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Влияние натурфилософии на инженерные науки, промышленный дизайн и современную Теорию механизмов и машин

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Преобразование логики в науку способствовало расцвету натурфилософии и научного метода в VI и V веках до н. э. в Китае, Индии, Арабском Мире, Древней Греции и на Ближнем Востоке. Динамичное развитие естественных наук сопровождалось систематическими попытками сформировать систему знаний. Этот процесс, продолжавшийся с IV по I век до н.э. в Греции и в Эллинистическом мире, достиг своей зрелости в Римской империи после II века н.э. В статье рассмотрено влияние натурфилософии на развитие механики и инженерии как науки. Приведена краткая истории науки о машинах и механизмах (HMMS) с древних времен до недавнего прошлого, включая сравнение технических аспектов. Изучение Истории науки о машинах и механизмах способствует пониманию исторических закономерностей, что, в свою очередь, будет активизировать усилия, направленные на развитие передовых технологий и, следовательно, на прогресс человечества.

Ключевые слова: механизмы, машины, логика, натурфилософия, история науки о механизмах и машинах.

The Influence of Natural Philosophy in Engineering, Design, Modern Mechanisms and Machine Theory

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Development of logic into a science served as an instrument for the progress in natural philosophy and the scientific method in the 6^{th} *and* 5^{th} *Centuries BC in China, India, the Arabian world, the Middle East and ancient Greece. Rapid advancements in natural sciences were followed by systematic attempts to organize knowledge in the* 4^{h} *to* 1^{st} *Centuries BC in the Greek and Hellenistic world, reaching maturity in the Roman Empire after the* 2^{nd} *Century AD. The influence of natural philosophy to the development of mechanics and engineering as a science is discussed here, along with an overview of the History of Machine and Mechanism Science (HMMS), from the earliest times up to recent past, including technical aspects. Studying the HMMS leads to greater motivation to currently increase the efforts needed for advancing technology and hence progress of humanity.*

Keywords: mechanisms, machines, logic, natural philosophy, history of mechanism and machine science.

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Machines and mechanisms are spoken early in history since man found his power inadequate for the tasks he set himself, among them moving heavy weights. Marcus Vitruvius Pollio (1st century AD) defined a machine as «*a combination of timber fastened together chiefly efficacious in moving great weights*». A century later, Heron (Hero) of Alexandria (ca. 10—70 AD) summarized the practice of his day by naming «*the five simple machines*» for «*moving a given weight by a given force*». Franz Reuleaux (1829—1905) in 1872 suggested as the earliest machine the twirling stick for starting fire and discussed further other early machinery such as water mills. The lever and the wedge are technology heritage from the Palaeolithic era [1—3].

The first known written record of the word machine (μηχανή–mechane) appears in Homer (ca. 800 BC) and Herodotus (ca. 484–425 BC), to describe political manipulation [1]. The word was not used with its modern meaning until Aeschylus (ca. 450 BC) used it to describe the theatrical device used extensively in the ancient Greek theatre as a stage device to lift actors, chariots or flying horses in the air. The mechane is also known with the Latin term Deus Ex Machina. *Mechanema* (mechanism), in turn, as used by Aristophanes (ca. 448–385 BC), means an assemblage of machines [1—3].

Aristotle (ca. 384–322 BC) gave *Engineering* a sense of wonder: «*Nature works against the man's needs, because it always takes its own course. Thus, when it is necessary to do something that goes beyond Nature, the difficulties can be overcome with the assistance of Engineering*». The development of the Theory of Machines and Mechanisms and the principles underlying design activity were investigated very early in history. The essentially random growth of machines and mechanisms was driven by the pressure of necessity [1—4].

A well-known Greek scientist on mechanical engineering Andrew Dimarogonas (1938–2000) in his notable two-volume *History of Engineering* (published in Greek) mentions that the term *Engineering* has been used, especially in literature on the History of Engineering, as synonymous with *Technology* and, in many instances with *Craft*.

Engineering is sometimes defined as the application of science to the solution of a problem of society at a profit. The accrediting agency for US engineering curricula, the Accreditation Board for Engineering and Technology (ABET), prepared the following more formal definition: «*Engineering is the profession in which a knowledge of the mathematical and natural sciences gained by study, experience, and practice is applied with judgment to develop ways to utilize, economically, the materials and forces of nature for the benefit of mankind*» [2].

In the Ancient Greek Society, there was a production surplus which allowed members of the society to be employed in tasks which were not of immediate use, such as arts and philosophy. The general use of steel in agriculture and war, and the popularization of the alphabet, was among the reasons for the rapid advancement of learning and science in ancient Greece.

Initially in history of engineering conception, design, and manufacture were the work of a single person and consequently, the first products were simple and of human proportions. However, in describing the history of machines, it is necessary to establish at least approximately the point of its origin as a science, the point that separates engineering science from technology and crafts.

The first machine designers were the master builders of the Potamic Civilizations (Mesopotamia, India, China, and Egypt). Those designers rose to the level of engineering in the Thalassic (great seas) societies of ancient Greece and Rome [1]. Much later, mass production caused the breaking of this process into distinct smaller ones and led to the separation of design from manufacturing. However, the principles underlying design activity were investigated very early in history. Mechanical design methodology has its origins in the writings of ancient Greek and Alexandrian authors between 300 BC and 100 AD when also the first aesthetic theory was proposed [1].

The philosophical foundation of knowledge, aesthetics and ethics and their implications in engineering design are discussed in the works of Dimarogonas, who documented that although the fundamental axioms of design were discovered during the middle of the last century in Europe, design rules and concepts were practiced extensively by the engineers of ancient times leading to machine design from machine elements to the design of a machine as a system.

Ancient Greek philosophy gave the first design theory [4]. By beautiful they meant a concept which included also functional (useful) and ethical (the good) implications. The function and the ethics were inseparable with the form. This society simply could not afford spending resources only for aesthetic pleasure. It was able however to afford a pleasing appearance for the useful goods of the everyday life and to pay attention to the more general societal needs [1—3].

German authors of the middle of 19th Century have introduced the foundation for Mechanical Design on basic Design Principles, modernized the machine element methodology and introduced the parallel development of the function with the form. Ferdinand Redtenbacher (1809–1863) introduced a set of design principles. Reuleaux (1852) introduced two fundamental *Design Principles* (Ground Rules).

A widely recognized Soviet (Russian) scientist Ivan Ivanovich Artobolevski (1905—1977) in his paper entitled *Some Problems in Mechanics and Machine Control* presented a brief history of the development of TMM [5]. He quotes the words of the outstanding physicist and creator of quantum mechanics, Werner Heisenberg, writing: «*To grasp the progress of science as a whole, it is useful to compare cotemporary problems of science with the problems of the preceding epoch and to investigate the specific changes that one or another important problem has undergone over decades and even centuries*».

The influence of natural philosophy in the 6th and 5th centuries BC in the philosophical inquiry, and the scientific method developed in the 4th to 1st centuries BC that have contributed to the establishment of mechanics and the principles involving the initial steps of building machines and its evolution to machine design, along with the fundamental axioms of machine theory from the classical times up to modern era, are discussed here.

Development of Logic and Natural Sciences in Classical Times. Since the 6th century BC parallel development of philosophy and logic took place in China, India, Iran, the Middle-East and Ancient Greece [1, 8]. Lao-Tzu (ca. 600 BC) wrote the Daodejing, one of the most significant treatises in Chinese cosmogony. Similar principles can be found in Heraclitus of Ephesus (ca. 535—475 BC) (a contemporary of Pythagoras, Lao-Tzu, Confucius (551—479 BC), and Siddhartha, the Buddha), and the dialectical method used by Socrates (ca. 469—399 BC) as described by Platon (Plato) (ca. 429—347 BC) [1—3].

Diogenes Laertius (ca. 3rd century BC) a biographer of ancient Greek philosophers divides Greek philosophers into two groups: the Ionians of the Ionic and the Eleatics of the Italic school [4]. He derives the first from Anaximander from Miletus (ca. 610 BC), the second from Pythagoras from Samos (ca. 569—475 BC).

In the 6th century BC, Thales (ca. 620—546 BC), founded the Miletian School of natural philosophy and developed the scientific method to investigate the basic principles and the question of the originating substances of matter. The Ionian philosophers are also referred to as pre-Socratic philosophers, as much of their work was completed before the time of Socrates. After Socrates, Diogenes divides the Ionian philosophers into three branches: (a) Platon and the Academics, down to Clitomachus (187—110 BC), head of the Academy in Athens around 127 BC; (b) the Cynics, down to Chrysippus (280— 206 BC); (c) Aristotle and Theophrastus (ca. 372—287 BC).

Thales, Anaximander and Anaximenes (ca. 560—528 BC), all from Miletos, studied the Universe and the laws describing its behavior. The later Ionians were Heraclitus of Ephesus, in the coast of Asia Minor (ca. 550—475 BC), Anaxogoras of Clazomenae (500—428 BC), Empedocles of Acragas (in Sicily) (492—432 BC) and the Atomists Leucippus (5th century BC) and Democritus (460—370 BC) from Abdera. Heraclitus mentions that things are constantly changing (universal flux), that opposites coincide (unity of opposites), and fire is the basic material of the world. Heraclitus is the first to separate the study of motion from dynamics, and introduced the principle of retribution, or change, in the motion of celestial bodies.

Anaxagoras (ca. 500—428 BC), a pre-Socratic natural philosopher formulated a molecular theory of matter and regarded the physical universe as subject to the rule of rationality (Reason). Although he insisted that the earth is flat he described eclipses mechanism, and the way light is reflected by the moon.

Leucippus, a student of Zeno of Elea (490—420 BC), is regarded as the founder of atomic physics. He devised the atomic philosophy in order to give answers to the problems raised by Parmenides of Elea (515—450 BC) and his followers. Democritus expanded the atomic theory of Leucippus. Epicurus (341—270 BC) borrowed the principal features of his philosophy from Democritus.

The Eleatic philosophy was founded by Xenophanes of Colophon (6th century BC) who lived in various parts of the ancient Greek world during the late 6th and early 5th centuries BC. Parmenides of Elea, Zeno of Elea, and Melissus from Samos (475—410 BC), are considered to be the Eleatic philosophers. In the search for truth, the Eleatics, in contrast with the Ionian philosophers rejected any input from sensory experience. The Eleatics felt mathematics to be the method of arriving at the truth. They argued that the true knowledge of being can be discovered through reason, beyond the false impressions of the senses.

Pythagoras from Samos made important developments in mathematics, astronomy, and the theory of music and vibration. Pythagoras studied under Thales before traveling to Egypt and Mesopotamia, then establishing his own school of philosophy in Croton.

Cratylus, a student of Heraclitus (late 5th century) brought Heraclitus' philosophy to Athens, where Platon heard it. Archytas of Tarentum (ca. 400—365 BC), is said to have written the first systematic treatise on machines based on mathematical principles. This is lost. Archytas built an air-propelled flying wooden dove.

Aristotle from Stagirus, Thrace (384—322 BC) at the age of 17 joined the Academy and studied under Platon, attending his lectures for a period of twenty years. Aristotle set up his own school, the Peripatetic school, at the Lyceum. Members of the Peripatetic school include: Theophrastus, a student of Aristotle, his successor as a director of the Lyceum, Straton (Strato) of Lampsacus (ca. 340—270 BC), the second successor of Aristotle in the Lyceum, at about 286 BC, Satyrus the Peripatetic (late 3rd century BC), and Eudemus of Rhodes (ca. 370—300 BC) the first historian of science, Alexander of Aphrodisias (late 2rd century BC) head of the Lyceum, the most celebrated of the Greek commentators on the writings of Aristotle, and Demetrius Phalereus (ca. 280 BC).

Aristotle's definition of substance states that it is «the being which exists by itself and does not need anything else for its existence» yielding the ontological, Cartesian definition. This definition of substance considered both the Heraclitus philosophy, everything is changing, as well as the Eleatics philosophers' inquiry of truth through mathematics [1—3].

Aristotle mentions gears around 330 BC (wheel drives in windlasses). By about 400 BC the Greeks were using compound pulleys. The principles of statics and dynamics were discussed by Aristotle in *Mechanica* (*Problems of Machines*), the first extant treatise on the design of machines, probably written by one of Aristotle's students in Lyceum.

Straton of Lampsacus, known in Latin as Strato Physicus, extensive writings included a non-teleological reinterpretation of Aristotle's physics that influenced later Alexandrian philosophers such as Heron [7]. His view — that the universe is self-explanatory and self-sustaining, and thus in no need of the introduction of a god or other extra-natural explanatory factor — was known as Stratonician atheism. Straton introduced an important kinematic criterion of equilibrium, the principle of virtual velocities. He also corrected Aristotle's claim that bodies fall at a constant speed, noting that in fact they accelerate.

Xenocrates of Chalkedon was explicit about the division of philosophical topics implicit in Platon, into 'physics', 'ethics', and 'logic'; this became the norm in Stoicism. Epicurus' philosophy was a complete and interdependent system, involving a view of the goal of human life, an empiricist theory of knowledge, a description of nature based on atomistic materialism, and a naturalistic account of evolution, from the formation of the world to the emergence of human societies.

Platon and Aristotle formulated the Eleatic philosophy; they developed logic into a science, this serving as an instrument for the parallel development of natural sciences. Rapid advancement in natural sciences was followed by systematic attempts to organize knowledge. In classical times, rigorous proof was introduced, based on deductive logic and mathematical symbolism. Abstract reasoning based on mathematical analysis, distinguished from mere empiricism, formed the basis for engineering as a science beyond the level of a mere craft.

The Alexandrian times. The decline of Greek civilization is followed by the rise of Alexandria, founded in honour of Alexander the Great (356—323 BC) in the Nile Delta in Egypt. Alexandria was the greatest city of the ancient world, the capital of Egypt from its founding in 332 BC to AD 642, and became the most important scientific centre in the world at that time, and a centre of Hellenic scholarship and science [2, 3].

The library at Alexandria was planned by Ptolemy I Soter, friend and biographer of Alexander the Great, after his death king of Egypt, founder of the Ptolemaic dynasty. The library came to fruition under his son Ptolemy II Philadelphus (309—246 BC), based on copies of the works in the library of Aristotle. Ptolemy II Philadelphus appointed one of Eratosthenes' teachers Callimachus (305—240 BC) from Cyrene, at about 630 BC, as the second librarian. When Ptolemy III Euergetes (266—222 BC) succeeded his father in 245 BC, Eratosthenes (273—192 BC) from Cyrene, now in Libya, North Africa, went to Alexandria as the tutor of his son Ptolemy IV Philopator. Eratosthenes became the third librarian at Alexandria around 240—235 BC, after Apollonius of Rhodes (librarian in 240—235 BC), Callimachus of Cyrene (librarian in 260—240 BC) and Zenodotus of Ephesus (librarian in 284—260 BC). The library contained hundreds of thousands of papyrus and vellum scrolls [2, 3].

Eratosthenes, became the third librarian at Alexandria around 240—235 BC. Although Pythagoras had been the first to claim that the earth was spherical during the 6th century BC, Eratosthenes proved the earth was spherical and measured its circumference within one percent of the present measurement. Details were given in his treatise *On the measurement of the Earth*, now lost. However, details of these calculations appear in works by other authors such as astronomer Cleomedes (1st century AD), Theon of Smyrna (ca. 70—135 AD) and Strabo the Geographer (ca. 64 BC-23 AD). Eratosthenes stated explicitly that the catapult was the chief practical reason for working on cube-root problems.

Euclid of Alexandria (325—265 BC), the most prominent mathematician of antiquity, best known for his treatise on mathematics *The Elements,* written about 300 BC, on geometry, proportions, and the theory of numbers. Euclid's *Elements* based on a small number of self-evident axioms, influenced the work of Archimedes (287—212 BC) [2, 3].

Ctesibius (ca. 283—247 BC) was the designer of the precision water clock. His many works are lost, and only references to them by his students, notably Philon and Heron, are extant. Ctesibius designed a device for lifting a mirror for a barber shop. This can be considered as a mechanism designed to order on the basis of engineering reasoning [1—3].

Philon of Byzantium (ca. 280—220 BC) also known as Philo Mechanicus (Engineer in Greek), a student of Ctesibius at the Museum used gears in water raising devices. Some fragments of an extensive treatise, *Mechanike syntaxis* (Compendium of Mechanics) exist. Most of this treatise is lost, and only parts of it as well as references to it are extant in other works. A section of Philo's *Pneumatics* includes the first description of a water mill in history [1—3].

Archimedes invented the field of statics, enunciated the law of the lever, the law of equilibrium of fluids, the law of buoyancy, and introduced mechanical curves as legitimate objects of study. He introduced step-by-step logic combined with analysis and experiments in solving mechanical problems and the design of machines and mechanisms. His works contain a set of concrete principles upon which design can be developed as a science using mathematics and reason [2].

The Greeks from Syracuse developed the first catapults; a result of engineering research financed by the tyrant Dionysius the Elder in the early 4th century BC. All the surviving catapult specifications imply that an optimum cylindrical configuration was reached. This optimization of the cord bundle was completed by roughly 270 BC, perhaps by the group of Greek engineers working for the Ptolemaic dynasty in Egypt, Thera and at Rhodes. Archytas and Eudoxus of Cnidus (ca. 400—350 BC) have devised elegant theoretical solutions for the stone-thrower formula [2, 7].

Ciceron (Cicero) (ca. 106—43 BC) writes that the Roman consul Marcellus brought two devices back to Rome from the sacked city of Syracuse. One device mapped the sky on a sphere and the other predicted the motions of the sun and the moon and the planets. He credits Thales and Eudoxus of Cnidus for constructing these devices. For some time this was assumed to be a legend, but the discovery of the *Antikythera mechanism* in 1900 has changed the view of this issue, and Archimedes possessed and constructed such devices [7].

Heron of Alexandria almost three centuries after Archimedes, expanded on his laws concerning levers [7]. Heron separated the study of particular machines and the general concepts of machines from the study of standardized elements. He introduced five simple mechanical elements for the solution of the general problem of moving a weight with a given force: wheel and axle, lever, windlass, wedge, and screw. He asserted that all five solutions are physical devices embodying the lever principle. Heron wrote texts for particular categories of devices; pneumatic machines, automata, optical instruments, balances, and artillery machines. Pappus of Alexandria (ca. 290—350 AD) wrote commentaries on Euclid's Elements and Ptolemy's Almagest. In his treatise Mathematical Collection, Pappus discusses the study of mechanics.

The Roman Times. The end of the Alexandrian era marked the eclipse of the ancient Greek science, and the systematic study of the design of machines became stagnant for a long time. The Roman Empire with the take-over of Egypt and Alexandria at the time of Julius Caesar (ca. 101—44 BC), Cleopatra (ca. 69—30 BC) and Christ, produced little in the way of inventing new machines. But, at this time bigger and better machines appear by the exploitation of the Alexandrian inheritance in science and engineering. Analytical reasoning gives place to pure empiricism and improvement by repetition. Progress, sometimes substantial as the invention of roller bearings, seem to have been achieved by chance discoveries, and trial and error experiments, than by the sustained use of intellect combined with analysis and experiments [1—3].

The Romans were great engineers and designers. Aesthetic and ethical dimensions were not important. The Roman effort was oriented towards the construction of buildings and roads network, while the principle Roman invention was hydraulic cement. The Romans further gave the world sophisticated legal and administrative systems and separated the professions of civil and mechanical engineering. Commentators on the classics flourished in Rome. They not only preserved most of the classical culture but made substantial advances of their own. Vitruvius' ten books *De Archetecture* (on Architecture) contained important material on the history of technology and on the design of machinery. *De Architectura*, after its rediscovery in the fifteenth century, was influential enough to be studied by architects from the early Renaissance to recent times.

The Arabian era. In 642 the Arabs conquered Egypt. From this time, scientific and technological progress was distinctly Arabian for the next centuries. The Arabs played an important role in the preservation of the Alexandrian and Greek science and engineering and made substantial contributions of their own. They devised ingenious mechanisms with a high degree of automation and control. One of the Arabic writers of this era was Ibn al-Razzaz Jazari (ca. 1206), who in his extensive and beautifully illustrated treatise on machines, *Book of Knowledge of Ingenious Mechanical Devices*, described a great number of ingenious mechanisms and automata. The records of machines and mechanisms during the «Dark ages» between 500 and 1000 are indeed scanty but large-scale changes in agricultural methods yielding agricultural surplus, led to rapid urbanization with a parallel development of mechanical devices suited to production to exploit the powers of wind and water. These new power sources were to spawn a multitude of machines with complex mechanisms [1—3].

Medieval and early modern era. The diffusion of Roman culture into highly religious medieval Europe shifted the emphasis to the practical needs of worshipping God. The influence of the works of the pioneers of science and engineering in classical times in medieval and the early modern era was due mainly to Latin and Greek-Latin versions handwritten, and then printed from the thirteenth to the seventeenth centuries. In the medieval monasteries, important mechanical devices were conceived. In the 9—10th centuries we already find clocks with gear drives. Documents of the twelfth and thirteenth centuries containing machine sketches are few [1—3].

The depletion of the population in the 14th century from the Black Death was followed by the development of arts, science and technology. This era became the period known as Renaissance. The 15th century was primarily the time of the absorption of classical studies and the adoption of Arabic mathematics. Design methodology returned to the level of a craft, and no noticeable advancements were recorded until the time of Leonardo da Vinci (1452—1519). The two manuscripts of Leonardo da Vinci (the Madrid Codex I and the Madrid Codex II) show that he had not only come close to the concept of a mechanism but even attempted to give a systematic description of mechanisms and their components. This had little impact on his contemporaries because his sketches were published centuries later. There was, however, substantial development and debate during that period related with the form and aesthetics [1, 4].

The early modern era is highlighted by the works of Galileo Galilei (1564—1642) and Isaac Newton (1642—1727) and includes the early stages of mechanization and the Industrial Revolution. Several studies and designs of machinery were developed during Renaissance, but the matter did not get the dignity of a discipline. The subjects of mechanics were still taught as an application of mathematics.

The first successful independent academic course on Mechanics of Machinery was given by Galilei at the University of Padua in 1597—1598. In this he used the short treatise *Le Mecaniche* that seems to have been written in 1593. The treatise *Le Mecaniche* can be considered as a first academic textbook on the Theory of Machines and Mechanisms [1].

Newton, further, was the first to place dynamics on a satisfactory basis, and from dynamics he deduced the theory of statics: this was in the introduction to the *Principia* published in 1687. Newton assumed that all geometrical magnitudes might be conceived as generated by continuous motion. This seems to be the earliest definite recognition of the idea of a continuous function [1].

The great influence to machine and mechanism science was made by Jacob Leupold (1674—1727), engineer, researcher and director of mining operations in Saxony. He wrote 11 books, covering different technical branches of machine and mechanism science. His *Theatrum Machinarium or Showcase of Lifting Devices* (1724) is the first experience of systematic research of mechanisms where he indicated the basic principles of mechanical engineering.

About the seventeenth century, as societal development moved from the Mediterranean region to the Atlantic coast, the power is in the hands of centralized, monarchical governments. The concentration of capital leads to the possibility of ample patronage of artists and craftsmen. Craftsmen are organized in guilds preserving their design secrets, but at the same time it confines it to mere empiricism.

An important role in the emergence of the science of machines is attributed to the works of the mathematician and mechanician Leonhard Euler (1707—1783). Euler published during the period 1736—1742 the book *Mechanica sine motus scientia analytice exposita* and according to Joseph-Louis Lagrange (1736—1813), it is *the first great work in which analysis is applied to the science of movement.* Euler states that machines and mechanisms should be considered not in a state of rest but in motion, regarding the kinematics of mechanisms as a separate science. Euler also wrote on the theory of friction, gear wheels, flexible links (belt, chain, rope) and gearing.

James Watt (1736—1819) in contrast with Euler concentrated on motion synthesis. Watt considered the motion of a point on the intermediate link of a four-bar mechanism thus, allowing him to build in 1784 a double-acting steam engine. The earlier chain connecting piston and beam was introduced in the Newcomen-type atmospheric engine circa 1775, was now replaced by a linkage able to transmit force in two directions instead of one. Watt had discovered the coupler-point motion a pivotal point along the road of synthesis [1].

By the second half of the eighteenth century, design has developed much beyond the royal court, and with the French Revolution the royal manufactories enter the commercial competition and the high aesthetic quality is shared by machines and products for the general public. Design of machines and mechanisms as a science was founded in 1794 when *The Ecole Polytechnique* in Paris, the first polytechnic school in Europe, established the study of kinematics separately from the study of machinery [1].

Gaspard Monge (1746—1818) one of the founders of *The Ecole Polytechnique*, the inventor of descriptive geometry, had proposed a course on elements of machines. He included Lagrange and Jean-Baptiste Fourier (1768—1830) among his teachers.

In 1808 Jose Maria Lanz and Agustin de Betancourt published their famous book *Essai sur la composition des machines.* Based on Monge's ideas they made a detailed study of types of movements and classified them according to how movement can be transformed by a variety of mechanisms [9].

Jean Nicolas Pierre Hachette (1769—1834), a colleague of Monge, in the book *Traité élementaire des machines* (1811) proposed the classification of the machine elements into six orders: *recepteurs*, *communicateurs*, *modificateurs*, *regulateurs*, and *operateurs*.

Gaspard-Gustave de Coriolis (1792—1843), road engineer and professor in Paris, simplified the classification system by reducing the concept of a complete machine to three parts of groups; *recepteurs, communicateurs and operateurs* [1].

Andre-Marie Ampere (1775—1836), in his work *Essai sur le philosophic des sciences* (1834) predicted «kinematics» as a study of movement of the bodies without considering the forces that cause it. Ampere was deeply convinced of the infinite human progress and science serving for the benefit of society.

In the nineteenth century, as the Industrial Revolution in England is fully developed, mechanization is generally adopted in production. This does not always mean change in design methodology and production technology. The raising middle class demands that their newly acquired wealth and social status will show in a decorative effect, often exuberant and vulgar. While academics and intellectuals are debating on aesthetic matters in industrial production, industry itself is striving for novelty adopting stylistic views of past cultures. This process results in severe violation of the natural and evolutionary process of the development of the form which, in many cases, is in sharp contrast to the product function [1–3].

As early as the beginning of the 19th century, mechanics became the theoretical basis of an increasing number of applied technical disciplines directly connected with the development of industry, new technological processes machines, and industrial plants and problems arising in railway transport, shipbuilding, internal combustion engines, automobiles and particularly aviation.

In the first half of the 19th century, after the Napoleonic wars, there is a systematic attempt to apply engineering science, reached a mature level by this time, to the design analysis of machines. A number of scientists effectively developed problems in the dynamics of machines. The need for controlling the steam engine has generated a wealth of investigations in kinematics and the design of linkages. Synthesis of linkages can be viewed as a formal design method. However, it cannot be considered as a general mechanical design theory because it is limited to linkages by its nature.

De Coriolis examined the problems of the dynamics of machines in the most general form with account taken of the forces acting on it. The works of Jean-Victor Poncelet (1788—1867) constituted a whole epoch in the science of machines, in particular, his fundamental treatise *A Course of Mechanics in its Application to Machines*. He derived the kinetic-energy equations for machines, considered the question of ensuring nonuniform operation of machines and the theory of a centrifugal governor.

In the mid-19th century in Germany, the *von Humbolt* model of universities developed strong ties with industry, in contrast to the *École Polytechnique* which was mainly supported by the French government. Consequently, there is a rapid dissemination of engineering science in mechanical engineering.

A considerable contribution to the science of mechanisms was made by the English scientist Robert Willis (1800—1875). In his *Principles of mechanisms* (1841) he set up a classification of mechanisms. The fundamental unit of his classification was the ratio of the speeds between the input and output links.

In the same period, the German scientist Julius Weisbach (1806—1871) published a three-volume work devoted to the engineering principles of designing machines and certain problems of kinematics and dynamics of mechanisms. A considerable contribution to the theory of mechanisms and machines was made by Felix Savary (1797—1841) [1].

Franz Reuleaux in 1875 published *Theoretische Kinematik* as an attempt to systematize and classify a great number of different machines and mechanisms, a «mechanical alphabet». The six basic mechanical components introduced by Reuleaux are: (1) the eye-bar link called crank in kinematics; (2) the wheel and gears; (3) the cam; (4) the screw for force and motion transfer; (5) the intermittent motion devices; and (6) the belts, chains and hydraulic lines. Each of these components was invented in antiquity and put in use fairly well in war machinery since the third century BC [1].

A Russian school in the Theory of Mechanisms emerged in the middle of the 19th century, associated with the name of Pafnuty Lvovich Chebyshev (1821—1894), mathematician and the founder of the theory of structural and kinematic synthesis of mechanisms. His work *Théorie des mécanismes connus sous le nom de parallélogrammes*, published in 1854, was the first approach of parametric synthesis, founding analytical methods for the synthesis of mechanisms. The *Chebyshev linkage* is a four bar mechanism that converts rotational motion to approximate straight-line motion. Chebyshev worked on mechanical linkage design for over thirty years, and his famous *Chebyshev polynomials* appeared. Chebyshev's ideas in approximation theory to applied problems (theory of mechanisms and computational mathematics) have now come to fruition [10].

Professor of Emperor Moscow Technical Secondary School (nowadays Bauman Moscow State Technical University) Nikolay Yegorovich Zhukovsky (1847—1921) got known not only for his work in the area of aerodynamics, but also in the area of theory of machines and mechanisms. He proposed the *Zhukovsky's lever*, interpreting the general dynamics equation for plane mechanisms.

Alexander Stepanovich Yershov's (1818—1867) book *Foundation of Kinematics or Elementary Theory* about motion in general and mechanisms. In 1854 it was the first Russian textbook of Theory of Machines and Mechanisms [6].

Later Fyodor Evplovich Orlov (1843—1892) in his books *Applied Mechanics* used the two level of classification, the 1st level is classification according to the connection of mechanisms links, and the 2nd level is Willis classification on motion transformation [6].

Dmitry Stepanovich Zernov (1860—1922) contributed to mechanism theory by writing the textbook *Applied Mechanics*: *Part 1 — Theory of Mechanisms and Part 2 — Theory of Machines*.

In the latter half of the 19th century, mechanics attracted the attention of naturalists. The discovery of the law of conservation of energy and attempts to elaborate a unified mechanistic description of the cosmos, required understanding of the basic concepts of mechanics [4].

Difficulties of a formal axiomatization of the concepts of mass and force brought forth a sharp discussion in the scientific circles. Reassessing Newton's laws of mechanics acquired great interest at those times. The Philosophy Department of Göttingen University awarded a contest in 1869 for the composition of a critical historic study on the basic principles of mechanics. The statement of the requirements pertaining to this investigation was posed as: *when and by whom and in what connection with specific problems was each separate essential principle of mechanics first found and enunciated*, and results were expected in accordance with an analysis of the principles and their interrelationship with philosophical theories.

A total of five compositions were submitted, first prize went to E. Dühring for his paper entitled *Kritische Geshichte der allgemeinen Principiender*

Mechanik (1st edition 1873). Next work by E. Mach *Die Mechanik in iher Entwiklung Historisch-Kritisch Dargestellt*. The philosophical issues arising from the works of Dühring and Mach caused criticism from Friedrich Engels (1820—1895) (*Anti-Dühring*, 1878) and Vladimir Ilyich Lenin (*Materialism and Empiriocriticism* (1909) from the stand of dialectical materialism, and an interesting debate took place.

The second half of 19th century can be considered as the Golden Age of the Theory of Machines and Mechanisms for the achieved theoretical and practical results that led to enhancements of machinery during the second Industrial Revolution. Various methods by which the different approaches and requirements of engineering design can be synthesized and evaluated appeared: mathematical analysis, computer modelling and simulation, experimental prototyping and testing, and extrapolating information from past experience. During the whole 19th century the traditional content of mechanics advanced in the field of applied mathematics [4, 5, 10].

Gruebler (1851—1935) developed criteria for the movability of a linkage, an important step towards number synthesis. Dimensional synthesis has been formalized by F. Freudenstein (1926—2006) and G. Sandor (1921—1996). Artobolevski's works are considered of fundamental importance in Mechanisms Theory and Mechanism Design [1].

In the 20th century, there is a reconciliation of aesthetic and utilitarian particularism as the result of a design aesthetics theory that emerged naturally in the process of social and economic evolution based on a rigorous foundation of the design and manufacturing sciences.

Conclusions. It was among the Eleatic philosophers that important beginnings of logic were developed by Platon and Aristotle into a science and served as an instrument for the parallel development of the natural sciences, especially mathematics and physics, by such pioneers as Pythagoras, Euclid and Archimedes.

The works of Willis, Chebyshev and Reuleaux constituted the basic scientific trends that later became the essence of the science today termed as the Theory of Mechanisms and Machines, greatly contributed and enhanced engineering design. Reuleaux design principles lead to a balance between form and function considerations, which were separated since the Alexandrian times and the decline of the ancient Greek philosophy and science.

A considerable contribution to the development of engineering design and the science of machines is being made in different countries thanks to the International Federation for the Promotion of Mechanism and Machine Science (IFToMM), the IFToMM Permanent Committee for the History of Mechanisms and Machines Science, the ASME Design Engineering Division, the Soviet Academy of Sciences and its continuation, and other International Organizations.

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