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Introduction to Micromechanisms and Microactuators

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Introduction to Micromechanisms and Microactuators

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Preface

Mechanisms have been used since time immemorial for various tasks. Apart from being indispensable for all kinds of mechanization, mechanisms have always fascinated the human mind. Perhaps, in a very rudimentary sense, mechanisms remotely resemble living objects. In the past, mechanism design and inventing new mechanisms were important activities not only for engineers but also for scientists. In fact, the contributions of mathematicians to mechanism theory have really helped this branch of engineering science grow. With the progress in technology, the role of automation and mechanization increased in importance and courses on Theory of Mechanisms and Machines occupied a major share of all Mechanical and Aerospace Engineering curricula.

However, from the second half of the 1970s and early 1980s a kind of gloom descended on the kinematics community. This was primarily because of the rise of microelectronics, programmable logic controllers, and computer control and numerical control (NC) technology. The need for careful and meticulous mechanism synthesis became redundant as any kind of motion and trajectory could be generated with extreme accuracy using multiple servo drive systems controlled by computers. Many universities the world over gradually removed the subjects in the domain of kinematics and mechanism theory from the curricula. Apart from being very accurate the multiple-drive-based NC motion generation has the added advantage of having the ability to quickly change from one geometric characteristic to another without any change in the hardware. This led many kinematicians to think that ‘mechanism theory’ was destined to become a dead subject.

Fortunately, along with the computer-based Second Industrial Revolution (which was a threat to the continued existence of the subject) came the trend of miniaturization. Though initially this trend was confined to electronic circuits and devices only, soon it spread to other fields. Now it is felt by many that once miniaturization revolution spreads to other fields the process of the Third Industrial Revolution will begin. The main feature behind the forthcoming revolution in technology will be based on miniaturization of three-dimensional machines and devices capable of manipulating material at the micro, nano, and even molecular levels. The pressure of miniaturization increased due to the huge success of miniaturized electromechanical integrated systems and a new branch of technology—Micro Electro—Mechanical Systems (or MEMS)—is emerging as a powerful entity for controlling the world economy. These are primarily lithography-based two-and-half-dimensional miniaturized devices. But the trend is already rearing its head which indicates the bright future for miniaturized machines and mechanisms also. And for the delight of members of the near-extinct community of kinematicians, the subject of mechanism synthesis has once again become important for applications in miniaturized machines and mechanisms. Using multiple-drive-based motion generation became infeasible and the technologists had to once again depend on synthesized mechanisms to generate the desired motion and trajectories as these became the only practical solutions. It can be safely stated that the rebirth of the subject 'kinematics and mechanism theory' has been possible because of the emergence of 'micromechanisms'.

Expectedly, the rebirth of the subject has brought along a number of fundamentally new concepts and paradigm shifts, which influence the basic configuration design, actuation, and fabrication. On many occasions engineers and technologists have started using principles from life science for the functioning of micromechanisms and microactuators. There are major changes from the point of view of the material used and the energy sources employed. Thus, it will be wrong to think that micromechanisms are just the miniaturized versions of their similar macroscopic counterparts.

As it happens with many new emerging branches of science and technology, in the emerging area of microsystems technology also, the subdivisions are not well-classified and considerable nebulosity exists in many definitions and characterizations. Because of continuous scaling down of microelectronic chips, industrial fabrication units started to become obsolete because of their limitations on size capability. These industrial units became useful for fabricating MEMS devices as, unlike microelectronic chips, these devices did not require a very high level of miniaturization. Since MEMS came directly as a product from the obsolete and abandoned microelectronic industry the growth of the subject has been fast and the expansion of its market very rapid. As a result, at present MEMS devices occupy a major part of the microsystems technology. The emergence of micromechanisms has been relatively slow because of their more involved fabrication process. Most often the subject 'microsystem' deals heavily with the discussions of MEMS technology. But it should be noted that the current area of microsystems, on the whole, consists of both MEMS devices (most of which are for sensing) and micromechanisms (which really perform the manipulation of material at the micro, nano, and molecular levels).

This introductory volume deals with primarily the active micro devices—micromechanisms—and the microactuators for driving the mechanisms. The design problems and concepts used in micromechanisms are substantially different from the traditional passive devices for sensing. It is hoped that this volume introducing the rudiments of micromechanisms and microactuators will be helpful to students of this subject and can be used to develop an introductory course.

Up till now, the development of the subject of micromechanisms has been somewhat disorganized in manner. A number of basic aspects are still in their infancy. Apart from this the R&D work on micromechanisms is mostly based on individual problems and specific systems. So, it is not always easy to identify a generalized discussion applicable to the whole class of these systems. In this introductory book, we attempt to identify the important aspects of miniaturization as it is expected to bring revolutionary changes in technology in the years to come. A separate chapter is included to discuss scaling laws as this topic is of utmost importance as far as miniaturization and microsystems are concerned. To make the volume self-contained, we have presented material on the general theory of mechanisms and techniques for synthesis of conventional mechanisms in the introductory chapters. Many micromechanisms are initially designed following the approaches adopted for their macroscopic counterparts. A general introduction to micromechanisms is given in a chapter preceding the chapter on their design. The chapter on design is followed by a chapter presenting some topics on the dynamics of micromechanisms.

The drive systems and actuators for micromechanisms are of extreme importance, as the impact of scaling effects is maximum on the actuation principles. Besides, there are many fundamentally new approaches for actuating micromechanisms. As it may have already become clear to many, when designing micromechanisms, a lot can be learned from the living world. Keeping this in view, similarity with biological systems has been pointed out in sections on design and structure of micromechanisms and microactuators. The chapter on microfabrication also discusses topics like 'self-assembly' that is closely related to life science.

Finally, the text presents the major fabrication techniques and the future possibilities.

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Contents

About the Authors

Amitabha Ghosh did his Bachelor's, Master's, and Doctoral degrees in Mechanical Engineering from Calcutta University in 1962, 1964, and 1969, respectively. After serving as a Lecturer in Mechanical Engineering at his alma mater, Bengal Engineering College, Shibpur (now an Institute of National Importance—Indian Institute of Engineering Science and Technology, Shibpur) from 1965 to 1970 Prof. Ghosh joined the Indian Institute of Technology, Kanpur, in January 1971 as Assistant Professor. Since June 1975 he served at the institute as Professor of Mechanical Engineering till his retirement in 2006. During 1977–1978 Prof. Ghosh visited RWTH Aachen as a Senior Fellow of the Alexander von Humboldt Foundation and, subsequently, he visited RWTH Aachen with Humboldt fellowship many more times till 2012. He served the Indian Institute of Technology, Kharagpur, as Director from 1997 to 2002. His primary areas of research include Manufacturing Science, Robotics, Kinematics and Mechanism Theory, and Dynamics of Mechanical Systems. Professor Ghosh has written a number of textbooks which are very popular both in India and abroad. He has guided many master's and doctoral students and has published a large number of research papers. He received many academic awards including a number of Calcutta University Gold Medals, D.Sc. (h.c.), Distinguished Teacher award from IIT Kanpur and Award for Excellence in Research by the National Academy of Engineering. He is a fellow of all the four national science and engineering academies in India.

Burkhard Corves is currently University Professor and Director of the Department of Mechanism Theory and Machine Dynamics at RWTH Aachen University, Germany. He received his Ph.D. in 1989 from the same university. Dr. Corves has to his credit several books and almost 200 technical papers covering different topics such as robotics, cam mechanism, glass machinery, pneumatic mechanisms, computer-aided graphical analysis and synthesis in mechanism theory, mechatronic development, and machine design strategy. He also actively teaches courses in machine and mechanism design, kinematics, dynamics, and robotics.

Chapter 1
Introduction

Abstract This introductory chapter provides a brief outline of the kinematic analysis and synthesis of plane mechanisms. In MEMS devices, the system's functions mostly depend on elastic deformation of simple elements like cantilevers. However, in case of micromechanisms, a system's operation depends on the coordinated movement of different links like a normal macroscopic mechanism. The only difference lies in the fact that the joints are replaced by flexural hinges. This chapter illustrates the methods of kinematic analysis. A later section presents methods of kinematic synthesis to achieve desired movements. The same methods are in general applicable to mechanisms of microscopic sizes. A brief discussion on actuators is also presented.

Keywords Mechanisms · Kinematic analysis · Dimensional synthesis · Actuators

1.1 Introduction

Since the dawn of civilization, man has been trying to make use of physical laws and principles for accomplishing useful tasks. In many occasions, the effort goes in achieving results which are beyond the capacity of unaided human beings—be it in moving fast, applying large forces, making accurate movements and so on. The idea of using appliances came with such objectives, and the origin of mechanisms and machines can be traced to that. It is known to us very well that one can draw a perfect circle using a compass irrespective of her/his individual drawing skills. A child can break a nut with a crusher irrespective of his/her personal strength. Thus, appliances can enhance the typical human capabilities.

Apart from using mechanical devices for improving and enhancing human physical abilities, devices or appliances had been used to impress common man by exhibiting miraculous phenomena—such as automatic opening of doors. This was the case with the group of people (mostly priests of ancient temples) primarily to command respect of common man.

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All such devices and appliances started being called machines, and many such machines for lifting heavy objects, generating mechanical power from flowing fluids, developing large forces and making warfare were developed since antiquity.

Of late, the trend has been to design and develop machines and devices of extremely small sizes. The reasons for such trends are many as will be discussed later in this volume. However, such small-sized machines and devices need special considerations for their design and development. This volume is an attempt to present a rudimentary introduction to the subject. Though the sizes and linear displacements differ enormously for macroscopic mechanisms and micromechanisms, their basic nature of functioning has considerable similarity. So, an introduction to the basic concepts of mechanisms is desirable before micromechanisms are taken up for discussion.

1.2 Mechanisms and Machines

For understanding micromechanisms and microactuation principles, it is essential to have a clear idea about the basic principles of conventional mechanisms and machines. This section is devoted to some foundational concepts that are essential to design, develop and understand mechanisms and machines.

1.2.1 Definition and Types

Although everyone has a vague idea about mechanisms and machines, a very scientific definition is necessary for the professionals. A mechanism is an agglomeration of several interconnected rigid bodies so as to transfer and transform mechanical movements and motions. It is also to be noted that some definite relationship must exist between the input motion and the resulting output movements. In cases where there is no significant force or power transmitted and the primary objective is to produce a desired movement only, the device is called 'mechanism'. On the other hand, if the objective includes transmission of substantial power doing some useful work, the device is called 'machine'. However, in both cases, mechanical movements of desired characteristics are essential features. It is, thus, clear that all machines must be mechanisms but not the vice versa.

As there exist hundreds of thousands type of mechanisms and machines, it is not a simple task to classify all of them. An attempt can be made for some broad classification at this stage. The most important characteristic that differentiates all mechanisms into two major classes—planar mechanisms and spatial mechanisms—is the spatial nature of motion. In case of plane mechanisms, all points of all the members of the device move in parallel planes. So, it is possible to observe the actual motions of all points in one view. It also ensures that motions of all points are either coplanar or confined to parallel planes. On the other hand, in spatial mechanisms, different points of the device move in a general fashion or, in the simplest case, in planes which are not parallel. Alternatively, planar mechanisms may be called two-dimensional mechanisms and spatial mechanisms may be called three-dimensional mechanisms. It is needless to emphasize that analysis and design of spatial mechanisms are far more complex than those in case of planar mechanisms.

Though members of a mechanism are generally rigid bodies, there are some situations where some members show flexibility which is essential for proper functioning. Such mechanisms are called compliant mechanisms. Compliant mechanisms play a very important role in the field of micromechanisms as will be discussed later.

1.2.2 Kinematic Pairs and Kinematic Chains

To begin with, the bewildering variety and complexity of hundreds and thousands of mechanisms create an impression that it is next to impossible to find any order in the matter. However, if one carefully identifies the basic building blocks of any mechanism, a considerable order can be created in the chaotic complexity. As mechanical motion can be transferred from one body to another by physical contact, only this contact of two bodies constitutes the basic building block of mechanisms and are called 'kinematic pairs'. When the contacting surfaces are of geometrically conforming shapes, the contact is over a surface as shown in Fig. 1.1.

In the case shown in Fig. 1.1a, the surfaces are flat and the relative motion of body 1 with respect to body 2 is along a straight line in case of planar mechanisms (where all objects move in two dimensions only). These kind of kinematic pairs are called 'prismatic pairs'. In the other case, the contacting surfaces are cylindrical in shape with same radii. Thus, the relative motion is circular, and the pair is termed as 'revolute pair'. Both these pairs belong to the same class called 'lower pair'. A major difference between 'prismatic' and 'revolute' pairs needs to be discussed here. Figure 1.2 shows a typical prismatic pair (slides) and a revolute pair (usually a hinge).

In case of slides, the force between the two elements 1 and 2 is the friction force ($=\mu N$) where μ is the coefficient of friction and N is the normal force between the

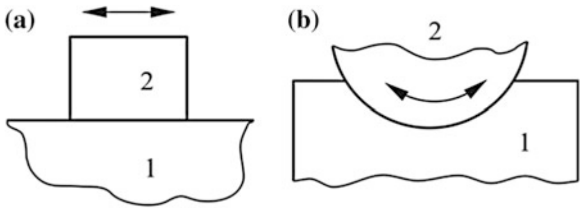

Fig. 1.1 Kinematic pairs with geometrically conforming shapes. **a** Rectilinear movement. **b** Angular movement

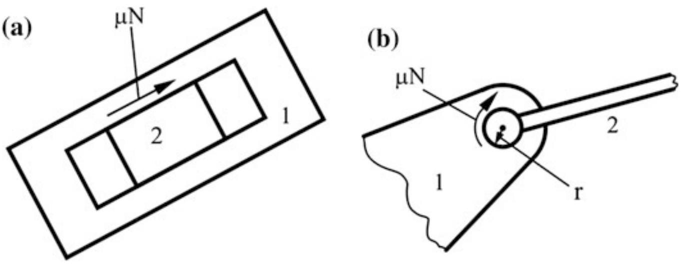

Fig. 1.2 Friction in lower kinematic pairs. **a** Prismatic pair. **b** Revolute pair

elements. In the hinge joint, the relative motion is angular and the frictional torque between the two elements is μNr where r is the radius of the cylindrical pin. Since r is typically much smaller compared to other dimensions of a mechanism, the frictional resisting torque is very small and does not impair the relative motion. This is a great advantage, and therefore, hinge joints (i.e. revolute pairs) are generally preferred over prismatic pairs.

The contact between two adjacent elements of a kinematic pair can be between surfaces which do not conform in shape as shown in Fig. 1.3. In such cases, the contact is along a line (or at a point) and not over a surface.

Such kinematic pairs are called ‘higher pairs’. It is readily seen that in case of lower pairs , the degree of freedom of relative motion between the elements is one (when planar mechanisms are considered) and that in case of higher pairs, it is two. Contacting cam and follower and contacting gear teeth are common examples of higher pairs.

A series of kinematic pairs constitutes a kinematic chain as indicated in Fig. 1.4. In cases shown in Fig. 1.4a, b, only lower pairs are used and often kinematicians prefer to call such mechanisms as ‘linkages’.

In Fig. 1.4c, the kinematic chain contains both lower and higher pairs. It should be further noted that a kinematic chain can be either open (as shown in Fig. 1.4a) or closed. A kinematic chain is as such of no use in transferring or transforming motions. For useful work to be done, it is essential to fix one link and this leads to a mechanism. The process of grounding one link of a kinematic chain is called ‘kinematic inversion’. Different inversions of a kinematic chain may give rise to different mechanisms. After inversion, if there is a unique relationship among the

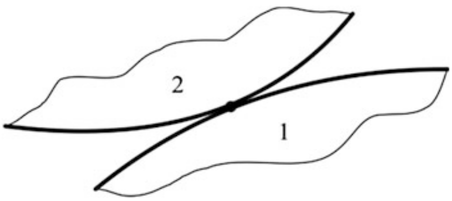

Fig. 1.3 Higher kinematic pair