics' emerged as a new concept in technological advancement, much mechatronization effort has already been made in rotating machinery. Automatic balancer, for example, is a typical mechatronics product in rotating machinery that has a long history of development. When smart actuators such as piezoelectric ceramics, electro-magnetic/dynamic actuators, shape-memory alloy, controllable fluids and hydraulic actuators became available to structural and control engineers, there has been immediate effort to employ such actuators in rotating machines. There have been many attempts to apply those actuators to excite the rotors for parameter identification, to control the motion of the rotating shaft and the bearing housing, and, to control the fluid pressure, flow, temperature and viscosity of the bearings, seals and dampers. Although there are a few successful cases, including active magnetic bearing, many mechatronics inventions need more time to be implemented for practical use in rotating machines in operation, some remaining as pure academic research interests and some as disappointing results, which seem to be far from practicality for the time being.

The rotor dynamics research has a tradition of practicality, growing from the industrial needs, and another of 'conservatism' that new techniques are absorbed in a slow fashion until they are matured and field proven. Mechatronization of rotating machines is no exception in this respect. We need a little more push to see more and more practical cases in the near future. Mechatronization is certainly the right way for the rotating machine community to go, as long as the need for enhanced reliability and safe operation of rotating machines accelerates with technological advancement.

## KEY WORDS

Mechatronics, sensors and actuators, automatic balancer, active bearing, active damper, active seal, micro rotor, intelligent rotor system

## 1. INTRODUCTION

Mechatronics, as an engineering discipline, is the synergistic combination of mechanical engineering, electronics, control engineering, and computers, all integrated through the design process. It includes the system design, system integration, power electronics and motion control, intelligent control, robotics, vibration and noise control, vehicle and manufacturing applications, and MEMS. Since the term 'mechatronics' was coined in 1969 by a group of Japanese scholars, it has been revolutionized by the advent of such key technologies as the high-speed microprocessors, the precision sensors and broad bandwidth actuators, the digital control and communication, and most recently the MEMS devices.

Perhaps, the typical examples of the classical and modern commercial mechatronics products in rotating machinery are the dynamically tuned gyroscope (DTG) [29] and the active magnetic bearing (AMB) spindle, as illustrated in Figures 1.1 and 1.2, respectively. The operational principle of DTG is as follows. As external moments or angular movements disturb the casing, a pair of proximity probes captures the relative displacements between the casing and the free gyro (DTG), which are fed back to a pair of torquers for rebalancing DTG. The currents to the torquers are then used to estimate the angular rate of the casing. The operational principle of AMB system is as follows. Proximity probes measure the motion of the spindle and the signals are fed back to AMB so that the spindle is levitated by the balanced electro-magnetic radial forces generated from two opposite magnetic coils. AMB is also used to control or reduce the radial and axial vibrations caused during operation. The AMB system equipped with force transducers, as shown in Figure 1.2, is capable of in-situ identification of system parameters [43].

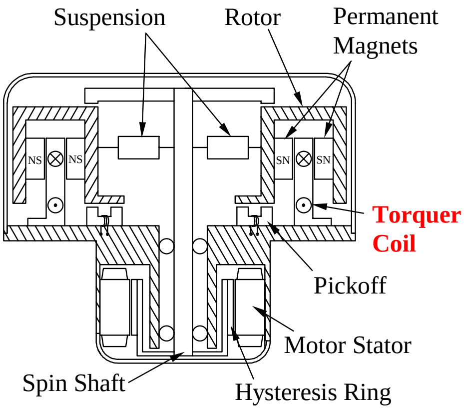


Figure 1.1 DTG [29]

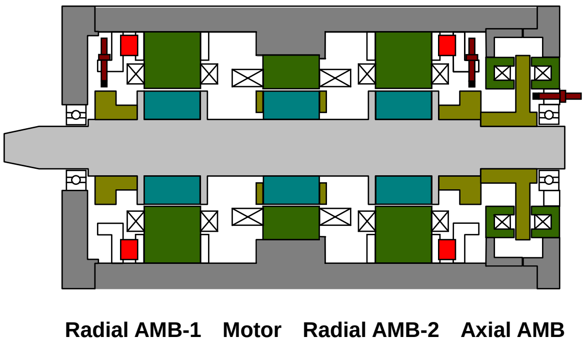


Figure 1.2 AMB System [43]

In this survey paper, we confine ourselves to mechatronics applications in rotating machinery, particularly in the area of vibration measurement and control of rotating machines. The term, 'rotating machinery' is often referred, in a narrow sense, to as the rotating machines mostly used in industry, such as fans, pumps, compressors, turbines, generators, gears and motors. However, we will refer the rotating machinery, in a broad sense, to as the rotating machines and the rotating elements in machines and devices, including washing machines, hard disk drives, grinding machines, gyro sensors and actuators, and, micro turbines. It is not a surprise to see that the mechatronics has not been well developed in the traditional industrial rotating machinery, although its history can be dated back to the age of industrial revolution. The main reason may be projected as the 'conservative' low-risk-taking nature in the design and operation of expensive facilities such as power plants and flight vehicles so that new technologies are cautiously adopted unless they become fully mature. In other words, the implementation of new technology including mechatronics has been rather slow, finding only a few successful applications to traditional rotating machinery. On the other hand, many investigators have been actively involved in research works, looking for potential, long-term applications of mechatronics since a couple of decade ago, which will be discussed here.

Rotating machines consist of sensors and actuators, balancing planes, dampers and squeeze film dampers, bearings and seals, and so on, all of which become natural targets for mechatronization. In this paper, we will focus on the efforts and attempts that have been made to mechatronize those elements in modern rotating machinery.

Finally, based on the survey of the current state-of-the-art of mechatronics in rotating machinery, we hope to come up with some prospects for the future technological development.

## 2. SENSOR AND EXCITATION TECHNIQUES

Sensors and exciters certainly form essential elements in mechatronics and in the process of mechatronizing rotating machines. In this section, we briefly discuss the sensor and excitation techniques developed uniquely for rotating machines.

### 2.1 Sensor techniques

In early 1920s, Campbell placed coils to measure the turbine disk vibrations during operation in the stationary and rotating frames [11]. He confirmed that the presence of the backward traveling wave modes could endanger the operation of turbine disks. The electrical resistance strain gauges, which became commercially available in early 1940s, have soon emerged as one of the standard sensors used in rotating machinery. For example, in 1950s, Russian engineers carried out a series of tests on a heavy generator rotor, which is a typical asymmetric rotor, weighing about 60 tons and with the bearing span of 10 m [16]. Measurements were taken of the mechanical bending stresses on the surface of the rotor and of the horizontal vibrations of the bearings, using strain gauges bonded on the rotor surface with a current collector and vibration pick-ups, respectively. They successfully observed the major critical speed region (the instability region associated with the rotating asymmetry) and the sub-critical speed.

As the eddy current type proximity probes became commercially available in 1960s by the Bently Nevada Corp., they, together with the traditional accelerometers and vibrometers, have quickly become the standard sensors for rotating machines. Development of capacitance-type proximity probes, and, optical encoders/array sensors and proximity switches were soon followed, which stimulated some evolutions in the use of such sensors in rotating machinery. A few notable sensor techniques, developed for rotating machinery, include [5]:

(1) a pair of sensors placed perpendicular to each other so that the whirling of the target shaft/bearing can be visualized as the planar motion;

(2) keyphasor that identifies the reference for angular motion; and

(3) z-pulse that can be used to identify the direction of whirls on monitors and oscilloscopes.

In recent years, more sophisticated, still expensive, sensors such as optical array sensor, optical fibre vibrometer, and scanning laser Doppler vibrometer become widely available as non-contacting displacement/velocity sensors for rotating machines.

## 2.2 Excitation techniques

System/parameter identification has long been an attractive area of research in rotating machinery as well as structural dynamics. Various experimental techniques have been developed to extract the dynamic properties of bearings and seals, mostly by shaking the stationary part of the machines or test rigs. Most of them are not much different from the modal testing methods developed for ordinary structures, which will not be treated here. A typical example is the hydraulic exciter shaking the seal housing for seal coefficient identification used in Texas A & M University [13]. In this section, we pay special attention to the exciters and excitation techniques developed solely for rotating machinery.

### 2.2.1 Impact

In 1975, Morton [54] first identified oil film bearing coefficients for a full operating turbomachine by means of the simplest broadband excitation technique, the impact. The preloaded rotating shaft with a static force is suddenly released by breaking the link and the impulse force is measured by strain gauges as shown in Figure 2.1. Later, the impulse hammer, which became so popular as an exciter for modal testing of stationary structures, has also been adopted for modal testing of rotating machines. For example, Nordmann [62] excited a simple rotor supported in oil film bearings by a hammer impact. The impact force and displacement signals were used for identification of the modal parameters of the rotor.

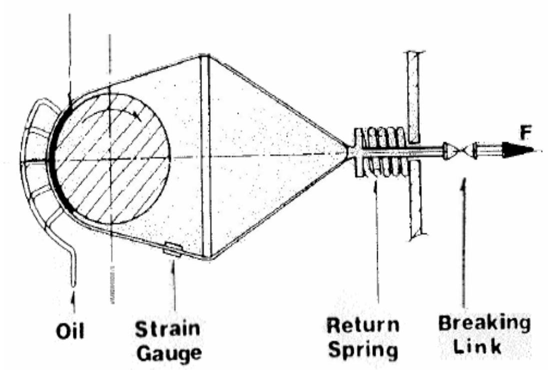


Figure 2.1 [54]

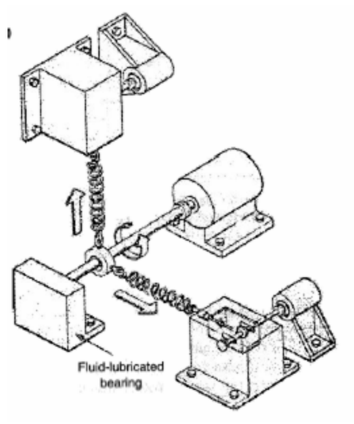


Figure 2.2 [30]

### 2.2.2 Harmonic excitation

The idea of applying rotating force to identify the rotordynamic properties can be dated back to late 1940s. Figure 2.2 shows an early version of nonsynchronous rotating force generating devices used for identification of fluid film bearing properties [30]. To identify the support stiffness experimentally, artificial excitation was applied to the vibrations of the free support of a heavy rotor of an electrical motor on a test rig with simultaneous measurement of the vibration amplitudes for different frequencies of excitation. The supports were shaken by a vibrator having two eccentric masses, rotated by an electric motor. The vibration set up a harmonic force in one direction. The amplitudes of the bearing housing vibrations were provided by the vibrator [16]. Later in 1986, a separate rotating disk with unbalance, which is run by an independent motor at different speeds, forward and backward, from the rotor operational speed, is attached to the free end of a rotor-bearing system for modal testing [55]. The device was capable of generating rotating, forward and backward, harmonic excitation to the test rotor in operation.

## 2.2.3 Random/harmonic excitation

Rogers [69] used an electro-dynamic shaker attached to the rotating shaft via a rider (an auxiliary bearing) in order to apply radial force to the shaft. The technique was limited to uni-directional random excitation, which is not different from the excitation method used for stationary structures, except the use of a rider.

Accounting for the rotating nature of the shaft, non-contacting type of actuators has been commonly adopted for exciting rotating machines in operation. Electromagnetic actuator without mechanical contact with rotating shaft is a good candidate for such purpose. Iwata, et al. [32] used a single electromagnetic exciter to generate random excitation force and to separate the forward and backward frequency response estimates of an isotropic rotor. Lee, et al. has extensively used a pair of electromagnetic actuators for identification of modal parameters and detection of anisotropy/asymmetry in rotors [33] [35] [47]. A pair of electromagnetic actuators placed perpendicular to each other is capable of generating various types of excitation electronically, including forward and backward, harmonic, rotating and random, excitations [34].

For modal testing of flexible rotors, a new non-contacting excitation device was introduced, which combines the sophisticated integrated laser displacement transducers as well as the electromagnetic exciter and the piezoelectric force transducer [41]. The same device was used for identification of the unbalance distribution of rotors [31].

In recent years, active magnetic bearing (AMB), which is a special form of eclectromagnetic actuator, is found to be an excellent excitation device for imposing non-contacting forces to the rotating shaft, in addition to levitating the shaft. For example, AMB has been used as an exciter to identify coefficients of a long annular seal [65].

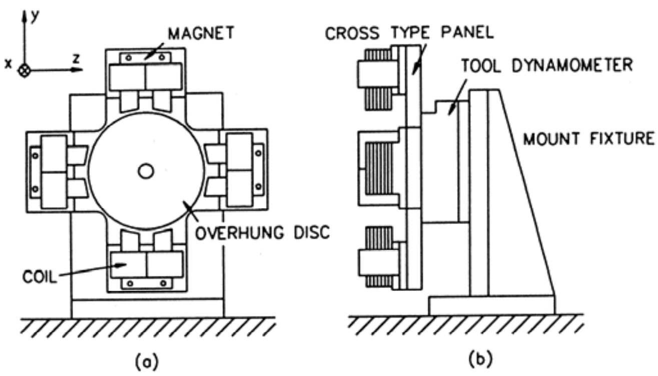


Figure 2.3 Schematic of a pair of electro-magnetic exciters. (a) front and (b) side views [46].

# 3. AUTOMATIC BALANCING

The birth of balancing techniques can be dated as far back as to 1870 [50]. It then stimulated the development of modern balancing techniques well known to the nowadays rotordynamics community. Automatic balancing has naturally been a dream for a long time among engineers in the industry, particularly for operation of grinding machines, which frequently requires rebalancing for precision grinding. In this section, we briefly discuss how the design and operation of balancing head has been evolved in recent years for automatic balancing of rotors.

## 3.1 Balancing head

Automatic balancing devices, however complicated in mechanism, essentially employ one of the four balancing methods: two angular arms, two sliding arms, one angular and sliding arm, or, one spirally sliding arm. Each unbalance arm can be realized by a solid eccentric mass or a fluid channel. In theory, we need a single or multiple ‘balancing heads,’ each with one of the above four mechanisms, for static or dynamic balancing, respectively. The critical disadvantage of the sliding arms [81] against the angular arms is that it requires large power to move the correction masses unless the springs are attached to counteract the centrifugal forces.

The most common automatic balancing devices use two arms clamped at desired angular positions, or free to seek the position of complete balance until all vibration ceases for balancing above the critical speed. For the latter case (invented by Thearle in 1930), two arms may be replaced by two balls or two loose rings which can move in a circular concentric track [15]. Automatic balancer using fluid as unbalance arm normally consist of two cylinders or four water pockets at right angles. The compensating fluid can be supplied to each cylinder or water pocket through flow valves. In practice, more than two arms may be used. For example, the Cincinnati automatic balancer developed for grinding machines uses three balls that can be unclamped and clamped by a hydraulically released plunger.

A single balancing head can also auto-balance couple unbalance. The simplest engineering solution for eliminating the couple unbalance is to attach a spherical joint (universal joint) to the center of suspension, allowing the disk to tilt sufficiently to eliminate the couple unbalance, as shown in Figure 3.1 [28]. Radial unbalance is reduced by pendulum in the super-critical region where unbalance and pendulum are out-of-phase.

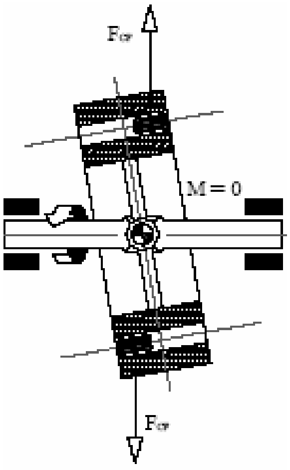


Figure 3.1 [28]

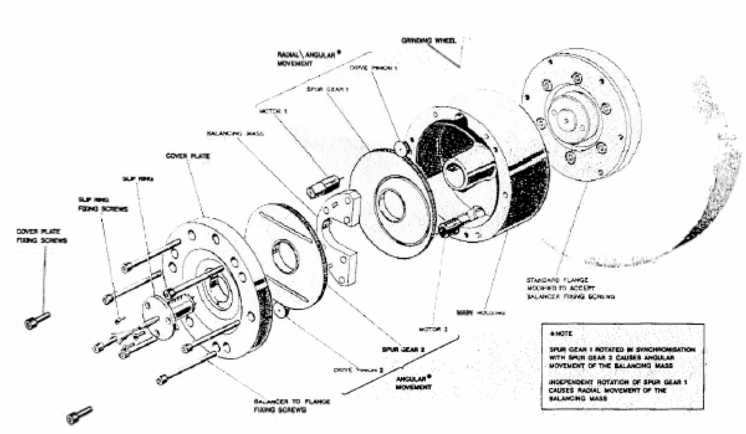

Figure 3.2 [37]

## 3.2 Automatic balancing of rigid rotors

Techniques for automatic balancing have been developed over the past 100 years, but effective methods for the whole range of operational speed became available late in 1960s [26]. A challenging problem with most of automatic balancing devices has been how to provide power to the rotor in order to activate the actuators of the balancing heads, while the unbalance is sensed and fed back.

Various automatic balancing techniques using a single balancing head have already flooded in the market, particularly for auto-balancing grinding wheels. Numerous patents and commercial products are still appearing. For example, Kaliszer developed a sophisticated automatic balancing device with a single angular and sliding unbalance arm [36] and an adaptively controlled automatic balancing system for grinding machines [37] as shown in Figure 3.2.

A self-automatic balancer, which uses the centrifugal force generated by the control fluid for compensating unbalance, was suggested and tested with a test rig [74]. An inner weight movable in radial direction is installed in the pocket. As the body of balancer deviates to the unbalance direction, the inner weight also deviates to the unbalance direction and its deviation becomes larger than the body's due to centrifugal force. The idea was that the valve in unbalance side keeps closed, while the valve on the opposite side opens and the liquid in the pocket flows into the chamber opposite side to the unbalance.

For dynamic balancing of rigid rotors, we need two auto-balancers separated along the shaft axis. One of the most recent and interesting applications of automatic dynamic balancing is with space structure. The centrifuge rotor, which is an artificial gravity generator of about 2.2g used in the International Space Station, is subject to imbalance due to the movement of two inhabitants in the module. An active mass auto-balancing system has

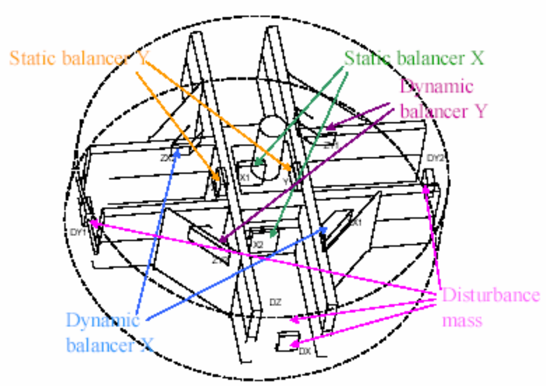


Figure 3.3 [66]

been developed for automatic canceling of the rotor imbalance [66], where the static and dynamic imbalances are compensated by two separate balancing masses.

3.3 Automatic balancing of flexible rotors

Precision balancing of a flexible rotor requires a multiple balancing planes in order for the rotor to safely pass through, at least, several flexural critical speeds. It has been analytically [6] and experimentally [44] proven that modal balancing of a flexible rotor requires only a single active balancing head, whose configuration changes to balance out the modal unbalances associated with different modes as the rotational speed changes. Figure 3.4 is the schematic of a typical balancing head, a computer controlled automatic balancer, which is equipped with two independently driven correction unbalance planes. It has been demonstrated that a single active balancing head can successfully cancel the first and second flexural modal unbalances, implying that a flexible rotor can be safely run through as many flexural critical speeds as desired.

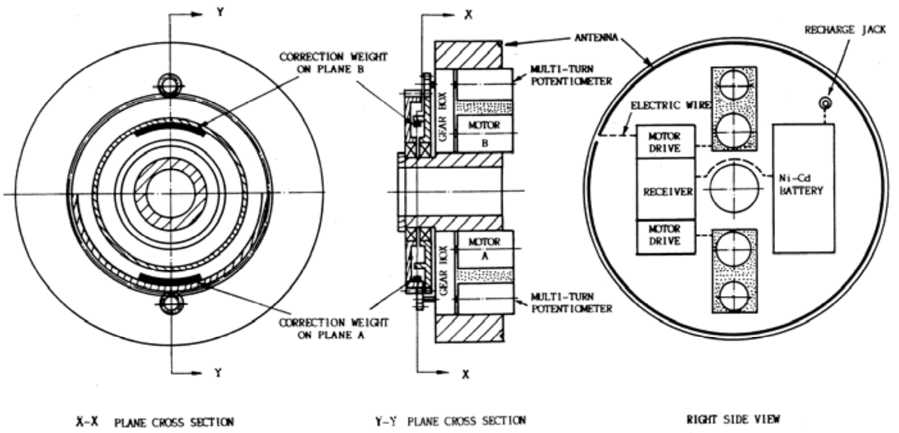


Figure 3.4 [44]

3.4 Automatic balancing: special techniques

In recent years, methods involving material removal utilizing electroerosion, electrochemical electronbeam and laser techniques have been invented. Another promising device involves the application of solidifying liquids or plastic balancing compounds to the 'light' points on rotor surfaces in discrete portions.

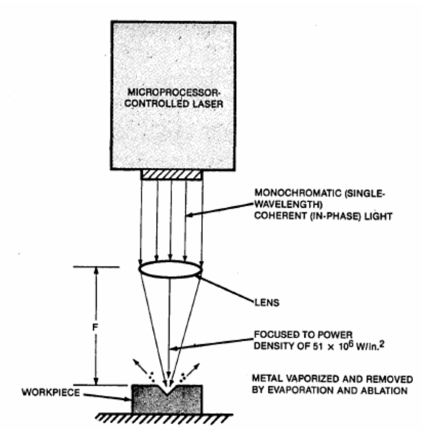


Figure 3.5 [14]

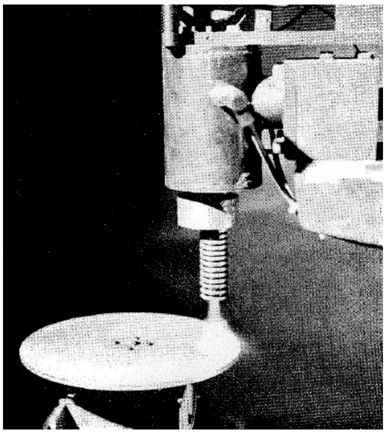

Figure 3.6 [75]

For the rotating parts whose mass eccentricity changes repeatedly by small amounts, automatic weight correction 'on the fly' is often required. DeMuth, et al. [14] documented balance correction 'on the fly' using a pulsed laser, which burns out the heavy spot of the rotating parts. One of the drawbacks of the method is significant reduction of fatigue strength. Figure 3.5 shows an automatic laser balancing system, providing complete and accurate balancing in a single load-and-spinup cycle of parts that may be inaccessible for installation of conventional correction weights. Smalley, et al. [75] successfully demonstrated the 'spray automated balance of rotors' technique with a test rig, which uses a high performance coating gun for short bursts of power (e.g., tungsten carbide) at high velocity and temperature into a rotating part (normally a low carbon disk), at an angle selected to reduce unbalance, as shown in Figure 3.6.

4. ACTIVE DAMPERS

There exist various types of passive dampers used in practice. They include squeeze film damper, seal, friction damper and eddy-current damper, which are not a mechatronics device, so they will not be further discussed here. Traditionally the most common type of active damper utilized either the electromagnetic force or the AC eddy current applied to rotating shafts. In recent years, more active (semi-active) dampers, including semi-active squeeze film dampers, are found with controllable fluid such as electro-rheological (ERF) and magneto-rheological fluids (MRF).

4.1 Electromagnetic damper

Electromagnetic dampers are similar in structure to the passive eddy-current damper, except that the magnetic flux is formed by electromagnets, instead of permanent magnets. They are able to change their damping properties depending upon the current levels to the winding coils. The generated magnetic forces can be attractive for a DC damper, repulsive for an AC damper or shear-resistive for an eddy-current damper activated by coils [80].

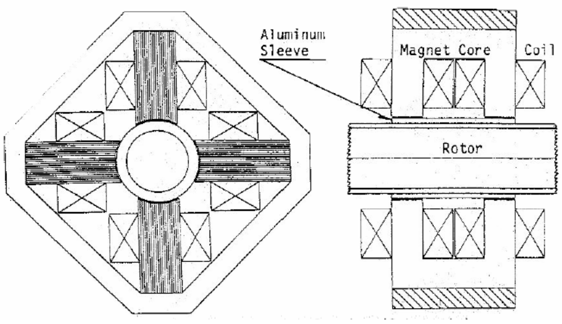

Figure 4.1 [57]

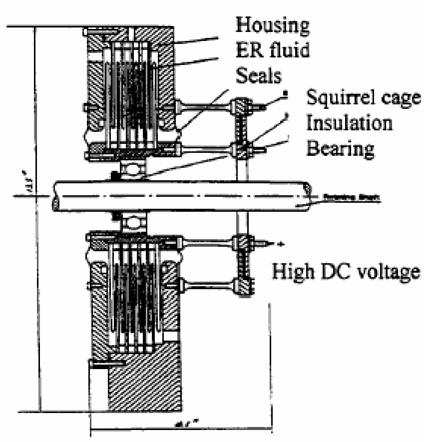

Figure 4.2 [59]

Nikolajsen, et al. first applied an electromagnetic damper to vibration control of a transmission shaft in 1970 [58]. Schweitzer also applied an active magnetic damper to stabilize self-excited vibration of a high speed centrifuge rotor in 1974 [71]. Matsushita, et al. [51] used an electromagnetic damper to produce the particular damping effect for stabilization of a centrifuge partially filled with liquid. Such centrifuge is notable for its self –excited vibration due to presence of cross coupled stiffness effect, inherent to the contained liquid rotors.

Figure 4.1 shows the schematic of the AC eddy-current damper bearing built by Nikolajsen [57]. He demonstrated that the damper, without feedback control, can stably support the short rotor but render damping in its full five degrees of freedom. However, the damping capacity is lower and, above all, the power consumption is much higher than the conventional DC eddy-current magnetic damper [22].

4.2 Controllable fluid dampers

Nikolajsen and Hoque [59] demonstrated with a rotordynamic test rig that the peak rotor vibration amplitude at a critical speed can be substantially reduced using a disk type of electroviscous damper shown in Figure 4.2, utilizing ERF as the working fluid. It consists of six thin nonrotating disks moving with the outer race of a ball bearing and with five nonrotating disks attached to the housing and sandwiched in between. The resistance force generated by controllable fluids such as ERF and MRF to shear motion is often well predicted by a Bingham type model, which is the combination of Coulomb-type friction and viscous damping models. Later, almost the same device was used to reduce the vibration of a test rig by Yao, et al. [84]

MRF inherently has higher yield strength than ERF, not requiring high voltage amplifiers. It stimulated the application of MRF as an active shear type damper for unbalance response control of rotors [82] [85]. Although controllable fluids are commercially available, they still suffer from, among others, sedimentation and stability problems that limit their practical applications in rotating machines as well as other structures.

4.3 Active squeeze film damper

Squeeze film damper (SFD) has become an effective machine element, because of its capability of high damping. It finds many applications to the rotating machinery, which are supported by lightly damped bearings (rolling element bearings) and foundations. In particular, SFDs have been used extensively in almost all aircraft turbines designed since 1970 to damp out unbalance response. However, it encounters some problems during operation that its damping property may deteriorate as the temperature, oil supply pressure, imbalance and speed of rotation vary.

To enhance the stability of rotating machines under varying and adverse conditions, active or semi-active SFDs have been sought by controlling the pressure [10] and flow rate [19] in the SFD. Since the advent of controllable fluids such as electro-rheological (ERF) and magneto-rheological fluids (MRF), there have been many attempts to introduce such fluids as the working fluid of SFD and to improve the performance of passive SFDs in the sense that the optimal damping property can be scheduled with the varying operation conditions, particularly the varying rotational speed of rotors.

A slotted ERF SFD, which has a predetermined clearance at its leakage sides and thus eliminates the electric discharge problems, has recently been suggested by Lee, et al [48]. It features that ER fluids are unexcited in a squeezed annular region, behaving as a Newtonian fluid, while the fluids are excited by an external electric field at the slot of ring, behaving as a Bingham fluid.

More recently, Forte, et al. [20] demonstrated that the unbalance response can be significantly reduced by increasing the current flow to the MRF SFD. Wang, et al. also developed an MRF SFD and applied it to on-off type control of unbalance response of a test rig at its critical speed [83]. As one way of improving performance of the conventional SFD, the controllable SFD with the electromagnetic coil wound around the inner damper of the SFD [1] has been proposed and tested with a test rig. The damping increases as the applied current to the coil increases. Experiment with a test rig demonstrated that the whirling amplitude is significantly reduced and the critical speed is lowered with the current applied to the SFD.

In 2004, Kim and Lee developed an MRF SFD shown in Figure 4.3 and experimentally derived its dynamic stiffness model, which varies depending upon the input current levels and the harmonic excitation amplitude. Employing a scheduled input current controller for the MRF SFD, they demonstrated with the laboratory test rig that the unbalance response of a flexible rotor could be effectively attenuated as the rotor passes through two flexural critical speeds [39].

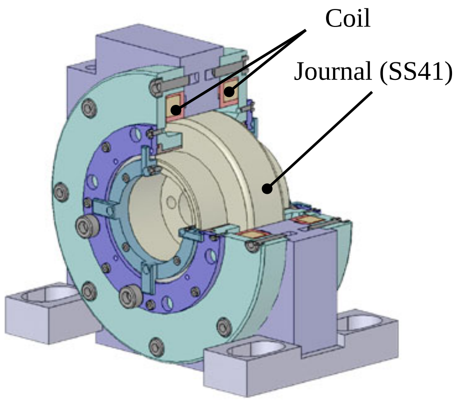


Figure 4.3 [39]

## 5. ACTIVE/SEMI-ACTIVE BEARINGS

Since early 1980s, many attempts have been made to actively control the conventional bearing housing (casing) position by using directly attached actuators, so that the unbalance response of rotor bearing systems can be significantly reduced, particularly as the rotor passes through several critical speeds. Most widely used actuators so far include the electro-magnetic, electro-dynamic, hydraulic and piezo-electric actuators.

With regard to industrial applications, the requirements for active bearings of great importance are: compact design, high forces, large regulating distances and wide frequency range [78].

### 5.1 Pressure control journal bearings

It was shown experimentally that by mounting the conventional rotor journal bearing in a hydrostatic bearing, the overall rotor support characteristics could be tuned to enable rotor critical speeds to be moved at will. Goodwin, et al. carried out this tuning by adjusting the resistance offered by capillaries connecting accumulators to the hydrostatic bearing [24]. Later, they combined the advantages of variable stiffness hydrostatic bearings with the damping capacity of conventional SFDs and applied to attenuate the unbalance response and suppress the instability of aircraft engines.

A new design concept of variable impedance hydrodynamic journal bearing has been proposed for controlling flexible rotor vibrations [25]. The design, which previously applied to hydrostatic oil film bearings, is different from the conventional journal bearings in that it introduces a recess hole in the bearing surface and a gas-filled accumulator connected to the recess through a remote-controlled valve as shown in Figure 5.1. The valve controls the in-flow of lubricant oil into the recess and thus the oil pressure in the bearing clearance. The theoretical investigation showed reduction in the unbalance response of a flexible rotor near the critical speeds up to 24%. A similar design concept to the variable impedance hydrodynamic journal bearing has been employed to effectively reduce the unbalance response, where the flexible sleeve activated by the chamber pressure, which is controlled by the servo valve in the hydraulic system [76]. The oil film of the bearing and the pressure chamber is separated by flexible sealant, preventing the chamber pressure from influencing the boundary conditions of the oil film. However, the effectiveness of the design and the multivariable self-tuning adaptive controller was not proven experimentally.

The concept of actively controlled waved bearing, which is basically similar in structure to a lobed bearing, has been proposed by Dimonfte in 1993 [17], to change the bearing dynamic forces and thus the rotor-bearing dynamic behavior. However, it did not mention about how to vary the wave amplitude of the bearings in practice.

Externally pressurized bearing is essentially a recessed hydrostatic bearing with the capability of pressure variation, ideally having a real time capability actively responding to the varying requirements of rotating machinery during operation, as shown in Figure 5.2. Externally pressurized bearing with high speed valves to control the fluid pressure was proposed by Bently [6] in late 1990s, but the simplified design with the constant external supply pressure, which is a fully lubricated hydrostatic bearing, was put in the market in 2000. Bently Pressurized Bearing Company designed the commercialized bearings such that the pressure level of supply oil could be adjusted according to the need in the field.

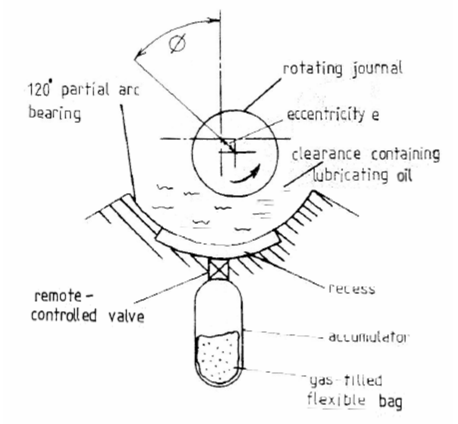


Figure 5.1 [25]

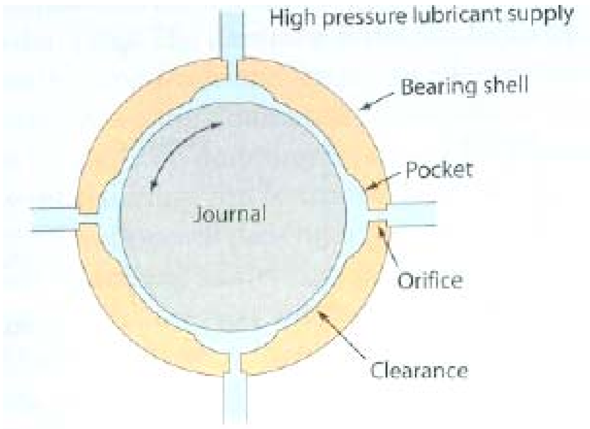


Figure 5.2 [6]

## 5.2 Hydraulic actuators

A hydraulic actuator capable to transmit controlled forces via conventional bearings to rotating shaft was applied to a test rig, demonstrating the good control performance using a simple output feedback controller [3]. For control along each direction, the actuator consists of one servo valve and two elastic chambers connected to the valve by oil pipes. Elastic membranes at both ends seal the cylindrical chambers. Additionally, operation of the rotor without control pressure and voltage applied to the servo valve is possible, because mechanical support of the bearing is always guaranteed by the elastic chambers. The similar hydraulic actuator was also used for position control of two facing pads of a tilting pad bearing so that the tilting pad bearing properties can vary accordingly [70].

## 5.3 Piezoelectric pushers

Piezoelectric actuators had been widely adopted in the precision positioning applications such as minute adjustments of lenses and mirrors in optical systems and high precision positioning of micro stepper tables used in semi-conductor industry. In 1989, Palazzolo, et al. [67] first employed the piezoelectric pusher as shown in Figure 5.3. The pusher is soft mounted to the machine case to improve the electromechanical stability and connected to the squirrel cage-ball bearing supports of a rotating shaft, to actively control the unbalance, transient and sub-synchronous responses of the test rotor, using the velocity feedback. The piezoelectric pushers, similar in structure to [67], were also connected to a hydrodynamic bearing to constrain the shaft of rotor. Since the actuators respond only in expansion, a reaction spring was set against each actuator [12]. Direct mounting of piezoelectric pushers with the reaction springs as active bearings has been attempted for active vibration control of a test rotor, which increased the system damping [2].

In order to reduce vibration levels in aero engines, the piezoelectric actuators were considered as a long-term alternative to the existing SFD [18]. The actuators, having a size of 60x60x60 mm, met the requirements of the control, size and power. With the large diameter of 56 mm, the actuators can withstand the loads even in resonance when a component fails. The main problem with actual implementation is the high dynamic load on the actuators leading to the fatigue of the actuators.

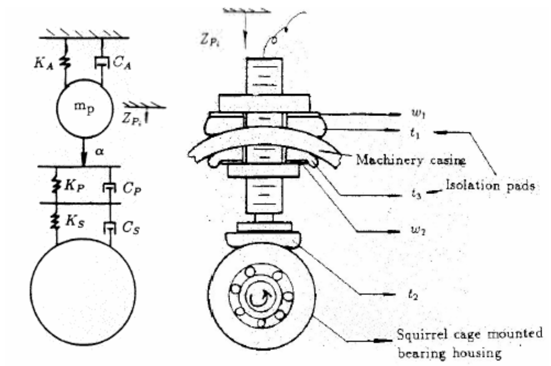

Figure 5.3 [67]

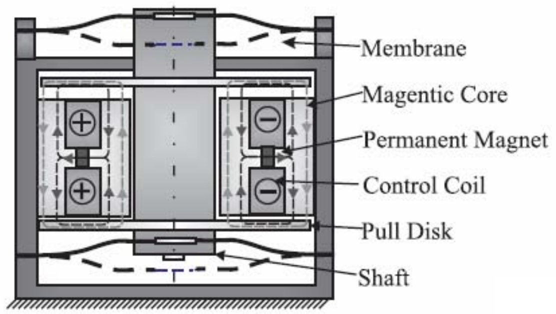

Figure 5.4 [79]

5.4 Electro-magnetic/-dynamic actuator

Moore, et al. [53] used the velocity feedback control with a test rotor using loudspeaker coils linked to the rotating shaft via ball bearings to control vibrations. Nonami, et al. applied various control schemes to a multi-disk rotor [61] and a flexible rotor [60] by using electro-dynamic actuators. Ulbrich [77] attempted to control a test rotor on actively controlled supports.

Two electromagnetic actuators, placed perpendicular to each other, were connected to an oil film bearing so that the forces generated by the actuators can be indirectly applied to the rotor [21]. The output feedback controller with a combined displacement and velocity feedback was used to improve the stability of the test rig. Lee and Kim used the similar electromagnetic actuators to attenuate the unbalance response of a flexible gyroscopic rotor as the rotor passes through the two flexural critical speeds [46].

5.5 Temperature Control Bearing

Although there is no evidence of experimental verification, the idea of constructing the pads of tilting pad bearings by the bimetal made of carbon steel and aluminum has been suggested by Kanemitsu, et al. [38] so that the radius of the pad changes through the lubricant temperature control. They found from the vibration analysis of the Jeffcott rotor supported by tilting pad bearing that the rotor can be stabilized by decreasing the radius of the pad as the rotational speed increases.

5.6 Active seal/backup bearing

Some manufacturers used the idea of reducing pre-swirl at entry to annular seals in turbomachinery to improve rotor stability. Hart and Brown [27] demonstrated that a deliberate injection of negative swirl in an annular space has potential for significantly reducing forced vibration near synchronous critical speeds.

Back up or emergency bearings are often used in rotor systems to prevent direct contact between rotor and casing when the rotor response is too large at normal operational conditions. In order to reduce the abrupt contact force under rubbing condition, an auxiliary bearing as shown in Figure 5.4, consisting of two unidirectional electromagnetic actuators, were developed for a rotor system, but its performance has not yet been experimentally verified [79].

5.7 Eddy current magnetic bearing

The eddy current magnetic bearing concept, in order to support shafts in rotating machines, has been taken from the transportation levitation device developed for light weight conducting but nonmagnetic materials. The advantage of the eddy current magnetic bearing is to use the repulsive force caused by eddy currents induced in the rotor shaft by the flux generated from either permanent magnets or electromagnets. On the other hand, its applications are limited to high speed light weight rotors [52].

5.8 Active Magnetic Bearings

AMB is perhaps the showcase of a mechatronics product used in rotating machinery, which consists of mechanical, electrical/electronic components, including sensors, actuators and microprocessors. In addition to the enhanced functions of AMB such as free of friction/wear and lubrication, in lieu of conventional bearings, rotating machines equipped with AMBs evolved as a smart machine that is capable of system/parameter identification, diagnosis and adaptive control action. Those capabilities not only lead to higher performance of machines than ever, but increase the reliability and thus the service life [40] [64].

For identification of frequency responses in rotating machines, force measurements are often required. For rotors with AMB, the electromagnetic forces generated by coils can be directly measured from built-in force transducers [43] and indirectly estimated from measurement of coil currents and rotor displacements (the current-displacement method), or magnetic flux using Hall sensors. Proximity sensors measuring rotor shaft lateral vibrations, incorporated with force measurements, frequency responses between the rotor displacement and the force can be obtained, from which, for example, fluid film bearing coefficients can be identified [64].

As stated previously, AMB alone is too big issue to handle here. Those who are interested in AMB should refer to the well documented literature such as Proccedings of the International Symposium on Magnetic Bearings, which started in 1988.

6. MICROROTOR

Beginning in the mid 1980s, numerous micro-electro-motors with a wide range of operating principles have been developed, most of which apparently intended to achieve the greatest possible miniaturization. Starting in the mid 1990s, many investigations were conducted on miniaturization of turbines, gears and pumps, hybrid electro-motors, thermal gas turbines and combustion engines. There are no microscopically sized ball bearings, although some efforts have been made to use electromagnetic, electrostatic, gas or fluid bearings. In general, the fact that no organic models for fixed rotation exist in the natural world is interesting [9].

Since 1988 when a description of the first rotational electrostatic micro-motor based on semiconductor manufacturing techniques was published, a number of improved rotating micro-systems have been investigated. They include ultrasonic motors driven by the friction generated by piezoelectric elements, miniaturization of classic electric motor driven by the electromagnetic torque or ponderomotive force, micro turbine generators driven by gas or air, gears, micro Wankel rotary engines and so on.

New manufacturing technologies allow the development of micro-motors with dimensions of a few millimeters. These motors work at high rotational speed and offer only small torque to drive their specific load. Small, millimeter-sized, micro rotors are of special interest to micro-techniques. Potential applications are video heads, medical instruments, hard disk drives, and optical scanners [73]. For example, the magnetically suspended micro-motor [68] of rotor diameter 1.5 mm has been successfully spun up to 600 rpm, using a four-quadrant photodiode to measure radial displacement. A very flat micro-motor has also been presented with the rotor thickness of about 250 micrometer, which was produced by chemical etching of silicon steel, incorporated with inductive sensors [8].

About seven years ago, an effort was undertaken at MIT to develop high-speed rotating MEMS. For the

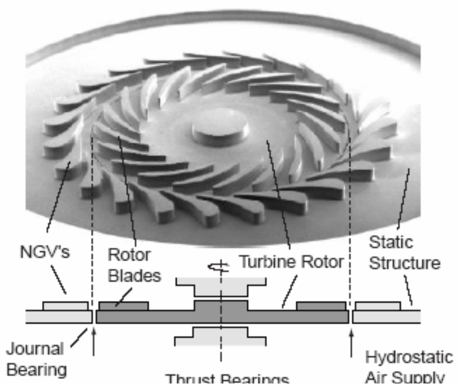


Figure 6.1 [49]

micro-turbomachinery to be comparable to conventional scale turbomachinery in power density, the tip speed of order 500 m/s, the rotating speed of order 2,000,000 rpm and the relatively low bearing aspect ratio of less than 0.1 are required. Performance tests of axial flow gas journal bearings were conducted in the MIT micro-bearing rig using a high resolution whirl response of the rotor with the bearing pressure difference and air flow rate varied [49]. Recently, a sub-millimetric spherical steel ball has reached 2.88 million rpm in partial vacuum by using a micro motor with three axes AMBs, in order to investigate the limitations of high speed rotation of small rotors [7].

## 7. INTELLIGENT ROTOR SYSTEM

In 1996, Bachschmid and Dellupi [4] proposed a model-based diagnostic system in an effort toward putting intelligence to rotating machines in power plants. The success of the diagnostic system depends heavily on not only the accuracy of the analytical or computational model but also the quality of the collected vibration data. In theory, any physical change in a machine is reflected in its operational vibration response, so that we can detect such a change solely from the vibration data.

The smart machine suggested by Sweitzer consists of three parts: the actual machine with its process, sensors, actuators and the controller, the mechatronics system model used for designing the control of the actual machine, and the management system that makes 'smart' use of the available information [72][73]. The main advantage of rotors equipped with magnetic bearings is the capability to change the bearing properties during operation, depending upon the situation and needs. This allows to add a number of novel features to rotating machinery and to make it a smart product, capable of active diagnostics and on-line corrections [72]. Nordmann [63] demonstrated the procedure of model-based diagnosis for turbomachines running in active magnetic bearings with a magnetically suspended centrifugal pump. It basically utilizes the special capability of an AMB system with on-line force and frequency response measurements, which are used for detection of system parameter change during operation.

In practice, operational vibration alone often fails in revealing a minor change in system parameters, because all the excitations are due to the natural shaft rotation. It is not a surprise that a carefully planned excitation can extract more information of the system than a natural, rotation-related, excitation. Scenario test that was proposed by Lee [42] is the identification routine performed according to a planned 'scenario,' which may be called an active diagnostic test. For the scenario to be meaningful, there may be two stringent requirements: availability of a rotor system model, which can predict the response of the interested rotor system to disturbances with fair accuracy, and an excitation device, which can generate appropriate forces or disturbances required by scenario as shown in Figure 7.1 [42].

On-line or off-line scenario tests can be designed with the exciter system to identify modal unbalance, runouts, system parameters; to detect such defects as cracks [45], misalignments, rubs, etc.; to actively control the transient and steady-state vibrations, including the unbalance responses, of interest along the shaft. With multiple exciters, the contents of the scenario tests may be enriched, but it is not sure yet if it is really worth employing more than a single exciter. The scenario tests are worth being carried out, when they are designed to enhance the analytical or numerical rotor system model. As the modeling accuracy is increased, the reliability of the diagnostic system increases, too. Eventually, the model will become a virtual rotor system. Once a reliable virtual rotor system model is constructed, not only the system malfunctions are well detected, but the system behavior under any, expected or unexpected, loading situations can be precisely predicted and thus any harmful situations will be appropriately avoided [42].

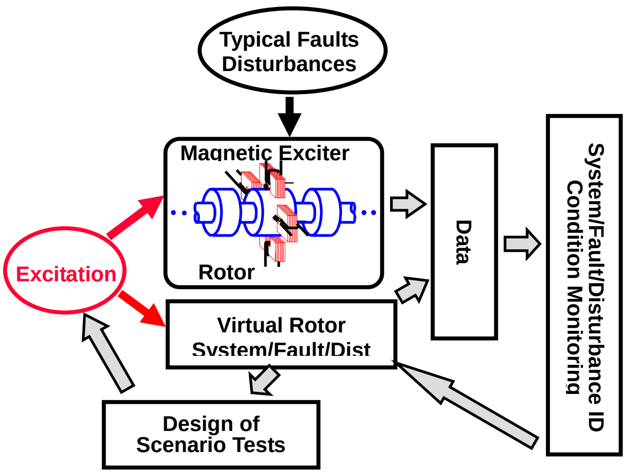


Figure 7.1. Intelligent virtual rotor system [42]

## 8. PROSPECTS

Even before 'mechatronics' emerged as a new concept in technological advancement, much mechatronization effort has already been made in rotating machinery. There are, to name a few old mechatronics products, DTG sensor, auto-balancer and pressurized hydrostatic bearing. When smart actuators such as piezoelectric ceramics, electro-magnetic/dynamic actuators, shape-memory alloy and hydraulic actuators became available to structural and control engineers, there has been immediate effort to employ such actuators in rotating machines as described in this paper. However, many attempts need more time to be implemented for practical use in rotating machines in operation, some remaining as pure academic research interests and some as disappointing results, which seem to be far from practicality for the time being. The rotor dynamics research has an ever-lasting tradition of practicality, growing from the industrial needs; instability analysis and balancing are typical of paramount important field interests. On the other hand, the rotating machine industry has another tradition of 'conservatism' that new techniques are absorbed in a slow fashion until they are fully matured and field proven. For example, FEM technique that had prevailed in late 1960s had to wait for another decade until it was first tried out for the rotor dynamic analysis [56]; Electro-magnetic levitation technique had to wait for a decade until AMBs are put into service in rotating machinery, yet its growth rate being rather slower than expected [23]. Mechatronization of rotating machines is no exception in this respect. So far, we have seen some successful cases of mechatronization in rotating machinery: automatic balancers and AMBs. We need a little more push to see more and more practical cases in the near future. Mechatronization is certainly the right way for the rotating machine community to go, as long as the need for enhanced reliability and safe operation of rotating machines accelerates with technological advancement.

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