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SYNERGY IN MECHATRONICS

Abstract. *Mechatronic approach in designing, prototyping, and manufacturing allows us to increase the competition of a new products by acceleration of their introduction to the market and by increasing of the task and function number realized by the products while keeping the same price level. Synergy effects are main advantage of the mechatronic system. As an example we consider magnetic bearing systems. It appears that adding of two current sensors to the displacement sensor in one axis of bearing allows us to increase the number of functions realized by magnetic bearing system. In this paper, we provide the overview of the concept and present the formulation for control and dynamics of rigid rotor supported on smart magnetic bearings. Using the proper software such smart system can realize identification of external excitations and system parameters, adaptive control, and diagnostics by detection and isolation of different faults.*

1. AIMS OF MECHATRONICS

Globalisation causes that producers are under press of competition not only in the local area but are also under press of world market. The main question is how to faster produce goods with higher quality. So more, in the case of machines, how to produce user-friend devices with broader range of operation and new functions still keeping the same price level.

The market life of all products dramatically reduces. In case of electronic devices it usually does not cross one year. There is not time for gathering of consumer opinion, and often new products are designed without feedback from users. So more there are other constraints for contemporary producers as follows.

- Shortened the design-prototype phase and cost reduction. It allows to be first at the market and to win the new product premium..
- Using of interaction between mechanics and electronics to design an user-friendly and more functional product.
- Adjustment of the products directed on the consumer.
- Fast answer to all challenges like new inventions, technologies, new materials and new needs of consumers.

Mechatronic approach to new products delivers a methodology to fulfill all above requirements and gives tools for constraints overcome. An important aspect in these solutions is the using of available software and computer systems for designing, prototyping, and research of new products.

In the title of paper we have two words "mechatronics" and "synergy". There are different definitions of mechatronics. For example in [1] we have - "The term "*mechatronic*" refers to synergistic integration of mechanics, electronics, control, computer science, diagnostics, and intelligent systems in the design and manufacturing processes of "*mechatronic*" products or systems". In almost each definition of machatronics the word "synergy" repeats. For this word we can find in [2] the following definition "Synergy means collaboration, cooperation of elements (agents) more effective than the sum of their separate influences". In the light of above definitions the mechatronics is not only a simple combination of mechanics and electronics. By smart connection of mechanics, electronics, control, and computer sciences we are able to invent entirely new generations of "intelligent" machines and devices.

Mechatronic approach to new products is useful on the designing, prototyping, manufacturing, and exploitation stages. It requires not only the collaboration but also of co-working by engineers of different professions. Organization of such co-working is not simple since the experience of engineers differs. As it results from investigations of the design stage [3] we know that a mechanic-designer has about 300 decisions to undertake, an electronic-designer about 50, while a computer-programmist decides only about few design variables. From opposite side the software technologies are changing very fast, electronic technologies are changing slower, while many of the mechanic technologies are fixed for decades while others are slowly changing. It means that a programmist is almost mature engineer after academic years, when an engineer in mechanics matures after several years of work. These and others differences strongly influence the team work, used tools, and design process.

Mechatronic approach in designing, prototyping, and manufacturing allow us to increase the competition of a new products by acceleration of their introduction to the market and by increasing of the task and function number realized by the products while keeping the same price level. As it was mentioned the mechatronic product is not only a simple combination of mechanics, electronics, control, and computer technologies. Additional quality of product can be achieved by adding of the following features (at least a one of them) to the technical device.

1. Realization of a new function or task not available in traditional technology.
2. Using of control elements to the generation of functions usually realized by man-operator; it means the replacement of man in some tasks.
3. Increase of design, operation and functional flexibility; it means variant designing and program adjustment of device for individual user.
4. Elimination of weak points in machines by using of digital electronic, for example dumping of noise and vibrations.
5. Integration of mechanics and electronics into one structure; it leads to reduction of dimensions, manufacturing costs, reliability, and so on.

Mechatronic system can have a logic subsystem in-built. Its action can be so sophisticated that lateral observer is not able to predict next actions of device. The manufacturing of mechatronic device is often simpler and cheaper than its mechanic equivalent, since the implementation and reprogramming of software is much simpler than rearrangement of mechanical hardware. Using of electronic elements means replacement of complicated technologically mechanical elements by mass-produced electronic parts. In last case, it is easier to introduce changes and to adjust mechatronic products to new requirements of the user. So more, electronics and microprocessor programs allows for communication between man and machine. Scheme of typical mechatronic system is shown in Fig. 1. It should be noticed that the microprocessors and software is a very important part of the whole system.

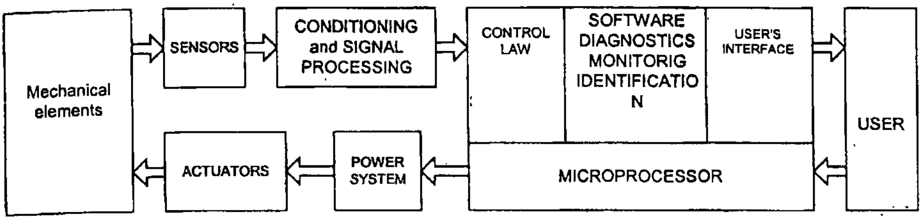

Fig.1. Structural scheme of mechatronic system

There is no common rules which indicate us what kind of technology or devices should be chosen for realization of given function of machine. It is a typical problem of the new-product designer. As usually, the engineer experience and knowledge is very useful. In any case, the designer of mechatronic system should take into account the following principles.

- **Extension of the system functions**. Sometimes, it is sufficient to add one sensor to design a complete diagnostic system, monitoring system, etc.
- **Synergy effect.** We should consider whether one of elements can be used for many goals. Whether one set of elements can be used for realization of different functions. For example, piezoelectric element can be used simultaneously as: sensor, actuator, and structure of the machine.
- **Digital technologies and signal processing.** These technologies allow reducing the number of cables (multiplexing of signals), reduce information noise (filtering, conditioning, aggregation), generate displayed information and control signals. In many cases it allows to change the expensive hardware solutions by more flexible software solutions.
- **Global or local controls and actuators.** Since the costs of microprocessors and electric drives decreases it is desired to disperse controllers and actuators in the mechatronic system. This tendency is seen in robotics, printers, copiers, cars, and so on.
- **Number of information and control devices.** We should consider if interface with user should have many displays or one screen with many posters, and one joystick or many switches.
- **Mass-produced elements or own parts.** In our mechatronic systems we can use commonly available parts and subsystems or design new ones. First of all, it depends on the cost calculation, reliability, and safety.
- **Miniaturization.** When it is possible we should use MEMS (Micro-Electro-Mechanical Systems) and nanotechnology. It leads to integration of sensors, actuators, and structure of the system.

As an example we indicate possibility of synergy in rotating machinery with magnetic bearings.

2. ACTIVE MAGNETIC BEARINGS

The overall goal of an active magnetic bearings (AMB) controller is to stabilize the plant and to reach optimal technical and economical performance. To achieve this, AMB system has to be optimized in an overall mechatronic design approach. As a result of such approach, the resulting "*mechatronic*" products should be smart (or intelligent) ones. In the case of rotating machinery applications it means that smart AMB can provide on-line diagnostics and predictive maintenance information. It should also be able to carry out automatic reconfiguration of control laws in a case of machinery malfunction occurrence. Smart magnetic bearings should be able to adapt the control laws to rotor parameters and loads, to diagnose and predict the operational condition of rotating machinery, and to realize additional goals essential for specific rotating equipment. One of the examples is the dynamic compensation of sudden rotor unbalance due to the blade loss, or another one is the necessity in gyroscopes to calibrate the measurement path to reduce the angular velocity measurement error. Summarizing, we can predict the following tasks for smart magnetic bearings.

1. Identification of dynamical and physical parameters of rotating machinery.
2. Identification of external disturbances (unbalance, sensor run-out, and so on).
3. Adaptive control of rotor motion.
4. Counteracting to external disturbances (for example - automatic balancing).
5. Diagnostics of rotating machinery.
6. Reconfiguration of the control system in redundant implementation.
7. Auto-calibration of measurement path in measurement devices.
8. Other tasks.

In the book [4] we have described an idea of smart radial magnetic bearings for rigid rotor with tasks reduced to the above five ones (see Fig. 2). Now, some ideas from [4] will be presented.

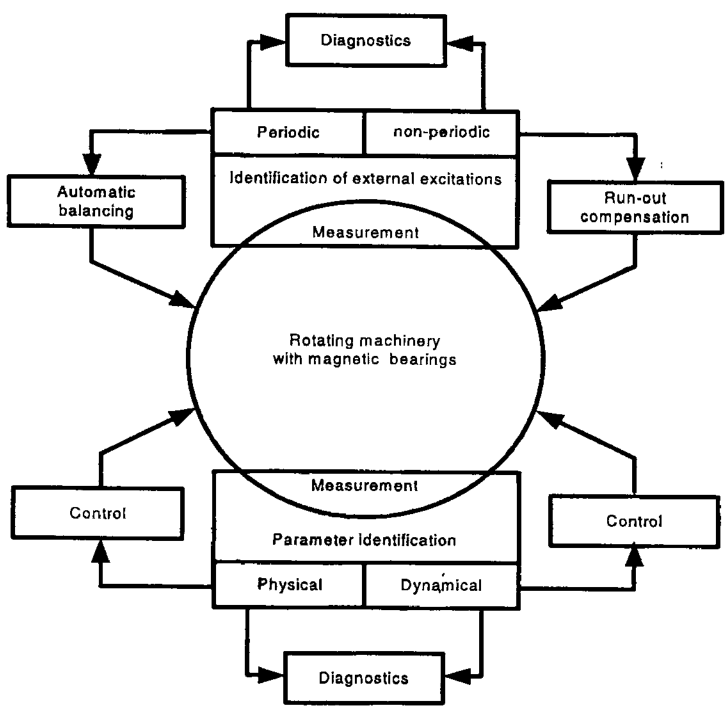

Fig. 2. Chosen tasks of magnetic bearings

In the case of rotating machinery with rigid rotor the control law can be designed [5] gradually from single axis, by single bearing plane, to the modal control of rigid rotor motion by two magnetic bearings (Fig. 3). A model for lateral motion of axially symmetric rigid rotor supported by two radial magnetic bearings was reduced to modal model with complex variables. Next this model was divided into two subsystems connected by two lateral modes: translation and rotation. As an example, the voltage-control scheme was chosen. The control system (observer and controller gains) was designed independently for each mode. This approach allows one to express analytically the controller and observer gains as functions of values of the desired closed-loop poles and the plant model parameters.

It appeared that gyroscopic effects strongly influence the controller and the observer parameters. From other side the magnetic bearing parameters are changing during exploitation. Therefore, it is desired to design the adaptive control to adjust the controller to the actual operation conditions. Derived control laws are functions of open –loop system physical parameters. Since these parameters are identified for purposes of the diagnostic system [6] we can use them directly to design the adaptive control system.

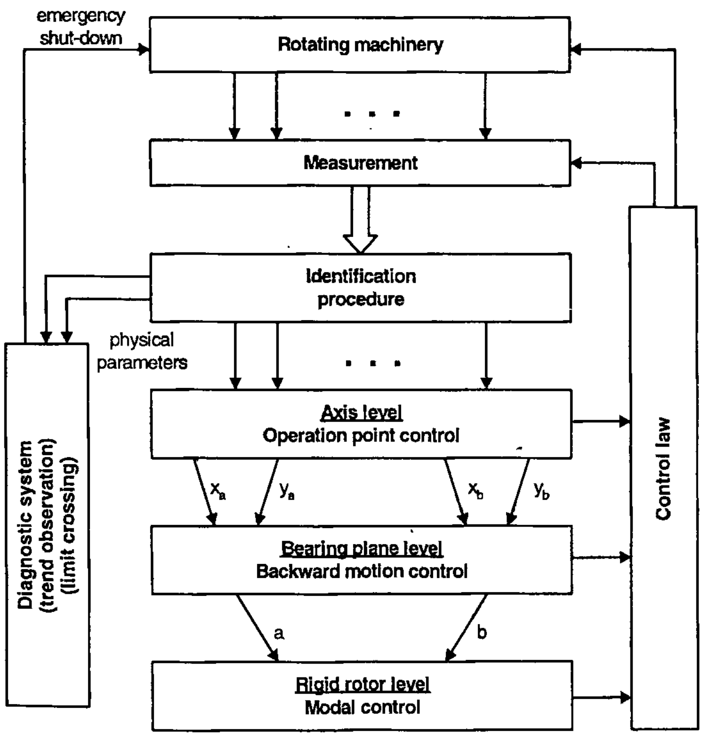

Fig. 3. Complete scheme of adaptive control and diagnostic for rigid rotor–magnetic bearing system.

The identification method of open-loop system physical parameters from [6] which is a modification of OKID method [7] is used in rigid rotor - smart magnetic bearing system. In this method it is assumed that the sum of input and output numbers equals to the state vector dimension. The deadbeat observer is used to design the observer/controller model of the closed-loop system. In our case the Markov parameters are not calculated from the observer/controller system realization but the ARX model of observer/controller is identified. From this model we can directly calculate (a) the open-loop physical system realization, and (b) the observer gain physical realization. Such approach was used to obtain the physical state-space model of the open-loop system for voltage controlled magnetic bearings.

The connection of the control system design and the above identification procedure leads to the adaptive control system. This time, the off-line identification [6] was replaced by the in-line identification procedure, assuming that the changes of the system parameters are slow. For the identified open-loop system parameters new control law parameters are calculated to obtain desired dynamics of the closed-loop system.

The in-line version of the above identification method is also useful for diagnostic purposes. In the physical model, the elements of matrices are usually a simple combination of system physical parameters (resistance, inductance, mass, moment of inertia, and so on) and therefore are useful for comprehensive diagnostics of the system. Trends in the physical parameter changes allow us to forecast the future technical condition of the system.

Smart magnetic bearing can not be considered as a complete intelligent device. Thus we should describe the minimal knowledge of the user and designer of rotating machinery. In the case of radial magnetic bearings for rigid rotor they should know: distances of bearing planes and measurement planes from mass center, rotor mass, approximate values of magnetic bearing parameters.

3. STRUCTURE OF THE ROTOR-BEARING SYSTEM

In mechatronic approach in design of smart magnetic bearings one should realize the following steps.

1. Complete a set of tasks for given application.
2. Select hardware: bearing type, sensors, actuators, controllers, and so on.
3. Optimize the actuator shape to maximize the electromagnetic forces.
4. Design the proper software for magnetic bearing tasks.
5. Simulate system in application environment .
6. Implement system.

Let us consider the problems described by 2 and 3 steps. There is some hardware and software selection flexibility in the design of magnetic bearing control system for rigid rotor [8]. We can select:

- the type and number of sensors,
- the type of controller (digital or analog),
- the type of control laws (voltage, current, magnetic flux, self-sensing),
- the structure of actuator (heteropolar, homopolar, number of poles).

There are some criteria in the choice of the rotor-bearing system structure related the application of rotating machinery. In the case of smart magnetic bearing system, we should choose such a structure, which will allow us reach the assumed goals: adaptive control, on-line diagnostics, and reconfiguration of the system. It is evident that we cannot use the current-control in such a system since the high current amplifier gains "hide" the coils parameters. It is also well known from redundant theory [9] that from the safety point of view, the bigger number of sensors the better.

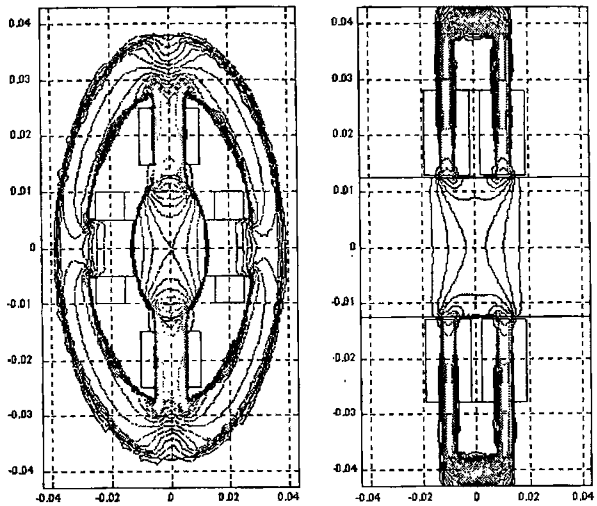

Fig. 4. Magnetic flux density in the homopolar magnetic bearing.

In any case we should carefully optimise the actuator structure to obtain the maximum load capacity. Computer-aided design methods (FEM) are very useful in this case. For example they allow us to shape the actuator structure by analysing the magnetic flux density as it is shown in Fig. 4 for the homopolar actuator [10]. As it is seen in Fig. 4. the permanent magnets and narrows edges strongly saturate magnetic paths. These places should be carefully shaped.

After some considerations we have chosen heteropolar voltage control system with measurement of rotor displacement and currents in the coils for further analysis. Finally, we assume the following solution.

1. Number of inputs plus number of outputs equals number of states.
2. In control system we use so called voltage control
3. Heteropolar magnetic bearings have better structure for our purposes.

4. PLANT MODEL AND CONTROL LAW

The dynamic equations of particular coils should be coupled with the model suspended rotor mass to implement the voltage control scheme. Finally, for each magnetic bearing axis we have the following model of the open-loop system [8]:

$$\dot{\mathbf{x}} = \mathbf{A}_c\mathbf{x} + \mathbf{B}_c\mathbf{u}, \quad \mathbf{y} = \mathbf{C}\mathbf{x} \qquad (1)$$

where:

$$\mathbf{x} = [X = x \quad \dot{x} \quad i_1 \quad i_2]^T, \; \mathbf{u} = [u_1, \; u_2]^T, \; \mathbf{y} = [x \qquad i_1 \quad i_2]^T$$

$$\mathbf{A}_c = \begin{bmatrix} 0 & 1 & 0 & 0 \\ \nu_1 & 0 & \nu_{21} & -\nu_{22} \\ 0 & -\nu_{31} & -\nu_{41} & 0 \\ 0 & \nu_{32} & 0 & -\nu_{42} \end{bmatrix}, \quad \mathbf{B}_c = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \nu_{51} & 0 \\ 0 & \nu_{52} \end{bmatrix}, \quad \mathbf{C} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{2}$$

and: x-rotor displacement from the point located at the bearing center to the operation point, u – coil voltages, i – coil currents, and ν - coefficients designed from system parameters.

Since dx/dt can be simply estimated from rotor displacement x the state feedback control law is as follows: $\mathbf{u} = -\mathbf{Fx}$.

Different control methods can be applied to implement the above state feedback control laws. In [11] the pole-placement method was used to obtain the controller gain matrix **F**. The LQR method is described for example in [12]. We use the deadbeat predictive control method [13] to obtain the gain matrix. For digital control purpose the continuous-time model (1) is changed into the discrete-time model:

$$\begin{aligned} \mathbf{x}(k+1) &= \mathbf{Ax}(k) + \mathbf{Bu}(k), \\ \mathbf{y}(k) &= \mathbf{Cx}(k) \end{aligned} \tag{3}$$

Gathering state equations for successive $q>n$ time steps we will obtain the predictive model:

$$\mathbf{x}(k+q) = \mathbf{A}^q\mathbf{x}(k) + [\mathbf{A}^{q-1}\mathbf{B}, ..., \mathbf{AB}, \mathbf{B}] \begin{bmatrix} \mathbf{u}(k) \\ \vdots \\ \mathbf{u}(k+q-2) \\ \mathbf{u}(k+q-1) \end{bmatrix} \tag{4}$$

We are interested in the minimum control energy solution, which can be obtained from a non-minimum time deadbeat solution:

$$\begin{bmatrix} \mathbf{u}(k) \\ \vdots \\ \mathbf{u}(k+q-2) \\ \mathbf{u}(k+q-1) \end{bmatrix} = -[\mathbf{A}^{q-1}\mathbf{B}, ..., \mathbf{AB}, \mathbf{B}]^+ \mathbf{A}^q \mathbf{x}(k) \tag{5}$$

where [ ]+ denotes the pseudo-inverse of the matrix in the brackets and q is a prediction horizon. The gain matrix can be taken as the first r-row partition of $[\mathbf{A}^{q-1}\mathbf{B}, ..., \mathbf{AB}, \mathbf{B}]^+ \mathbf{A}^q$, where r is the number of inputs. Finally, to obtain zero steady-state error a loop with an integral part should be added (see [6]).

5. FAULT LIST

Methods of fault detection can be divided into two groups [14]: methods basing on the analysis of process signals and methods basing on the analysis of connections among process signals. In the first group the statistic or spectral analysis of signal is carried out to detect faults. These methods are simple so we have not to know the process model. On the second hand the quantity of diagnostic information in the single signal is small. Moreover, the information is unreliable because of many causes which influence on the process signal.

In the second group of methods we use quantitative or qualitative models of the systems describing connections among process signals. This approach is particularly useful in the case of multi-inputs and multi-outputs control systems (MIMO). The most popular are analytical models. Differences between signals from analytical model and measured signals are called the residua. To generate residua we use linear and nonlinear physics equations, state observer or Kalman filter models of process, parity equations of input-output models, or identified models.

A linearized analytical model of the magnetic bearing is available. Moreover, the identification method of magnetic bearing parameters was described in the [15]. The identification method of the open-loop system parameters will be used as a part of the diagnostic system. Another part will be devoted diagnostics of sensors. The tests which allow isolate different faults will be described. Due to the digital microprocessors and digital controllers have built-in diagnostic tests we omit their diagnostics.

A rotating rotor has high kinetic energy which is approximately proportional to its mass and to square of the angular velocity. A such energy during emergency, for example after shut-up of the electric power supply to the magnetic bearings, can destroy all rotating machinery and be hazardous for people. To avoid such case the backup bearings are build-in and the additional source of power (usually accumulator) is joined to the energy power system.

Beside the emergency case there are other faults as a result of exploitation and of local damages. Such faults do not cause the catastrophic shut-up but gradually deteriorate performance of the system, what can finally lead to its damage. In the paper we consider detection an isolation of such faults since they are important in the case of the bearing system.

We assume that each of the axes in the single radial magnetic bearing is controlled independently and the rotor mass is reduced to the magnetic bearing plane. The plant consists of two electromagnetic coils, two amplifiers, and rotor as a point mass. The measurement system has a displacement sensor and two sensors of the coils currents. We will limit the discrimination of the faults to this parts of the control system. In such case the list of faults is as in Tab.1, where faults are denoted by f_k, for k=1÷8.

Tab.1. List of faults for single axis of magnetic bearings

f_k	**Discription of faults**
f_1	Fault of displacement sensor
f_2	Fault of 1 coil current sensor
f_3	Fault of 2 coil current sensor
f_4	Fault of 1 amplifier
f_5	Fault of 2 amplifier
f_6	Rotor mass change
f_7	Fault of 1 coil
f_8	Fault of 2 coil
f_9	Unbalance
f_{10}	Displacement sensor run-out

As faults we can consider the external excitations: rotor unbalance, displacement sensor's run-out, denoted as f_k, for k=9, 10. These faults can be isolated by identification method [15].

We can establish values of above faults f_k for which the diagnostic system generates the following actions: warning signal, alarm signal, counteraction to the external excitations, system reconfiguration, and the others.

Profoundness of diagnostics depends on the needs of a user. For example, when we have found an amplifier is failed we can need to isolate failure deeper inside the amplifier. Since amplifier is a complex electronic device in the place of faults f_3, f_4 we have many other faults connected with different components of the amplifier.

6. FAULT MODELS

The faults change the model parameters from their nominal values as follows:

$$\underline{\mathbf{A}}_c = \mathbf{A}_c + \Delta\mathbf{A}_c, \quad \underline{\mathbf{B}}_c = \mathbf{B}_c + \Delta\mathbf{B}_c, \quad \underline{\mathbf{C}} = \mathbf{C} + \Delta\mathbf{C}. \tag{6}$$

Analyzing the state and measurement equations we can notice that in our case the information about faults f_1, f_2, f_3 is in matrix $\Delta\mathbf{C}$, about faults f_4, f_5, in matrix $\Delta\mathbf{B_c}$, and about faults f_6, f_7, f_8 in matrix $\Delta\mathbf{A_c}$. Faults f_9, f_{10} are connected with unbalance $\mathbf{w}(t)$, and sensor run-out $\mathbf{p}_r(t)$, respectively. In the correctly working system those external excitations should be reduced, and they are considered as faults. Taking into account the model with faults we have:

$$\begin{aligned} \mathbf{x}(k+1) &= \underline{\mathbf{A}}\mathbf{x}(k) + \underline{\mathbf{B}}\mathbf{u}(k) + \mathbf{B}_d\mathbf{w}(k), \\ \mathbf{y}(k) &= \underline{\mathbf{C}}\mathbf{x}(k) + \mathbf{C}_p\mathbf{p}_r(k). \end{aligned} \tag{7}$$

Output vector $\mathbf{y}$(k) can be expressed as a function of vectors: control $\mathbf{u}$(k), unbalance $\mathbf{w}(k)$, and run-out $\mathbf{p}_r(k)$:

$$\mathbf{y}(k) = \underline{\mathbf{C}}\underline{\mathbf{A}}^k\mathbf{x}(0) + \sum_{i=1}^{s}\mathbf{Y}_i\mathbf{u}(k-i) + \sum_{i=1}^{s}\mathbf{Y}_{wi}\mathbf{w}(k-i) + \mathbf{C}_p\mathbf{p}_r(k), \tag{8}$$

where the first component describes the transient signal, while:

$$\mathbf{Y}_i = \underline{\mathbf{C}}\underline{\mathbf{A}}^{i-1}\underline{\mathbf{B}}, \quad \mathbf{Y}_{wi} = \underline{\mathbf{C}}\underline{\mathbf{A}}^{i-1}\mathbf{B}_d, \quad \mathbf{Y}_{ri} = \underline{\mathbf{C}}, \quad i = 1,\ 2,\ 3,\ ...,\ s$$

are Markov parameters of: system, external excitations, and signal run-out, respectively. To design the state observer we add and subtract the component $\mathbf{Gy}(t)$ to the first equation in (7):

$$\begin{aligned} \mathbf{x}(k+1) &= (\underline{\mathbf{A}} + \mathbf{G}\underline{\mathbf{C}})\mathbf{x}(k) + \underline{\mathbf{B}}\mathbf{u}(k) + \mathbf{B}_d\mathbf{w}(k) + \mathbf{G}\mathbf{C}_p\mathbf{p}_r(k) - \mathbf{G}\mathbf{y}(k), \\ \mathbf{y}(k) &= \underline{\mathbf{C}}\mathbf{x}(k) + \mathbf{C}_p\mathbf{p}_r(k). \end{aligned} \tag{9}$$

where $\mathbf{G}$ is the observer gain matrix.

We assume that control signal $\mathbf{u}(k)$ is a sum of persistent pseudo-random signal $\mathbf{r}(k)$ and of feedback signal $\mathbf{u}_f(k)$ as follows:

$$\begin{aligned} \mathbf{u}(k) &= \mathbf{u}_f(k) + \mathbf{r}(k), \\ \mathbf{u}_f(k) &= -\mathbf{F}\hat{\mathbf{x}}(k). \end{aligned} \tag{10}$$

Introducing equations (10) into equations (9) we obtain the observer/controller model of the closed-loop system in the form:

$$\begin{gathered}\hat{\mathbf{x}}(k+1)=\underline{\bar{\mathbf{A}}}\hat{\mathbf{x}}(k)+\underline{\bar{\mathbf{B}}}\begin{bmatrix}\mathbf{u}(k)\\ \mathbf{y}(k)\end{bmatrix}+\mathbf{G}\mathbf{C}_p\mathbf{p}_r(k)+\mathbf{B}_d\mathbf{w}(k),\\ \mathbf{y}_u(k)=\begin{bmatrix}\hat{\mathbf{y}}(k)\\ \mathbf{u}_f(k)\end{bmatrix}=\underline{\bar{\mathbf{C}}}\hat{\mathbf{x}}(k)+\mathbf{C}_r\mathbf{p}_r,\end{gathered}\tag{11}$$

where: $\underline{\bar{\mathbf{A}}}=\underline{\mathbf{A}}+\mathbf{G}\underline{\mathbf{C}}$, $\underline{\bar{\mathbf{B}}}=[\underline{\mathbf{B}}\quad -\mathbf{G}]$, $\underline{\bar{\mathbf{C}}}=\begin{bmatrix}\underline{\mathbf{C}}\\ -\mathbf{F}\end{bmatrix}$, $\mathbf{C}_r=\begin{bmatrix}\mathbf{C}_p\\ \mathbf{0}\end{bmatrix}$.

To reduce the estimation time we introduce the deadbeat observer where matrix **G,** fulfills the condition: $(\underline{\bar{\mathbf{A}}})^i=(\underline{\mathbf{A}}+\mathbf{G}\underline{\mathbf{C}})^i=\mathbf{0}$, for: $i\geq p$. In this case the output signal can be expressed by reduced number of Markov parameters of observer/controller model:

$$\mathbf{y}_u(k)=\sum_{i=1}^{p}\bar{\mathbf{Y}}_i\mathbf{v}(k-i)+\sum_{i=1}^{p}\bar{\mathbf{Y}}_{wi}\mathbf{w}(k-i)+\sum_{i=0}^{p}\bar{\mathbf{Y}}_{ri}\mathbf{p}_r(k-i),\ \text{for}\ k\geq p,\tag{12}$$

where: $\mathbf{y}_u(k)=\begin{bmatrix}\mathbf{y}(k)\\ \mathbf{u}_f(k)\end{bmatrix}$, $\mathbf{v}(k-i)=\begin{bmatrix}\mathbf{u}(k-i)\\ \mathbf{y}(k-i)\end{bmatrix}$,

$$\bar{\mathbf{Y}}_i=\underline{\bar{\mathbf{C}}}\underline{\bar{\mathbf{A}}}^{i-1}\underline{\bar{\mathbf{B}}},\quad \bar{\mathbf{Y}}_{wi}=\underline{\bar{\mathbf{C}}}\underline{\bar{\mathbf{A}}}^{i-1}\mathbf{B}_d,\quad \bar{\mathbf{Y}}_{r0}=\mathbf{C}_r,\quad \bar{\mathbf{Y}}_{ri}=\underline{\bar{\mathbf{C}}}\underline{\bar{\mathbf{A}}}^{i-1}\mathbf{G}\mathbf{C}_r,\ i=1,\ 2,\ \ldots p.$$

Identified Markov parameters (particularly first of them) will be used in diagnostic tests.

6.1. Isolation of failed sensor

Omitting external excitations we have the model of the system with faults:

$$\begin{gathered}\mathbf{x}(k+1)=(\mathbf{A}+\Delta\mathbf{A})\mathbf{x}(k)+(\mathbf{B}+\Delta\mathbf{B})\mathbf{u}(k),\\ \mathbf{y}(k)=(\mathbf{C}+\Delta\mathbf{C})\mathbf{x}(k)=\mathbf{C}\mathbf{x}(k)+\mathbf{y}_F(k),\end{gathered}\tag{13}$$

where $\mathbf{y}(k)$ is real measured signal and $\mathbf{y}_F(k)$, is signal generated by sensor faults. To isolate sensor fault we use the method IFD – Instrument Fault Detection [17] with residua generated by the observer bank. We denote that $\hat{\mathbf{x}}(k)$ is estimated state vector, so the estimation error is: $\boldsymbol{\varepsilon}(k)=\mathbf{x}(k)-\hat{\mathbf{x}}(k)$. For observer gain matrix **L** it leads to the following estimation error equation:

$$\dot{\boldsymbol{\varepsilon}}=[\mathbf{A}-\mathbf{L}\mathbf{C}]\boldsymbol{\varepsilon}+[\Delta\mathbf{A}-\mathbf{L}\Delta\mathbf{C}]\mathbf{x}+\Delta\mathbf{B}\mathbf{u}-\mathbf{L}\mathbf{y}_F.\tag{14}$$

It means that all faults: $\Delta\mathbf{A}$, $\Delta\mathbf{B}$, $\Delta\mathbf{C}$ influence on the estimation error. Such approach allows to detect faults in the system but not to isolate them. The situation is much simple if only the sensor is failed. Then we can isolate such sensor by the observer bank. So we have to design a test to separate the diagnostics of measurement system from the other faults. Identification of Markov parameters will be used to separate faults $\Delta\mathbf{C}$ from $\Delta\mathbf{A}$, $\Delta\mathbf{B}$.

6.2. Diagnostic tables

A diagnostic table written in the binary matrix form shows dependences among diagnostic signals and different faults. The table enables the isolation of particular faults. In the binary matrix the columns are connected with faults, while rows with diagnostic signals. When a fault influences on a diagnostic signal we put value *true* (integer 1) in the proper place of the matrix. In opposite case we put *false* (zero).

The residua from the observer bank and the residua obtained during identification of the open-loop system parameters will be diagnostic signals. First three diagnostic signals are generated by the observer bank of the measurement system:

$$s_1(t)=r_1(t),\quad s_2(t)=r_2(t),\quad s_3(t)=r_3(t). \tag{15}$$

where *r(t)* are signals designed to isolate faults of particular sensors. Unfortunately, if there are faults in other components of system they influence above diagnostic signals. Therefore, these signals are functions of faults connected with sensors, amplifiers and coils as follows:

$$\begin{aligned} s_1 &= s_1(f_1, f_4, f_5, f_6, f_7, f_8),\\ s_2 &= s_2(f_2, f_4, f_5, f_6, f_7, f_8),\\ s_3 &= s_3(f_3, f_4, f_5, f_6, f_7, f_8). \end{aligned} \tag{16}$$

The next diagnostic signals are obtained from identification procedure. Using the ERA algorithm we calculate real matrices of the open-loop system. They are compared with nominal matrices by introduction of array division in the form:

$$\mathbf{A}_\mathrm{p}=\frac{\mathbf{A}_{\mathrm{Ce}}-\mathbf{A}_\mathrm{C}}{\mathbf{A}_\mathrm{C}}\cdot 100\%,\quad \mathbf{B}_\mathrm{p}=\frac{\mathbf{B}_{\mathrm{Ce}}-\mathbf{B}_\mathrm{C}}{\mathbf{B}_\mathrm{C}}\cdot 100\%, \tag{17}$$

Array division is a division of respective matrices elements. Elements of matrices $\mathbf{A}_\mathrm{c}$, $\mathbf{B}_\mathrm{c}$ are shown in equation (2). The elements of matrices $\mathbf{A}_{\mathrm{ce}}$, $\mathbf{B}_{\mathrm{ce}}$ are estimated in identification procedure. So, we have the following matrix indicators of faults:

$$\mathbf{A}_p=\begin{bmatrix} 0 & 1 & 0 & 0\\ v_{p1} & 0 & v_{p21} & -v_{p22}\\ 0 & -v_{p31} & -v_{p41} & 0\\ 0 & v_{p32} & 0 & -v_{p42}\end{bmatrix},\quad \mathbf{B}_p=\begin{bmatrix} 0 & 0\\ 0 & 0\\ v_{p51} & 0\\ 0 & v_{p52}\end{bmatrix}, \tag{18}$$

Analyzing physical parameters of the system we can notice that elements of above matrices are generated by different faults according to the following relations:

$$\begin{aligned} &v_{p1}=v_{p1}(f_6,f_7,f_8),\quad v_{p21}=v_{p21}(f_6,f_7,f_8),\quad v_{p22}=v_{p22}(f_6,f_7,f_8),\\ &v_{p31}=v_{p31}(f_7),\quad v_{p32}=v_{p32}(f_8),\quad v_{p41}=v_{p41}(f_7),\\ &v_{p42}=v_{p42}(f_8),\quad v_{p51}=v_{p51}(f_4),\quad v_{p52}=v_{p52}(f_5). \end{aligned} \tag{19}$$

The information about the same faults is contained in a few diagnostic signals. Thus, we can reduce the list of diagnostic signals as follows:

$$\begin{aligned} &s_4(f_4)=v_{p51},\quad s_5(f_5)=v_{p52},\quad s_6(f_6,f_7,f_8)=v_{p1},\\ &s_7(f_7)=v_{p31},\quad s_8(f_8)=v_{p32}. \end{aligned} \tag{20}$$

As it results from identification method these functions are valid for normally working sensors. In real situation we have to take into account the failure of sensors. Then, above diagnostic signals are functions of the following faults:

$$s_4 = s_4(f_1, f_2, f_3, f_4),\quad s_5 = s_5(f_1, f_2, f_3, f_5),$$
$$s_6 = s_6(f_1, f_2, f_3, f_6, f_7, f_8), \tag{21}$$
$$s_7 = s_7(f_1, f_2, f_3, f_7),\quad s_8 = s_8(f_1, f_2, f_3, f_8).$$

The full binary matrix has the form shown in the Tab. 2. The matrix is fulfilled by logic values 1 (*false*). We omitted and replaced by blank the logic values 0 (*true*) to make the table clearer. As a limit for values *false* we assumed 5% changes in the physical parameters which lead to system instability.

Tab.2. Binary diagnostic matrix for single axis of magnetic bearing

S/F	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8
s_1	1			1	1	1	1	1
s_2		1		1	1	1	1	1
s_3			1	1	1	1	1	1
s_4	1	1	1	1				
s_5	1	1	1		1			
s_6	1	1	1			1	1	1
s_7	1	1	1				1	
s_8	1	1	1					1

As an example we consider the electromagnetic coils. The coil fault can be a result of short circuit between parts of coils. It reduces the number of active coils. As a result it changes the coefficient of displacement stiffness, coefficient of current stiffness, inductivity, and resistance. During a computer simulation we can find the limit number of failed coils causing the closed-loop system instability (for fixed control law). If total number of failed coils cross the 5% of the limit number then corresponding values of elements in matrix indicators should show appearance of the fault.

According to Gertler [16] the faults are detectable when all columns of binary matrix are different. If two columns differ only in one row the faults connected with these columns are weakly isolated. When all columns differ in two rows all faults are strongly isolated. It takes place when binary matrix is square and diagonal. In that case we are able to isolate multiple faults. Analyzing the Table 2 we can notice that all faults are strongly isolated except the f_6 fault because rotor mass change is weakly isolated.

7. DIAGNOSTIC SYSTEM

From the binary matrix (Table2) results that test of measurement system by observer bank is sufficient to detect faults in the system. A set of diagnostic signals s_1, s_2, s_3 reacts to all faults. To isolate fault we have to carry out the other tests. The isolation of all faults is available by the following tests.

1. Measurement system test by the observer bank.
2. Test separating faults of measurement system from faults in plant or actuators.
3. Identification of physical state matrix and physical control matrix.
4. The isolation of the faults.

Ad.1. Residua of measurement signals are generated on-line by the observer bank realized beside control loop. It can be realized by a microprocessor using parallel the measurement and control signals. Since that test is realized on-line it allows to emergency shut-down of the rotating machinery in the case of fast progression of the failure. The method of observer bank was checked in many industrial applications [16,17].

Ad.2. It is desired to have a test in which faults of the measurement system are distinguished from others faults. The test allows to avoid the identification procedure which consumes microprocessor time. In the case of sensor fault this test stops further tests. The previous test indicates which sensor is failed.

To check if the fault is in measurement system we can use observer/controller Markov parameters, particularly the first one which has the following form:

$$\overline{\mathbf{Y}}_1 = \overline{\underline{\mathbf{C}}}\overline{\underline{\mathbf{B}}} = \begin{bmatrix} \underline{\mathbf{CB}} & -\underline{\mathbf{C}}\mathbf{G} \\ -\mathbf{F}\underline{\mathbf{B}} & \mathbf{FG} \end{bmatrix}. \tag{22}$$

We can see that the diagnostic signal can be designed basing on elements of submatrix $\underline{\mathbf{C}}\mathbf{G}$ where observer gain matrix **G** is constant. Faults in measurement system cause changes in matrix **C**. Submatrix $\underline{\mathbf{C}}\mathbf{G}$ has dimension 3×3. If matrix **C** has a similar form to diagonal then the best diagnostic signals can be designed from diagonal elements of the submatrix $\underline{\mathbf{C}}\mathbf{G}$.

To identify Markov parameters we are forced to excite the closed-loop system by additional signal **r**(t). Such test should be realized in an off-line regime. It means that the technological process of rotating machinery shoud be stopped to carry out test. Therefore, we can not resign from the observer bank because it does not disturb the technological process.

Ad.3. Above remarks apply to identification procedure of open-loop physical parameters. After identification we obtain matrix indicators. As it was mentioned the diagnostic signals are calculated from elements of the indicators. This test should be also realized in off-line regime.

Ad. 4. After above tests we are able to indicate faults. It can be noticed that after first two tests the binary matrix (Tab. 2) may be split into two simpler matrices (Tab.3, 4).

Tab.3. Diagnostic binary table for fault in measurement system

S/F	f_1	f_2	f_3
s_1	1		
s_2		1	
s_3			1

Tab. 4. Diagnostic binary table for fault subset of plant and actuators

S/F	f_4	f_5	f_6	f_7	f_8
s_4	1				
s_5		1			
s_6			1	1	1
s_7				1	
s_8					1

These matrices are almost diagonal and faults are strongly isolated with exception of rotor mass change.

8. SUMMARY

Mechatronic approach in designing, prototyping, and manufacturing allows us to increase the competition of a new products by acceleration of their introduction to the market and by increasing of the task and function number realized by the products while keeping the same price level. Synergy effects are main advantage of the mechatronic system. As an example we consider magnetic bearing systems. It appears that adding of two current sensors to the displacement sensor (one for each opposite coils) in one axis of bearing allows us to increase the number of functions realized by magnetic bearing system.

In this paper, we provide the overview of the concept and present the formulation for control and dynamics of rigid rotor supported on smart magnetic bearings. Using the proper software such smart system can realize identification of external excitations and system parameters, adaptive control, and diagnostics by detection and isolation of different faults.

The diagnostic system is more detail presented since it focuses all problems typical for mechatronic system. More information about smart magnetic bearings is available in [4]. There are described computer simulation and chosen experimental investigations of magnetic bearings.

It should be mentioned that considered system does not drain the possibility of synergy in magnetic bearing systems. It is known from literature that electric motor can be used as a magnetic bearing [8], and magnetic bearing actuator can be used as a displacement sensor [4].

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