Geared Designs from the Past for Today Inspiration

Marco Ceccarelli and Fernando Viadero Rueda

Abstract This paper is a short-illustrated survey of past designs in gearing systems as a tribute to the memory of Prof. Veniamin Goldfarb, who included in his expertise on Gearing Technology also its History. The paper outlines main gear designs that can be considered milestones in the development of Gearing Technology up today. Design aspects and evolutions are discussed with illustrative examples to show main aspects of the evolution of design solutions and expertise in geared systems with indication of challenges and future trends for a successful development of the field and its application to modern machine technology.

Keywords Gearing technology · History of gears · History of MMS · History of IFToMM · Prof goldfarb

1 Introduction

Gear transmissions are mechanical systems used in various applications to transform and transmit power or motion.[1] The objective of gear transmissions is to allow the transmission of movement between shafts through the contact of different elements

[1]Prof. Veniamin Goldfarb (1940–2019) was a worldwide reputed scientist of gearing systems with a successful activity of technological transfer also with a production of industrial products, at Institute of Mechanics of Kalashnikov Izhevsk State Technical University. He was also a leader in IFToMM—International Federation for the International Federation for the Promotion of Mechanism and Machine Science (MMS) as being Vice-President and Chair of Technical Committee for Gears with several international activities among which it is to note that he was the initiator of SIOMMS, the IFToMM Student Olympiad on MMS.

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called teeth. These transmissions are present in sectors such as automotive, energy, agriculture, manufacturing or aerospace. Gears have always been considered fundamental for machines and for the innovative development not only of mechanical transmissions but also of new machine solutions and their evolution. This importance is also recognized on a historical level as it is outlined in the history of engineering both in technical or specific monographs in the history of transmissions, for example [1–3], as in encyclopedic works on the history of machines and inventions, for example [4–6].

In the general treaties, however, a fundamental role of gear technology is not clearly recognized, so much so that even today in the research funding programs the issues relating to mechanical transmissions and particularly gears are not considered of priority but they tend to think that this technology is now so mature that it does not require further funding and can only be left to commercial industrial development for the design and application of gears. Historical development, however, indicates that gears have always had to support both the design of the machines and the materials used in them with innovative solutions as well as responding to the needs of greater functional and energy efficiency which today is even more stringent, especially when designed as linked to problems of sustainable energy and pollution that are due precisely to the intrinsic dissipative phenomena in power transmission.

Among the classic authors of research on gear drives are famous names such as Olivier, Willis, Giulio, Buckingham, Wildhaber, Dudley, or Musser, who contributed significantly to gear developments since the early days of Industrial Revolution up today. However, in the last forty years and due, among other things, to the growing demand for quieter transmissions, with lower development and maintenance costs, it has led to a huge amount of researches and publications on gears whose wide variety in this paper is shortly described as per the future trends in the field of gear research.

In this work with an illustrative approach we want to outline this fundamental role and the evolution of concepts and solutions for gears that have led to a significant development in the technology of mechanical systems up to today's robotic and mechatronic systems in which a functionality can still be recognized essential due to mechanical transmissions when such systems perform mechanical functions with transmission of movement and force. The examination that is reported in this paper also wants to indicate how solutions of the past contain concepts and even solutions of current interest that can be used and further elaborated to obtain new solutions and also to update the successful designs of the past towards applications with increasingly higher structural and functional characteristics.

2 Gear Solutions and Applications

Gears have been fundamental since the first mechanical transmissions which led to the development of the first machines both in terms of efficiency and functionality. The solutions of antiquity remain mostly bibliographic sources with few archaeological findings which, however, surprisingly show technological levels that were unthinkable for those times until recently.

An emblematic example is shown in Fig. 1 regarding the Antikythera mechanism, dated of 2nd century B.C., for which studies of a few decades, [7, 8] have highlighted with the high technological levels in antiquity, being this mechanism recognized as a first digital computer based on the operation of trains of gears. In addition to the complexity of the assembly of the gear trains, Fig. 1a, the specific design of the tooth profiles is remarkable, resulting in triangular profiles, Fig. 1b of precise execution well suited to low speed operation as the typical one for the instrument for which they were designed. This example demonstrates that already in ancient times the design of gears not only had a wide use in machines as emphasized also in the first specific treatises such as that by Vitruvius, but they were considered fundamental for the design and operation of systems with high precision and efficiency.

The re-flourish of machines during the Renaissance, [9], also saw an intense design activity on mechanical transmissions with traditional structures and with solutions

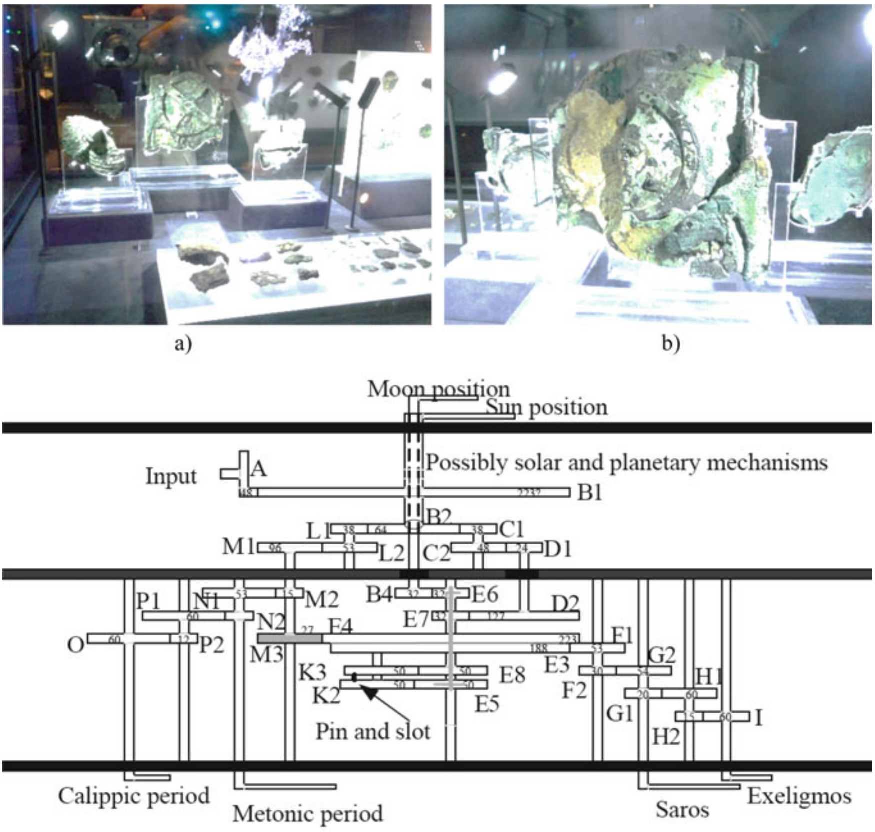
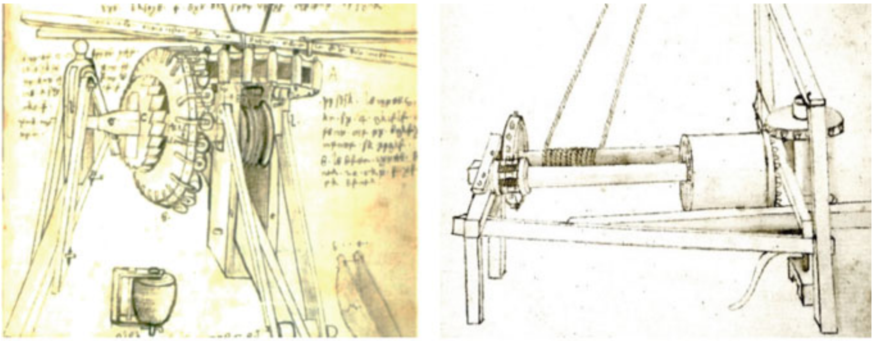


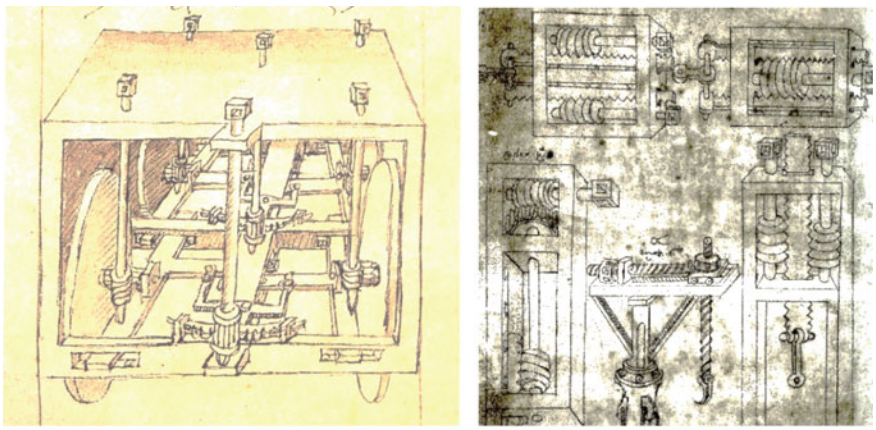
Fig. 1 Antikythera gearbox, an example of gears in Antiquity: **a** museum exposition of remains in Athens; **b** a detail of a geared sector; **c** a modern model [8]



a) b)

Fig. 2 Example of geared systems designed at the beginning of Renaissance in 13th century by Filippo Brunelleschi: **a** a composed gear train; **b** a powered capstan

made of new solutions in order to improve both the operating conditions and the efficiency of old and new machines. Emblematic examples are shown in Figs. 2 and 3. In particular, Fig. 2 shows examples of mechanical transmissions for weightlifting systems in traditional and innovative cranes with gear systems that are adapted to the specific needs and specific structures of the tower crane. Figure 2a shows the work of Filippo Brunelleschi for his cranes in the construction of the Duomo of Florence in the mid-13th century as the combination of a traditional pin wheel with an innovative roller toothed wheel with remarkable, concept of high modernity, in the such as the sturdiness of the pin gear wheel is combined with the high efficiency of the roller gear wheel to limit the effects of friction in power transmission. In Fig. 2b it should

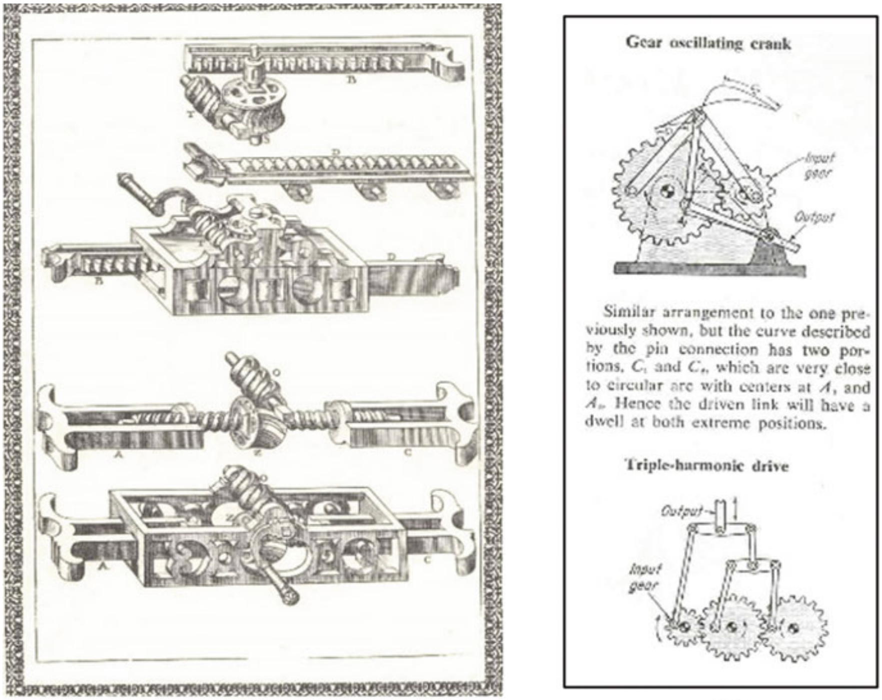


a) b)

Fig. 3 Example of geared systems designed during Renaissance in: **a** steering vehicle by Francesco di Giorgio in 14th century; **b** a selection of geared solution by anonymous in 15th century be noted how gear trains with toothed wheels of different nature are combined for the efficiency in the operation of a hoist whose functionality is not detailed to indicate the versatility of the proposed solution.

Figure 3 shows how the renewed interest in gear transmission systems has also produced innovative and widely practiced solutions. Figure 3a, [10], shows the application of gear sectors for the steering of vehicles of innovative design, as well as mechanical transmissions with orthogonal axes for the actuation of the wheels. This activity was also source and motivation of an identification of a community of experts, with anonymous and famous experts like the case of Francesco di Giorgio, [10].

In Fig. 3b practical solutions of transmissions for lifting loads by an anonymous engineer are reported as a result of a practice widespread at the end of the Renaissance. This interest in innovation and the dissemination of practical solutions can be recognized with the distinctive features of modern approaches which in the field of gears are concretized on the one hand in research activities and on the other in the industrial development of extensive production of solutions. This need for dissemination has given rise to manuals as in the case of Fig. 4 where we represent the first manual of 1588, [11], and a modern manual in 1961, [12], which report the centrality of gear solutions in the design of machines and mechanisms.



a) b)

Fig. 4 Examples of collections of geared transmissions in: **a** first handbook of mechanical designs by Agostino Ramelli in 1588 [11]; **b** a modern handbook of machine design [12]

The explosive development of machines during the Industrial Revolution required and gave rise at the same time to considerable developments in the design and functionality of gears, leading to theoretical developments and manufacturing processes still valid today. Remarkable are, for example, the definition of involute profiles and various other geometric topologies as well as the notching manufacturing processes for mass production. The application of gears in all types of machines has been a source of functionality and robustness of the machines in a large variety of solutions that starting from structures for flat transmissions have also reached solutions with skewed transmission axes giving rise to the solutions shown according to the diagrams modern in Fig. 5. Furthermore, the ever-increasing need for high performance has also given rise to innovative gear inventions both in terms of train structures such as planetary solutions, as well as radically different solutions such as the harmonic drive in Fig. 6, [13]. The complexity and robustness of modern mechanical gear transmissions can be summarized by the gearbox represented in Fig. 7 with the high efficiency that can be obtained today, [14].

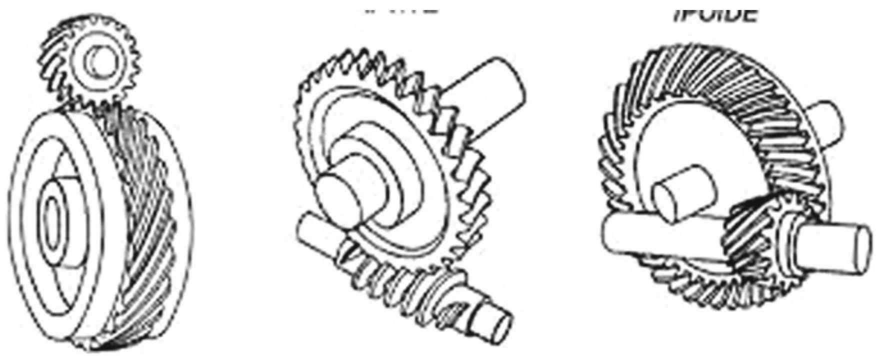


Fig. 5 Gear designs for power transmission between skew axes

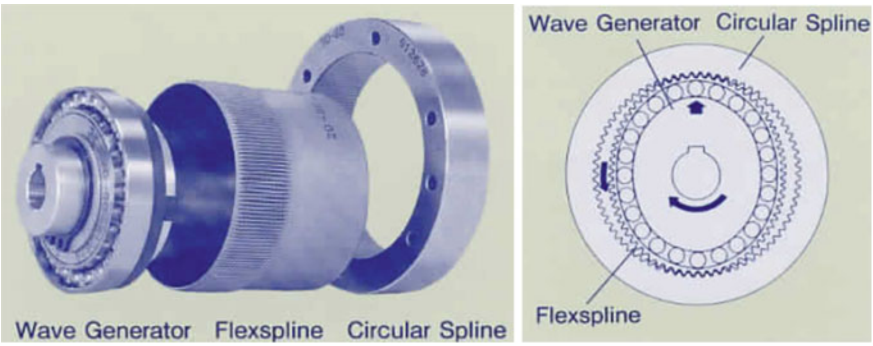


Fig. 6 The geared design of Harmonic Drive invented in 1960s [13]

Fig. 7 A gearbox as gear train for transmission in modern vehicles

Such a significative activity with inventions by inventors and engineers can be recognized as produced by a worldwide disseminated community that today is expresses also in thematic technical-scientific committed like the IFToMM Technical Committee on Gears [15].

3 Modelling and Analysis

Together with the development of practical and constructive solutions, an interest was directed to a rationalization and a theory for designing the functionality of gears since the beginning of machine design. An emblematic example is a first study of mechanics in the functioning of the thread of a gear by Guidobaldo del Monte, recovering the concepts of Archimedes' mechanics in Fig. 8a [16]. The gear theory has been developing over the centuries as an application of descriptive and then analytical geometry with relevant developments not only on a theoretical but also practical level as in the example of the beginning of the 19th century shown in Fig. 8b [17], regarding the profile geometry and a study of the phenomenon of interference in involute profiles.

Figure 9 wants to summarize the further theoretical development for the design and characterization of complex gear systems using abstraction techniques and the mathematization of functionalities by reporting a current example that is relative to an epicycloid train with a representation in the form of a graph [18].

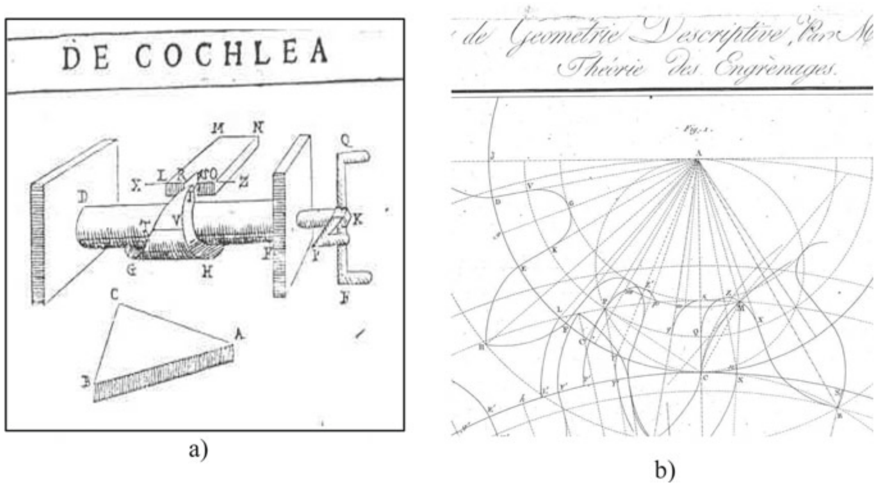


Fig. 8 Modelling and analysis of gear characteristics: **a** an early modern analysis of worm characteristics in geared system by Guidobaldo Del Monte in 1577, [16]: (**a**) a scheme of 19th century for operation analyse of gear profile under the risk of interference, [17]

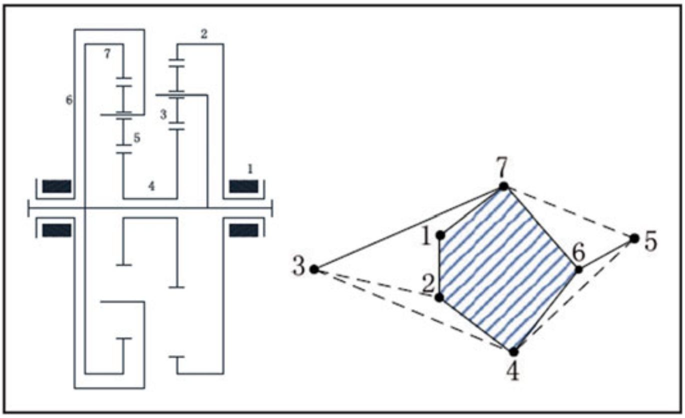


Fig. 9 A modern modelling for epicycloid gear characteristics using graph theory [18]

4 Modern Design Problems and Research Activities

Next some of the research lines in the field of gear transmission dynamics, which have been developing from the middle of the last century to the present, are presented

Özgüven and Houser [19] carried out a review of the dynamic models, establishing the following as ultimate objectives: bending and/or contact stresses in the teeth, determination of the loads acting on other elements (especially on the supports), emitted noise level, transmission efficiency, reliability, durability, tooth defects such as pitting and scoring, natural system frequencies, vibratory movement and stability. Parey and Tandom [20], approached the simulation of the behavior of gear transmissions under fault conditions, in order to develop new maintenance strategies and procedures. To do this, they made a compilation of dynamic spur gear models that incorporate the existence of defects. Wang [21] also carried out a compilation work, focused on the non-linear aspects that characterize the dynamic behavior of gear drives. Among other aspects, he addressed the non-linearities due to variable stiffness, the presence of clearance and friction. However, as indicated in [19] it is difficult to group the different mathematical models used in the analysis of the dynamic behavior of gears given the wide variety of models proposed.

The study of the dynamic behavior of gear transmissions requires addressing different approaches related to the design and analysis of this type of elements, such as: description of the geometry of the wheels, location of contact points or areas, definition of contact forces or the formulation and resolution of dynamic equations.

Determining the geometry of the tooth profiles, as well as the development of tools and procedures for their manufacture and verification, is a fundamental aspect of gear drives. The procedure for the construction of tooth profiles that is widely accepted, using generation tools, is based on Litvin's proposal collected in various texts [22, 23], which have been evolving, incorporating new developments.

The determination of the contact points or areas between profiles can be carried out following a similar procedure to that used to obtain their geometry [24–26], in order to analyze the path or path of contact and define manufacturing settings that provide trans- missions with low noise and vibration. At this point, we want to highlight the contributions of V. Goldfarb [27] on investigation of spiroid gears as well as on general issues of theory of gearing.

Regarding the study of contact efforts, different approaches must be distinguished depending on the objective pursued. Thus, on the one hand, there are those who intend to study local phenomena at the level of the contacts between teeth, such as the distribution of the load on the contact surface, the influence of the shape of the tooth on said distribution, or the tension level, with an approach it is of the quasi-static type [28, 29]. On the other hand, there are the more global approaches whose objective is to know the interaction between the different elements of the transmission and ultimately to study the dynamic behavior of the system as in [30–34].

Five different groups in the dynamic models of gear transmissions can be considered [19]: models with simple amplification factors, models with tooth flexibility, dynamic models, rotor-dynamic models and torsional models. The first proposal that considered the vibratory behavior of the transmissions has been attributed to Tuplin [35], who proposed a mass-spring model excited by means of a wedge that represented the possible shape errors of the profiles as in Fig. 10. However, this model does not consider a fundamental aspect such as the periodic nature of the excitement. Soon the need arose to incorporate this factor and the first formulations appeared that took into account the variable contact stiffness because of the oscillation in the number of pairs of teeth supporting the load as in Fig. 11.

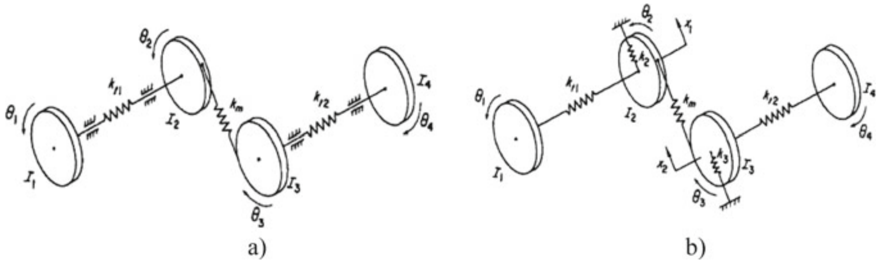


Fig. 10 Dynamical models of gears, [19]: **a** a rotational scheme; **b** a rotational-translational dynamic scheme

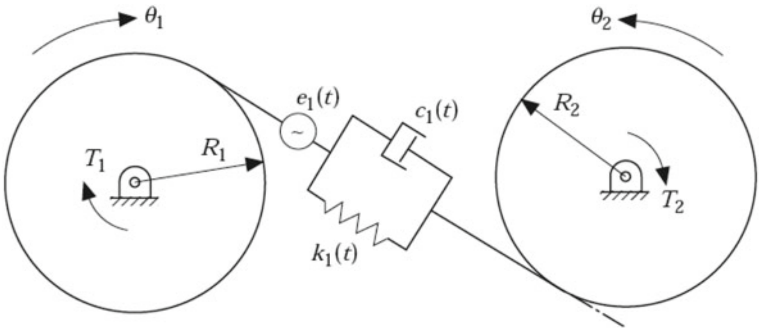


Fig. 11 A torsional model with contact in a single pair of teeth [32]

The main characteristic of this type of problem is the presence of a parametric excitation that arises as a consequence of the fluctuation in the contact stiffness, so the way to approach this aspect allows the different models developed to be classified more reasonably [36].

5 Conclusions

This paper presents a very brief account of the history but of the importance of gears with illustrative examples of design solutions and issues addressed for the development of the theory and practice of gears in machine applications. The work, even if limited in the analytical examination of the contributions and in the temporal developments, may be of interest to recognize ideas for professional practice and research activities as inspired by solutions and problems of the past.

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