Personal Impressions on
40 Years of Magnetic Bearings

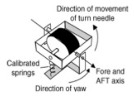
1 Introduction

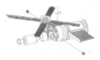
Welcome to the world of memories. This presentation will be different from a scientific one. I intend to show my impressions on the development of magnetic bearings in a truly personal way, and I hope I can show it in a somewhat entertaining and colourful way. It might be interesting especially for young people to see how motivations develop, how ideas grow, how realisations can be difficult and not at all straightforward. It needs a good team, good friends and colleagues, financial resources, as well as understanding and patient customers. And as to the experienced researchers among you, you may recognise situations where you can nod your head and say "that's how it was", but I never talked about it. I will show critical decisions and give personalized recommendations, summarizing them as *lemmas* .

2 Background, Gyrodynamics

In the beginning I became a mechanical engineering, studying, in particular, gyrodynamics, the theory of rotating bodies. Their behaviour is fascinating and the applications range from spinning tops, to inertial navigation instruments, to satellites and to industrial rotors.

My first encounter with spinning bodies, in the 1960ies, at the Technical University of Stuttgart in Germany, was a gyroscope for measuring the rate of rotation, small rates, much less than the rotation rate of the earth, that is one revolution per day. Such rate gyros were at the core of inertial platforms for airplanes, and for the Polaris Submarine which had to stay under the Arctic ice with no external information about its location. Nowadays, such rate measuring devices, are used in cars for automated breaking and dynamic control system, with a totally different technical realisation, however.





3 Satellite Dynamics, Control

Working on gyroscopic instruments was interesting, but in my opinion too special, and thus, I came to the conclusion

Lemma 1: if you do not feel the challenge any more you should change the subject.

Therefore, in the beginning of the seventies, when I had the opportunity as a postdoc to work for the NASA, the Marshall Space Flight Center in Huntsville, Alabama, I was attracted to satellite dynamics, investigating the behaviour of a spinning Skylab. The rotation was supposed to create centrifugal forces for the astronauts as a substitute for gravitation. Some of you may remember: this was a time of big challenges - everything seemed to be possible, you didn't have to be afraid to start something new. I had the opportunity to watch the start of Apollo15 at Cape Kennedy, Figure 3, and I just show the very private foto of my family watching the start, and I don't have to go into details about their impressions. It was breathtaking.

Well, not only the emotions at that time were going high, the methods and tools, developed with the space activities, went far beyond the spectacular travel to the moon. It became possible to build theoretical models of hitherto unknown complicated systems and to simulate their behaviour before they could be tested in reality. You became confident in mathematical modelling and simulation and in the power of computation. You had the feeling as well:

Lemma 2: Yes, you can do it.

The rotating Skylab, I had been working on, was flexible as well and sufficiently complicated, and furthermore its dynamics had to be controlled. And that's how I came into contact with control theory. At that time control theory was still a kind of magic science, and I had to learn much.

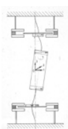
The success of the space activities in the US had a sad consequence, too, however. Once a product or a procedure had become "space-proof", there was no necessity anymore to change the design or to invent something new. The challenges became less, and it became obvious that the time of big money for NASA was over. I went back to the Technical University of Munich and was lucky enough to start a fascinating research on a very special spinning body.

4 Rotor Dynamics

An Austrian scientist, Gernot Zippe, who had been working in Russia before coming home again, wanted to optimise the dynamics of a special centrifuge, and obviously he had some backup of industry. His gas centrifuge was to enrich uranium from the gas hexafluorid, and the centrifuge consisted mainly of a long tube of about 20 cm diameter spinning at a rate of about 90'000 rpm. Our team at the university succeeded in modelling, simulating and optimising the dynamics.

We were surprised by the interest our research arouse - we had correspondence and questions from quite a number, sometimes strange countries, and when we felt the problematic implications of our work, we did not feel well, and we did not continue with the industrial realisation of the centrifuge. Some others did. Nowadays it is a big political issue where the plants with thousands of these centrifuges are working and how to control their outcome. I would say:

Lemma 3: Follow your emotions, but keep a clear head!



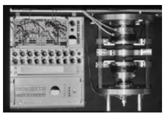
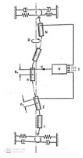
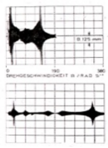
5 Control of Rotor Dynamics

Concerning the dynamics of the centrifuge one particular question, at that time a rather scientific question, remained. Would it be possible to control the dynamics of a spinning rotor by active means, using control theory?

Lemma 4: Once you have found a good solution for a problem, always new questions come up.

If it did work in space for a spinning satellite, it should be possible for an industrial rotor as well. When I had been working on gyroscopic instruments I saw a report proposing a strange rate gyro: the rotor was suspended magnetically and the bearing forces, represented by the current through the magnets were an indication of the motion of the rotor and the rate to be measured. The proposal never made it to practical use as a rate gyro but it looked quite interesting to me. However, what I wanted was just the other way round: I wanted to generate magnetic bearing forces in order to prevent motions of the rotor. All I needed was some extra knowledge about magnetic forces and electrical engineering. In our family winter vacation in the Austrian Alps, the family was skiing, I was sitting in the skiing hut high up in the mountains and got a new start to study electrical engineering.

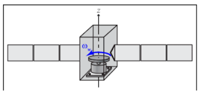
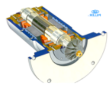
And it actually did work. With rather clumsy efforts I succeeded in building a magnetic actuator for generating radial forces. I measured the deviation of the spinning rotor with contact free eddy current sensors, used an analogue computer for deriving control signals from the sensor signals, Figure 8, and analogue audio amplifiers. I succeeded in generating suitable damping forces acting on the spinning rotor. Figure 9 shows the model for it. The measured lateral vibrations of the initial rotor had been very large and unstable at a certain speed, but after switching on the active damping the operating speed could be much increased with less vibrations.

6 Magnetic Bearings

During all this work I became familiar with many nice results on magnetic levitation that bright people had already achieved in this field. My paper has a comprehensive list of references, and I will not go into details. For example, you will find a good survey on the history and the state of the art on the very recommendable website of the University of Linz.

At that time I thought of applying this magnetic suspension technique to industrial products. As I was working in Munich I had good contact to the development of the first levitated train, the MAGLEV Transrapid, and I even did some work for it. And I saw an application of a magnetically supported flywheel by the German company TELDIX as a means of controlling the attitude of spacecraft, an area that was already familiar to me.

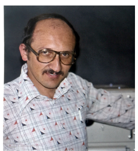
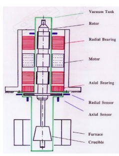
But I also looked into industrial rotors and visited S2M in France. I was much impressed by the work already going on there. I met Mr. Habermann, the chief engineer at S2M, a German from former Czechoslovakia who found a new live in France - you know Europe was a mess after World War 2 - He was a truly great person, and I am sorry that S2M didn't have a photo of him any more. And then I had to make a decision, and there was a saying,

Lemma 5: if you work for government, usually you are paid by the hour, sometimes well paid, but government depends on unpredictable politics - if you work for industry you are paid by the result, as industry follows the money very predictably. Thus, you only need good results.

The MAGLEV meant public money just as the aerospace business at NASA; in industrial rotors, however, you have more choices. Which one would be more reliable to you?

7 Magnetic Bearings at the ETH Zurich

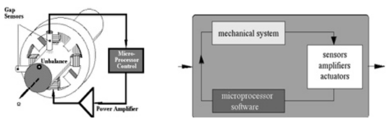
I continued with magnetic bearings for spinning rotors, and, for example, for a Max-Planck-Institute in Germany, we built a centrifuge, running in Ultra-High-Vacuum. The Active Magnetic Bearing was completely outside of the vacuum, chamber, and, what we had not expected, we had to become specialists in vacuum technology as well. Heinz Ulbrich, you may know him, became my first doctoral student

We published some papers which were nicely accepted, helped to organise a prestigious Symposium on the Dynamics of Multibody Systems, chaired by my highly esteemed teacher Kurt Magnus, and I received an offer from the highest level of Swiss Government to work for the ETH in Zurich, the Swiss Federal Institute of Technology, as a professor of mechanics. The president of ETH obviously liked my idea to bring mechanical and electrical engineering closer together. But everybody of you who is familiar with departmental structures at universities knows about the difficulties of bringing mechanical and electrical engineering together. In the beginning I didn't have much confidence in the promises of the university to support my research - and I asked the vice-president of research: where do you get the rooms which I will need? And the answer was: when a professor becomes successful he will become well known, he will become a high ranking member of academic societies, a member of advisory boards, edit a journal, chairing conferences - and actually he will not have time enough to do further research - and then we take his rooms back and give it to the young ones. And when I am already talking about Switzerland: The country is well known for its banking, chocolate and tourism - but this is not the essential part: Switzerland does not only have an efficient administration, it has a stable government, politics close to the people, an excellent education system, a lot of high-tech industry, and the population has more than 20% of foreigners, definitely more than most other countries in the world. As to the educational area: the ETH has 37% foreigners, 70% of doctoral students are foreigners, the school has about 25 spinoffs per year, and, as an example, in 2018 the bank Credit Suisse has given 7 Million $ for another professor of robotics.

Thus, at the ETH I had the opportunity to do research on magnetic bearings. But I was still in the department of mechanical engineering, and I needed students from electrical engineering and computer science as well. I was lucky enough to find young colleagues who were ready to cooperate, and after some time I was an associated member of the department of electrical engineering and their students got credits for working with me. This led to the founding of an inter-departemental research group on Mechatronics. The term Mechatronics had been created by a Japanese engineer, and it meant the cooperation of Mechanics and Electronics. We arranged a framework around the definition.

8 Mechatronics



Mechatronic System: The system picks up signals from its environment, processes them in an intelligent way and reacts, for example, with forces or motions

Methods for connecting the various areas of knowledge - mechanical, electrical engineering and computer science - are provided by the basic engineering sciences, by system theory, control techniques and information processing. In 1984 already we offered a postgraduate course on Mechatronics. I guess, next to Finland, Switzerland was the first country in Europe to formalise education in Mechatronics. In the meantime, Mechatronics has become a successful curriculum in many universities all over the world. The term is extensively used for any combination of electrical and mechanical engineering. And in most modern technical products you will find a microprocessor, and you can say that embedded computers and their software have become a machine element. This is characteristic, for example, in modern cars, robots, sewing machines and most household appliances. And even more: the combination of a classical technical area with electronics and computer science has spread: nowadays you find thermotronics, the control of heating, chemotronics in batteries and fuelcells, domotronics in the security management of houses, biotronics in medical devices, and what so ever.

9 Projects on AMB

Our research group has been working on quite a number of magnetic bearing topics and projects, I will not go into technical details, but would rather tell some entertaining stories which illuminate the human background of the scientific development.

10 People

Among my first doctoral students at the ETH was Hannes; he is now a professor at the Swiss Federal Institute of Technology in Lausanne. Most of you know him personally - he was a chairman of the ISMB 10 and he never missed one of our symposia. I hope he will excuse my liberty to say a few personal words. We had many visitors in our lab at the ETH, among them Osami Matsushita. At that time he was a chief engineer with Hitachi in Japan. You know, later on, he became the driving person behind the very useful ISO-Standards on Magnetic Bearings. Well, during his visit at the ETH he met Hannes Bleuler, and soon enough Hannes was working with Hitachi in Japan. Hannes quickly proceeded to become a professor at the Tokyo Institute of Technology, then at the University of Tokyo, before he returned to Switzerland. And, as life is, in Japan he got married with a wonderful Japanese lady, and of course his boss at Hitachi, Osami Matsushita, came to the wedding in Switzerland, sharing some responsibility as is the duty of a good Japanese boss. Well, Hannes Bleuler was not the only one of my students going abroad. My guideline was

Lemma 6: send the good students abroad.

It is good for the students, and there are bright colleagues at foreign universities all over the world who like to work with good students. I made it a point not to keep my good students at my place to work for my research topics only. As an example, I will mention Marcus Mueller. He was doing research on a high speed milling spindle, and he was using the signals created in the magnetic bearings for monitoring the wear of the milling tool.

It was an early application of the nowadays very popular topic "Internet of Things " or the "Industry 4.0". Marcus Mueller went to Brazil, working at first with Embraco in Joinville, then with Walter Weingaertner, at the Precision Lab of the Federal University of Santa Catarina in Florianópolis. And, as it happens with young people, he got married to a charming Brazilian girl, and I had the privilege to attend the wedding in Joinville. Well, more than 20 years later they are still happily married, with a nice family, in Switzerland now.

11 International Contacts

Another one of my guidelines was related to sending young people abroad. Early in my career I had decided to spend 10% of my time to sponsor and support good students from abroad. And it worked very well. At some time I had 11 different nationalities in my research group. Understanding was not a big problem, leading to

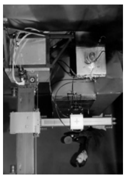
Lemma 7: if people don't understand one another it's hardly ever a problem of language.

But there were other problems, for example: one guy from Norway, who had started his studies at a British university, met a nice Chinese girl in Switzerland, and they wanted to get married. Just imagine the pile of documents they needed. When the last document arrived after some months the first one had lost its validity and they had to start the applications once over. Thus it took a year for finalising the licence. And I became a well known visitor to the Swiss Immigration Office which is just as friendly and welcoming as all the other ones all over the world. But, in the end, I had never expected the good outcome of my principle. Most of these foreign students went back to their home countries after completing their theses, and had a successful career. Now, I can travel all over the world, and I can meet friends. It is a very rewarding outcome of

Lemma 8: do something for the benefit of others !

12 Robotics

Let's go back to the scientific area: In 1988 I organised an international Symposium on the Dynamics of Controlled Mechanical Systems, together with a colleague from the Department of Electrical Engineering - with a rather unexpected consequence We presented examples, of course on magnetic bearings, but also other ones: as a hobby and for the fun of my students on Mechatronics I had started projects on robotics, and the students built a robot that could play Ping-Pong, not really good, but a few times back and forth against a human.



It helped that one of the students came from Spain and was a member of a national table tennis team. To make a complicated story short: the ETH offered me the opportunity to found an Institute of Robotics, and thus I had to divide my time between Magnetic Bearings and Robots. But from a scientific point of view the areas are quite related anyway. In the meantime "Robotics" has become a very successful key topic at the ETH. Now, there are about five colleagues working in this field, attracting excellent students from all over the world and making the ETH a hotspot in this field.

13 ISMB - International Symposium on Magnetic Bearings

On the other hand, the research on magnetic bearings became more and more intense: I was lucky enough to find very good colleagues in Japan, Professor Toshiro Higuchi at the University of Tokyo in Japan, and Professor Paul Allaire at the University of Virginia, in the USA, who were also interested in starting a specific Symposium on Magnetic Bearings.

Thus, in 1988 the first ISMB took place at the ETH, and in a biannual sequence the next ISMB's took place in Japan and then in the USA. The idea was spreading, mainly among researchers at universities. However, to get contributions from industry about relevant applications we first had to generate a market. We had to talk to industry, asking them: "Do you have a problem? - We have a solution!" And one of our industrial partner was asking: "Do you still talk at conferences about magnetic bearings? If they are so good you would be selling, not talking"

In the meantime, I guess, that attitude has been changing. Of course, there is a difference in the tasks of industry and university: an industrial company has to be just a little bit better than its competitor, and universities should try to get insights and to solve potential problems of the future. But there has to be a close contact, and this is most essential. Let me tell you an example: years later I was helping our university to build up a research group in nano-technology. And my colleague from Technology Management wanted to know how much was or would be the interest of industry in this area. He sent a master student to interview the research director of a large well known Swiss company in machine industry. The research director shrugged his shoulder and did not know and did not want to know anything about "Nano". You know: one nano-meter is about how much the fingernails grow in one second. The consequence of this attitude was quite dramatic: two years later the research director was no longer director of research any more.

14 Industrial Development

Let me talk now about the start into the industrial development of our AMB activities. Actually, in the 1980ties, at the ETH, we were building magnetic bearings and selling them, mainly to other colleagues at universities. I will not go into details, but I should mention that, of course, not everything went so smoothly, but usually you never talk about it: for example, we received an emergency call from a colleague in Germany that the bearing we had delivered had gone crazy. It had become unstable and was hammering up and down permanently during a whole weekend, making a lot of noise. Of course, I immediately sent one of our best students to fix the control and do any repair. The student seemed to like the task and he went often to that university in Germany to take care of our product. After some time I became curious about the ongoing technical problems, and I found out that he had met a nice girl there, his future wife. Well, he took care of everything. It is not only about magnetic bearings, it is about real people.

Each time, when I had a chance to do it, I made use of a sabbatical leave from the ETH, and this time, in 1987, I went to California, working for Stanford University for some time. During my absence, a good postdoc, Alfons Traxler, took care of the institute at the ETH. He did it perfectly well, and obviously he liked the feeling of being the boss, and when I returned from my sabbatical, he had developed the idea for a spin-off company himself. He named it MECOS - an abbreviation for *Me*chanics and *Co*ntrol *S*ystems.

He convinced some of his colleagues in our research group that magnetic bearings had an industrial potential. They put their money together, even the wives were risking their savings, and they collected about 1 million $ as a starter, and they all became shareholders. In 1988 they started the business in the garage and painter's workshop of the retired father of Alfons.



The ETH is an open minded university, and it supported the spin-off company by allowing initial part-time work for the research team and the borrowing of expensive measurement equipment. The company grew steadily, and was producing small series of industrial compressors and pumps, it gave licences to other companies, and it moved to a larger, very professional building. Financially, liquidity became a problem during a depression time, but the team succeeded in attracting some venture capital. And another problem was - but you could also see it as a positive side effect - a few of the excellent team members left and made a career as professors in Mechatronics at various universities. A few years ago the founder, Alfons Traxler, and a prominent team member, René Larsonneur, passed away,. We miss them. In 2012 the company was sold to the large company "MAN

Turbo & Diesel" in Zurich, and now they continue to produce magnetic bearing systems, mainly for turbo-machinery.

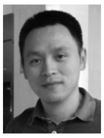
15 Growth

At the same time at the ETH the activities in magnetic bearings were growing as well, and in 1992, in order to have an organisational frame, we got a real and separate lab at the ETH and gave it a nice name, "International Center for Magnetic Bearings". There was a lot of activity, and we participated as well in several European Research Programs, cooperating with other colleagues, mainly with Professor David Ewins at the Imperial College in London, and with Professor Rainer Nordmann at the Technical University of Darmstadt in Germany. It resulted in very nice scientific results, touching for example topics such as the "All Electric Airplane of the Future", and of course I was happy about the generous funding as well.

In 2001 I had a visitor at the ETH, Prof. Yu Suyan from the TsingHua University in Beijing, Figure 22. And as I was about to retire from official duties at the ETH I accepted his offer to work in China, and, temporarily for about two years, I became a professor at the TsingHua University at the Institute of Nuclear and Novel Energy Technology INET. The task was challenging, and the cooperation with the team of very bright young people was very stimulating

This experience in China, with the concentration on teaching magnetic bearing technology, and the persistent good advice of Professor Yu Suyan, led to my decision to write a comprehensive book on magnetic bearings. I realised that it would be not professional and too ambitious for me to cover all the topics myself. I was very glad to find really experienced colleagues who agreed to contribute their knowledge. And with Professor Eric Maslen, I found an excellent co-editor and contributor, and we found careful reviewers from the AMB-community as well, Phillip Buehler from Mecos and Larry Hawkins from Calnetics. Finally with many specialised contributions the book was published in 2009 by the Springer-Verlag. Shortly after, the Chinese edition was published at the TsingHua University. The translator was Dr. Xu Yang, a former member of the research team. I met him again at the last ISMB in Beijing and he looks just as young as I remember him from 15 years ago.

When I was in China I had the opportunity to learn the Chinese language and I missed it. Now I am in Brazil and I am busy learning Brazil, as clumsy as my efforts still are. Therefore, as my advice to young people, I would I would recommend another lemma

Lemma 9: Don't be afraid to learn languages, and when you fail - fail better the next time!

This leads to my final remarks, my connections to Brazil:

16 Brazilian Connection

During my active time at the ETH I had quite often been visiting Brazilian universities, and I came to know that country reasonably well. I liked the people, the Mediterranean atmosphere - the winter in Switzerland can be quite cold - and I decided to move my winter home to Brazil and to keep in contact with my many Brazilian friends. There are, just to mention three of them, my old friend Professor Hans Weber, Professor of Mechanics at the PUC in Rio, who is the spiritus rector of the well attended German/Brazilian biannual conference "Diname" which I have been supporting for many years, there is Professor Walter Lindolfo Weingaertner, the head of the Precision Lab in the Mechanical Engineering Department at the University Federal Santa Catarina in Florianópolis, and last but not least there is Professor Richard M. Stephan, at the COPPE in Rio, working on Magnetic Levitation himself, the chairman of this symposium.

Now, after all, I would be quite able to dwell on prophesies and outlooks for magnetic bearings, looking to the future and not just talking about memories. But I would rather give another advice from lessons learned:

***Lemma 10: It is good to have friends*.**

Lemma 11: enjoy what you are doing