

Preface

Rotor dynamics is an important branch of dynamics that deals with behavior of rotating machines ranging from very large systems like the power plant rotors i.e., turbogenerators, to very small systems like a tiny dentist's drill, with variety of rotors such as the pumps, compressors, steam/gas turbines, motors, turbopumps etc. as used for example in process industry, falling in between. Speeds of these rotors vary in a large range from, may be a few hundred RPM to more than hundred thousand RPM. Complex system of rotating shaft(s) depending upon their specific requirements, are supported on different types of bearings e.g., the rolling element bearings, different kinds of fluid film bearings, foil and gas bearings, magnetic bearings etc. The present day rotors are much lighter, handle a large amount of energy and fluid mass, operate at much higher speeds, and therefore are most susceptible to vibration and instability problems. These have given rise to variety of interesting physical phenomena, some of which are fairly well understood today (for example the oil whirl/whip), while some are subject of continued investigation (fluid-structure interaction, various forms of instability, nonlinear and parametric effects, chaotic behaviour etc.). Research in rotor dynamics started more than one hundred years back. The progress of research in early years was slow. However, with the availability of larger computing power and the versatile measurement technologies, research in all aspects of rotor dynamics has accelerated over the past several decades. The demand from industry for light weight, high performance and reliable rotor-bearing systems is the driving force for research, and the new developments in the field of rotor dynamics.

The history and development of the subject of Rotor Dynamics is an interesting one. Early research with the first analysis of a spinning shaft by Rankine (1869) followed by the work of several researchers during the period of late 19th century and the early 20th century, clearly indicates that the researchers of that time struggled with deficient mathematical models, with an inadequate understanding of 'whirling/critical speed(s)', and were ceased with a practical question, whether or not a rotor could operate in a stable mode above these speed(s). Once these questions got addressed and the basic mathematical models were fairly well established and understood (Jeffcott 1919), research driven by the needs of a rapidly expanding industry progressed at an exponential rate.

That brings us to two important questions, (i) what have we achieved till now in terms of research in Rotor Dynamics and (ii) where are we heading to? An attempt was made to address these questions in a special session of nearly 3 hours duration, devoted to an open discussion on ‘Emerging Trends in Rotor Dynamics’. All the participants representing 21 countries (including India) shared their views. The first question pertains to identifying important milestones in the development of the area of Rotor Dynamics. The second question is an attempt to peep into the future. There was convergence of view that the future research has to be directed towards development of intelligent/smart rotor systems which will be extremely robust and ultra-reliable. This would require further research on diagnostic and prognostic aspects. To develop a better understanding of various phenomena in rotor systems, future research would require a highly interdisciplinary approach to account for the interactions of the rotor with the surrounding fluid medium and the support structure. Considerable electronics would be inbuilt into the next generation rotor systems; a new term ‘*rotortronics*’ was coined during discussion to represent such rotor systems as a class distinct from ‘*mechatronic*’ systems of today. No doubt, the long term requirements from industry will set the direction of future research, for example the development of micro rotors.

The preparations for the present symposium actually started as far back as in August 2006, after the first communication was received from IUTAM informing us about the acceptance of our proposal to organize the symposium. It was indeed a proud moment for us, particularly noting that the last IUTAM symposium on Dynamics of Rotors was held 35 years back in 1974 at Lyngby, Denmark; which was organized by Prof. Niordson, the Scientific Committee comprising of Professors Bishop, Crandall, Dimentberg, Tondl, and Ziegler. There were 87 participants from 18 countries.

The Scientific Committee comprising of Professors Nicolo Bachschmid from Italy, D.H. van Campen from The Netherlands, David Ewins from UK, Yukio Ishida from Japan, Chong-Won Lee from South Korea, Richard Markert from Germany, Agnes Muszynska from USA, Nalinaksh Vyas, Narinder Gupta and K. Gupta (Chairman) from India, was constituted. It undertook the most important task of finalizing the list of invited (keynote) speakers through mutual discussions extending over a period of more than a year. Finally 33 speakers accepted the invitation, out of which 31 speakers participated in the Symposium and delivered their keynote lectures of 30 minutes duration each. To encourage wider participation, the Scientific Committee also decided upon a format under which 40 poster papers were selected for presentation in two poster sessions. Finally 33 poster papers were presented. The authors of the poster papers were given an opportunity to make a presentation of 5–7 minutes duration before the display of their papers in a conventional poster session. Total of 45 papers are selected for the Symposium proceedings after a rigorous review of all the papers. This comprises of 30 invited (keynote) papers and 15 poster papers.

Presented papers on various important aspects of rotor dynamics, could be broadly classified as:

- Modelling and general aspects
- Developments in bearings
- Turbomachine blades
- Vibration control strategies
- Nonlinear dynamics
- Fault diagnostics and condition monitoring
- Cracked rotors

The symposium aimed at bringing together, leading researchers from all over the world to share their research experiences, and more importantly to set up the directions for future research in rotor dynamics. I have no hesitation in stating that the above objective was more than duly achieved.

The breakup of 36 participants from 20 countries other than India is given below:

Australia – 1, Austria – 1, Brazil – 1, China – 2, Czech Republic – 1, Denmark – 1, Egypt – 1, France – 1, Germany – 6, Greece – 1, Israel – 1, Italy – 3, Japan – 1, Korea – 1, Lithuania – 2, Poland – 3, Sweden – 1, Switzerland – 1, UK – 3 and USA – 4.

In addition to this, there were 50 delegates from India representing Indian industry, academia, and R&D laboratories.

An important highlight of the symposium was an open session to discuss ‘Emerging Trends in Rotor Dynamics Research’ all over the world. The session was chaired by Prof. Gordon Kirk, and after his opening remarks, he invited several speakers to initiate the discussion. This was followed by an intense discussion on Emerging Trends in Rotor Dynamics.

First and foremost, I wish to thank Indian National Science Academy (INSA) for making this symposium possible by submitting and presenting our proposal to IUTAM Bureau. I also wish to thank the various agencies in India namely, the Council of Scientific and Industrial Research (CSIR), All India Council for Technical Education (AICTE), Indian Space Research Organization (ISRO), Bharat Heavy Electricals Ltd. (BHEL), the Triveni Engineering and Industries Ltd., Indian Institute of Technology (IIT) Kanpur, Altair Engineering India, and ANSYS India, for providing financial support towards the organization of symposium.

I am grateful to my colleagues and associates, in particular to our Director and Patron of the Symposium, Prof. Surendra Prasad, the Head of Mechanical Engineering, Prof. J.P. Subrahmanyam, members of organizing committee, Professors Chandra Shakher, S.P.Singh, S.K. Saha, Sudipto Mukherjee, Drs. A. K. Singh, S.V. Modak, J.K. Dutt, H. Hirani, and organizing secretary Dr. A.K. Darpe, for their continuous support throughout the period of organization of the Symposium. The prompt advice and guidance received throughout from Prof. J.S. Rao, who also agreed to be the co-patron of the symposium, is gratefully acknowledged. Thanks are also due to Mr. K. N. Madhu of Vibration Research Laboratory, staff of various sections and units of the Institute, and all the student volunteers, for their untiring efforts.

I am particularly grateful to all the members of the Scientific Committee for providing support and valuable guidance on all important matters beginning with the finalization of the format of the symposium, then the list of invited speakers, and in the end the organization of symposium sessions. Finally I wish to thank all the invited speakers who delivered their keynote lectures, and all participants and authors for their efforts in contributing the papers to the symposium, and all reviewers for their invaluable help in selection of papers for the symposium proceedings.

New Delhi, March 2010

K. Gupta

Welcome address by Professor Surendra Prasad, Director, Indian Institute of Technology (IIT) Delhi

Distinguished delegates and participants of IUTAM, chief guest Professor D.V. Singh, distinguished faculty colleagues, friends, ladies and gentlemen;

It is a matter of great pleasure for me to welcome you to IIT Delhi, on this very significant occasion of the organization of this IUTAM meeting on Rotor Dynamics, being held for the first time in India. I know how hard my good friend and colleague, Professor Kshitij Gupta from the Department of Mechanical Engineering, Professor N.K. Gupta, Emeritus Chair Professor in the Department of Applied Mechanics, and an esteemed mentor and senior ex-colleague of IIT Delhi, Professor J.S. Rao, have worked together with many other colleagues from India, to bring this meeting to New Delhi, and hence to IIT Delhi. On behalf of the entire Institute Community, I extend my thanks and greetings to the organizers of this meeting for giving us the privilege to host a galaxy of eminent individuals and scientists in our lovely campus.

All of us are aware of the high standards of the meetings of ICSU in general, and IUTAM in particular. These meetings are outstanding events with high scientific impact, and we are proud that with the efforts of our colleagues we have been able to hold this meeting in our campus. Like many other similar meetings that we hold in our campus every year, this too will be an occasion for our students and faculty to savor the scholarship of international experts, while also using this opportunity to develop international linkages for collaborative research.

Rotor dynamics is an important area not only for research in academic Institutions, but also for the Industry. Rotors find application in practically all machinery, and in all types of industries. Often a rotor forms a critical component of these machines and plants. Several catastrophic accidents, for example in power plants, in all parts of the world triggered by failures in rotors have been reported in published literature.

Traditionally rotor dynamics has been an area of active research in several departments and centers (Mechanical Engineering, Applied Mechanics, and Industrial Tribology Machine Dynamics and Maintenance Engineering Centre ITMMEC) of IIT Delhi, for the past several decades. There has been considerable interaction with power sector on problems of vibrations and rotor dynamics. BHEL, a major

manufacturing industry for power plant equipment in India, has created a Chair in IIT Delhi with an objective to provide an impetus to research in the area of rotor dynamics. It is just befitting that this prestigious symposium on Rotor Dynamics is being held at IIT Delhi, with the primary objective to have on a single platform, leading researchers from all over the world to share their experiences and to set the directions for future research.

As a host of this important meeting, it is my privilege to share some thoughts with our distinguished guests today about IIT Delhi. But before that, it would be appropriate to tell our distinguished Guests something about the IIT system. The idea of Indian Institutes of Technology was born even as the country was achieving its freedom from centuries of foreign rule, and was turned into a reality soon after Independence. Our first Prime Minister, Pundit Jawahar Lal Nehru, strongly believed in the power of Science and Technology to transform the country's fortunes, and therefore supported this initiative enthusiastically with a dream to see these Institutes come up to the international level and serve the country in its march towards prosperity. IIT Delhi was the fifth such Institute to come up in 1963, although our Institute was born a little earlier as the College of Engineering and Technology in 1961. In this brief history of 50 years, IIT Delhi has indeed come a long way and we have not only successfully established our presence in the international arena, but have been ranked amongst the top 50 technological universities by the Times Higher Education Supplement, and other international rankings. The IIT system has recently expanded from a system of seven Institutes, to one of 15, in view of the high demand for quality education in science and technology in the country.

Let me now briefly tell you a little about IIT Delhi, but instead of giving you data and statistics, which you can find on our website, I would like to talk about the three pillars on which we stand and which, in some sense, also represent our core strengths.

First and foremost, IIT Delhi stands for free thinking. We aspire to be known as a place where exploration of truth and knowledge is pursued earnestly, where young people can be freed from the presumptions and prejudices with which they were raised, freed by the power of ideas to pursue their own path in life - a place where our students feel inspired to develop an approach towards life and profession that brings dignity and honor to human affairs. So, while we share the universal dreams of all great research universities of the world and wish to be known as a place where science, technology, humanities and management, are pursued at their frontiers to bring benefit to the society and mankind, we equally wish to try to be a place where the mind becomes free in the true sense of freedom spoken of by the poet Laureate Rabindra Nath Tagore.

Second, IIT Delhi stands for scholarship and learning. Needless to say that our faculty, who are selected and rewarded for these virtues, and our students who are amongst the best that any institution can wish for, make it easy for us to pursue these goals.

Third, IIT Delhi stands for a value system which recognizes the important challenges which our planet and society face today – the challenges of energy security, environment, climate change and in our part of the world, the challenges of inequity,

poverty and lack of access to basic amenities and quality education. No doubt some of these challenges have surfaced as a result of indiscriminate use of technology and human greed. But we believe that the answer to these ills lies not in less, but more technology, and of course, more scientific and value-based management of human affairs, which would make it possible for mankind to work its way towards sustainable development and growth, rather than the unsustainable and chaotic growth of the last few decades with its dire consequences.

Ladies and gentlemen, I hope this brief introduction about IIT Delhi will be useful to you. I do hope that you will find not only the scientific deliberations of this meeting to be useful, but also that you will make many friends in this part of the world.

Welcome address by Professor Narinder K. Gupta, Member IUTAM Bureau, and Vice-President INSA, IIT Delhi

The Chief Guest Prof. D. V. Singh, Prof. Surendra Prasad, Director IIT Delhi, Prof. J. S. Rao, Prof. J. P. Subrahmanyam, Prof. K. Gupta, Chairman of the Symposium, distinguished delegates, ladies and gentlemen;

On behalf of the Indian National Science Academy (INSA) and International Union of Theoretical and Applied Mechanics (IUTAM), I am delighted in welcoming you all to this important IUTAM symposium on Emerging Trends in Rotor Dynamics.

This symposium is special in many ways and leaves its imprint in the process of our (Indian) participation in IUTAM activities. IUTAM is one of the adhering bodies of ICSU, the International Council of Science, formerly called International Council of Scientific Unions.

ICSU, was founded in 1931 to promote international scientific activities in different branches of science and applications for the benefit of humanity. Its membership consists of National Scientific bodies and also International Scientific Unions. Wide spectrum of scientific expertise drawn from such membership allows ICSU to address major international, interdisciplinary issues which requires participation of scientists from various disciplines and various countries. India has been its member right from its inception and has been participating in its various programmes actively over the years. Prof. M. G. K. Menon and Prof. G. Mehta, both past Presidents of INSA, have been Presidents of ICSU during 1989–1995 and 2006–2008 respectively.

IUTAM came in to being in 1946 with the aim of promoting development of mechanics, both theoretical and applied, in various ways which include forming linkages between scientists and holding congresses and symposia. Its plan seems to have been initiated by ICSU. The history of conferences which made IUTAM possible dates back to 1922 – with the one organized by von Karman at Innsbruck. Conferences thereafter were organised every four years till 1938 (in Zurich (1926), Stockholm (1930), Cambridge UK (1934), and Cambridge USA (1938)). Then there

was a disruption due to the world war. The first congress of IUTAM was held in 1948, and INDIA became member of IUTAM in 1950. Till 1949, there were only 3 adhering bodies. Today IUTAM has nearly 450 members representing 55 countries and 18 affiliated organizations.

Mechanics in India in those years had found its place as an important discipline by itself. There were major initiatives for bringing together scientists working in various disciplines of Mechanics and for promoting Mechanics in its various forms. Indian Society of Theoretical and Applied Mechanics (ISTAM) came in to being in 1955 through the efforts of Prof. B. R. Seth of IIT Kharagpur. The first congress of ISTAM was held in the November of 1955 in IIT Kharagpur under the Presidentship of Prof. K. S. Krishnan, renowned Physicist, who had worked with Prof. C. V. Raman. Prof. B. R. Seth was its first Secretary, who later became its President in 1964. Since then, ISTAM has been holding its annual congresses every year and over the years it has been contributing to the cause of Mechanics. Prof. Seth represented India in the IUTAM during the early years.

From 1968, Indian National Science Academy (INSA) was given the responsibility of representing India in ICSU and its adhering bodies. INSA has thus been responsible for representing India in IUTAM. National committees were formed which are expected to establish close linkages with the international unions and with the scientists and professional bodies within the country. IUTAM national committees over the years have been constituted which encourage the participation of Indian Scientists in IUTAM Congresses and promote Mechanics through Symposia, Workshops and Congresses within the country. Prof. Roddam Narasimha, has been representing India and has been member of the IUTAM Bureau in the past.

Our societies and institutions have been holding National and International conferences and symposia on various areas of Mechanics in India with great success, and participation from within the country and abroad has been quite good. However, in the last 6 decades of our association with IUTAM, we have yet not organized any quadrennial congress of IUTAM in India. Though in the past we have organized IUTAM Symposia/ workshops in India, but their total number has relatively been not as much.

Prof. D. V. Singh our Chief Guest today, has been associated with ICSU bodies for almost three decades. We have lately been making efforts in enhancing our participation in IUTAM activities. Prof. K. Gupta worked out the proposal for the present Symposium on Emerging Trends in Rotor Dynamics. Soon there were more proposals from other parts of India. Fortunately we were able to present four proposals over two IUTAM meetings and three of them were approved – this symposium is one of those.

Therefore, personally and on behalf of INSA and IUTAM, I thank the Director Prof. Surendra Prasad and Prof. K. Gupta for making this symposium possible to be held in the Indian Institute of Technology Delhi. The ball is set rolling and we do hope that such symposia on various specializations of Mechanics will henceforth be held in IIT Delhi or other parts of the country every year. I must specially thank Prof. D. V. Singh and Prof. J. S. Rao for being with us on this occasion.

Today, we have nearly 36 distinguished scientists from 20 countries, and several distinguished researchers from India. I am conscious that organizing an event of this magnitude is not very easy. Prof K. Gupta and his colleagues have certainly done a splendid job.

I end by wishing you all a very pleasant and memorable stay, and with the hope that the symposium is a big success.

Address by the Chief Guest, Professor D. V. Singh

Professor Surendra Prasad, Prof. J. S. Rao, Prof. N. K. Gupta, Prof. J. P. Subrahmanyam, Prof. Kshitij Gupta, Distinguished Delegates, Ladies and Gentlemen:

I consider it my privilege and pleasure to be invited to the IUTAM Symposium on “Emerging Trends in Rotor Dynamics”. I would like to compliment IIT-Delhi for hosting this IUTAM Symposium, which has attracted leading researchers in the field of rotor dynamics from twenty countries. Hosting a IUTAM Symposium is an honour and a recognition of the high standing of the Institute in the subject of the Symposium.

Recalling the history of IUTAM Symposium, Prof. N. K. Gupta pointed out that the first IUTAM Symposium was held in the year 1922 in Denmark. Prof. Kshitij Gupta mentioned that the first IUTAM Symposium on Rotor Dynamics was held thirty five years ago. I have found that the best glimpses of history of a subject area can be had in the prefaces of books.

I would like to share with you a few pieces of history of rotatory motion. By the middle of the eighteenth century the dynamics of translation of bodies took much of the form it now has. But the scientists of the day did not quite know how to treat general cases of rotation. They recognized that “there was some thing about rotation, either its mechanical laws or just its mathematical description, which some how made the rotation problem of a higher order of difficulty. We now know that problem is in mathematics and not in physics”. The problem is still with us when dynamics of complex multibody systems, within which rotation of one or more of its parts occurs, is to be analysed and understood.

The history of rotor dynamics shows interplay of theory and practice. Supercritical speeds of spinning shafts attracted attention of scientists since the middle of the 19th Century. I am referring to the analytical work of Rankine (1869) and experimental work of (Carl Gustav) De Laval (1889), and of Dunkerley (1895). Kerr published his work in 1916 showing evidence of a second critical speed.

Commissioned by the Royal Society of London to resolve the conflict between theory and practice, Henry Jeffcott published a paper, now considered a classic, in the *Philosophical Magazine* in 1919 in which he confirmed the existence of stable supercritical speeds. August Föppl had earlier published much the same conclusions in 1895, but history largely ignored his work.

Post Jeffcott and until the start of the Second World War II, a lot of work in the area of instabilities and modeling techniques was done culminating in the work of Prohl and Myklestad which led to the Transfer Matrix Method (TMM) for analyzing rotors. Now of course FEM is generally used for rotor dynamics analysis.

The rotor-bearing systems of modern rotating machines have interesting and challenging complexities. The challenging nature of rotor dynamics problems have attracted many scientists and engineers whose investigations have contributed to the impressive progress in the study of rotating systems. With the advancement in high-speed machinery and increase in their power/ weight ratio, the determination of the rotor dynamic characteristics through reliable mathematical models have become more important. The advancement in modern instrumentation and computational capabilities has helped in implementing simulation techniques of these complex models. Modern machinery must fulfill increasing demands concerning durability as well as safety requirements. On-line condition monitoring strategies are becoming increasingly commonplace in a bigger range of systems.

Rotors are often prone to mechanical vibrations, which may lead to machine failure. Correction is only possible when proper and accurate diagnosis is obtained through understanding of rotor operation and all of the potential malfunctions that may occur. Mathematical modeling, in particular modal modeling, is key to understanding the observed phenomena through measured data and for predicting and preventing failure.

Rotor dynamics considerations that are important to successful design or troubleshooting of a turbomachine include bearings, fluid seals, rotor geometry configuration, and rotor environment, which affect system behaviour and can be computationally handled for system analysis.

Rotating machines, depending on their environment, could be subjected to fluid-structure interactions, electromagnetic forces and pressure fields, which result in complicated vibration patterns that are to be resolved to distinguish the physical attributes of the machines.

The unsteady and non-linear approaches allow simulation of dynamic response of various systems. So it is possible to create calculation based diagnostic algorithms without numerous expensive specific experiments.

Recent developments in microfabrication techniques permit production of complex geometries and micro scale systems. Many researchers have been working on the development of devices such as micro electric motors, micro turbines, micro pumps, micro reaction wheels, micro gyroscopic sensors and micro spindles. These systems require high speed rotating parts to achieve the same performances as in macro level. Classical rotor dynamic modeling approaches are not sufficient for micro systems due to various effects becoming crucial in small scale, such as viscous forces, which are more important at small scale. Heat transfer is another important aspect since micro devices operate in a much smaller design space than do large-scale machines. The high angular speeds require un-traditional levitation systems for low friction operation. More accurate dynamic analysis tools are needed for the design of micro systems with high speed rotating parts considering multi-physical effects and to tackle the problems of rotor dynamics such as imbalance and eccentricity.

One of the critical technology areas is aircraft engine design and engine rotor dynamics. Improvements of engine dynamics models and their validation continue to be subjects of research, where the needs are to predict dynamic performance to produce lighter, more efficient engines, through the development stage, where more rapid resolution of problems will contribute to reduced time and cost for manufacture and reduction of maintenance cost.

In rotor dynamics problems, often empirical and intuitive methods are risky and can be avoided since predictions of rotor dynamics analysis are quite accurate if accurate values of machine parameters are used in the mathematical model. These predictions some time are contradictory to intuition and disprove them. For example, damping in the rotor of a turbomachine can produce a violently unstable whirling motion at high speeds.

Commercial softwares are now available for advanced modeling and simulation of all kinds of bearings (foil bearings, hydrostatic bearings, hydrodynamic bearings, magnetic bearings and rolling element bearings), seals (labyrinth, honeycomb, and damping seals), and rotor dynamics design and analysis. Evaluations can be completed quickly using advanced steady-state and time transient solutions as part of their bearing, seal, and vibration analysis codes. Advanced Nonlinear software solutions (e.g., ADINA, Nastran) enable analysis of models with nonlinearity from contacting parts, material nonlinearities and geometric nonlinearities (large deformations).

With reference to modern computer models, Dara Childs could be quoted, “the quality of predictions from a computer code has more to do with the soundness of the basic model and the physical insight of the analyst. Superior algorithms or computer codes will not cure bad models or a lack of engineering judgment.”

Though the knowledge and understanding of rotor dynamics and stability have steadily increased through the years, much more work is needed to fully understand the dynamics profile of high speed rotors.

In the above context, the importance of research in rotor dynamics becomes much more to meet the needs of the machines of the future for industries, power plants, Space and Defense.

I have scanned the abstracts of the papers to be presented in the Symposium, which were sent to me by Prof. K. Gupta. These papers offer the excitement of the current research being done by the experts in the area in several countries that are represented here. I am sure that the Symposium will be highly successful in achieving its objectives and the deliberations of leading experts in the field of Rotor Dynamics will be very fruitful.

With my best wishes for the success of the Symposium, it is my privilege to inaugurate this IUTAM Symposium.

Thank you.

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