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THE KINEMATICS OF MACHINERY.

TWO LECTURES

RELATING TO REULEAUX METHODS,

Delivered at South Kensington Museum,

BY

Prof. ALEX. B. W. KENNEDY, C.E.

WITH AN INTRODUCTION BY

Prof. R. H. THURSTON, A.M., C.E.

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INTRODUCTION.

The following reprint of Professor Kennedy's lectures illustrating Reuleaux's new methods of treatment of the study of the kinematics of machinery, and the science of pure mechanism, as it has been termed by Professor Willis, is published at the request of the writer, for the purpose of placing in the hands of every mechanical engineer an exhibit of the methods devised by one of the most distinguished engineers and men of science in Europe for the study of the motions of connected parts of machinery. It is hoped that these short and well-considered lectures may assist the student in the effort to comprehend those new methods, and to make use of them in professional work, and especially that they may have a wider range of influence, and may lead to a more general introduction of Reuleaux's treatise*—Theoretische Kinematik—the publication of which will probably come to be admitted to be the most important event in the history of kinematics. In fact, the science of related motions, as the writer has called it, has never before assumed that definite, logical and thoroughly complete form which should distinguish every true science.

The defects of the usual method of studying a simple machine as a whole, and without reference to general elementary principles; the acknowledged want of a defined system of study and of a fixed nomenclature, and a natural and logical method of expression of principles and facts, and the difficulty met with in securing a general comprehension, among teachers, of the radical distinction between the two sciences relating to motion and to forces, have been serious obstacles to the advance of the former.

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* The Kinematics of Machinery. Outlines of a Theory of Machines. By F. Reuleaux. Translated and edited by A. B. W. Kennedy, C. E. London: 1876

Reuleaux has done much to clear away these obstacles, and has made a splendid effort to place the science of the kinematics of machinery in its proper relations to the older branches of dynamics. He first outlines the theory of machines, studying their various forms and determining what conditions are common to all, and therefore essential. The machine is studied as a useful and practically valuable apparatus in the light of a science thus founded. The distinction between the theoretical and the practical departments of the study is recognized—or rather as the able author says, between theory and empiricism—and the endeavor is made to aid in the substitution of practically applicable exact methods for the empirical and "rule of thumb" determinations, which, although unavoidably adopted in the absence of precise scientific knowledge, are gladly abandoned by every intelligent engineer when precise and logically correct methods become practically available.

The methods of treatment of the philosophy of mechanism have hitherto been the algebraic or geometric solution of detached problems, and the study of unrelated sets of elements. The origin of the science and the basis upon which it stands have been hardly perceived, and no attempt had previously been made to reveal foundation, framework and covering, and to exhibit their relation to the architectural whole, when Reuleaux began his work of analyzing mechanisms, detecting elements, studying their combinations and discovering those laws of their operation which constitute the new science. The result has been the production of a work which contains both a general theory of machines and a scientific treatment of their movements; if not absolutely complete in itself, this is, at least, more complete than the earlier treatises. The work will, in some respects, prove disappointing to the engineer familiar with every-day practice, but the fact gives him the opportunity to do a great work, by building into the frame erected by the great German engineer the detached members to be found in Willis and in Rankine and other less well-known works, and thus making the structure more complete and more valuable. Reuleaux has led the way, and has pointed out a path in which all are at liberty to walk as far as their ability and their strength may permit.

Those whose time and inclination may lead them to the examination of the work, to which attention is here called, will find that the author is as systematic in his methods, and as logical in his statements and conclusions as Euclid, himself, could have desired. He first defines a machine: "A machine is a combination of resisting pieces arranged in such manner that the mechanical forces of nature may be caused to do work with certain determinate motions."

Practical mechanics has been subdivided into:

The Study of Machinery in General.
The Theory of Machines.
Machine Design.

The Science of Pure Mechanisms.

Reuleaux would construct a single homogeneous philosophy of the science of machinery; the manner in which this is done will be comprehended after the reader has become acquainted with the illustrations of his method, given by Professor Kennedy. The basis of all is found in the following definition:

"A mechanism is a closed kinematic chain, which is compound or simple, and consists of pairs of elements; these carry the envelopes for the motion which the parts in contact must be given, and by these envelopes all other motions are prevented." When an effort is applied to this combination, work is done, and done in a fixed and definite way, the re sistance being overcome through a certain predetermined path; *this mechanism so operated, constitutes a machine*; and, the combination existing, it remains a machine whether actually put in motion or not; many machines do not necessarily move, although, assuming motion to take place, the relations of effort to re-sistance and of motions of parts are as definite as if the machine were in continuous operation doing work.

The treatise of Reuleaux begins with the study of the various motions which occur in mechanism, and the conclusion is promptly reached that all relative motions of parts in any given plane—con-plane movements as he calls them—may be considered as rolling motions, and that they become determinable by the study of their "centroids," *i. e.*, of the pairs of curves which, rolling together, would produce the motion. This treatment is evidently very closely related to that made so familiar by Rankine and earlier writers, in whose methods instantaneous axes are taken as the centers of such revolution. As stated by Reuleaux: "Every relative motion of two con-plane bodies may be considered a cylindrical rolling, and the motions of any points in them may be determined so soon as their cylinders of instantaneous axes are known." Each line of coincidence, or of contact of the elements, of these rolling curved surfaces is an "instantaneous axis of rotation." Only one pair of these centroids can exist for any one relative motion.

Seeking these curves for cases of motion not confined to one plane, it is found that motion about a point may always be considered as a "conic rolling," the cones being generated by the instantaneous axes determined by the given motion. Proceeding still further, a more general —the most general—case is studied and it is found that "all relative motions of two bodies may be considered as twisting or rolling of *ruled* surfaces, or "axoids." Pairs of ruled surfaces may be made to exhibit *all possible motions.*

Where the ratio of twist to translation becomes indefinitely small, the motion becomes that of sliding; when infinitely great, it becomes simple revolution. The detection and study of these axoidal surfaces is as attractive and interesting as it is useful, and the student becomes quickly familiar with this method of representation of a mechanism, and soon learns to see the machine as a set of pieces playing their relative parts in the whole, in direct relation with the invisible geometrical, and always graceful, forms of the "axoids" which—and not the frame and solid portions of the structure—really constitute with them the real machine. The laying out of the common teeth of wheels is an example of the determination of plane centroids; hyperboloidal wheels have axoids.

Elements of mechanisms become now capable of ready classification,* and their combinations are easily made known and classified, and it becomes almost self-evident that, in the machine, the office of the several parts is to secure the relative motions appropriate to each pair of elements and perfect restraint against all other movements. The laws of such restraint are simple, and are easily discovered and readily enunciated. Thus,

* Fluids and flexible and elastic bodies are, as a matter of course, elements of any machine in which they appear.

the study of mechanism becomes truly scientific, and the examination of detached and special problems, illustrated by the methods of Willis, and more markedly by Rankine, becomes secondary to this primary general treatment.

As remarked in the beginning, a systematic notation and the development of a system of scientific expression of the laws of machine movement, in which such a notation is used, constitutes a grand feature of this work. Earlier attempts, by Babbage and others, have been barren of valuable results, simply because the scientific foundation was not first laid down; and, in less degree, because of their imperfect nature. It is wonderful that this later system, once developed, should be found so simple. A dozen primary symbols designate all the parts used in machinery; four symbols indicate forms, and two identify liquid and gaseous elements, while something more than a dozen of the familiar algebraic symbols find appropriate application in exhibiting relation of parts.

These symbols are simply and relatively combined to represent any machine, and a number of convenient contractions render their use more convenient in the more frequently occurring cases. The special formulas thus constructed as representative of particular machines, and the general formulas representing classes, are constantly used in analysis, and in synthesis as well, and the identity of visibly differing machines, or the radical differences between mechanisms seeming to the eye almost identical, become at once evident when the material disguise, in which they appear to the untaught mind, is stripped off, and they become known only through their kinematic, or true mechanical, relations.

This last point is best exemplified by the analysis of "slide crank-trains," including "quick-return motions" of crank trains generally, and especially and most beautifully in the study of "rotary engines," in which familiar motions take a peculiar disguise while retaining all their original kinematic characteristics. For example: Galloway's rotary steam engine is shown to be simply an awkward combination of steam "cylinder" with Watt's planet-wheel rotation.

An analysis of complete machines, and an historical retrospect brings out very strongly the fact which every engineer must have remarked: that attempts to follow the kinematics of Nature have almost invariably been misleading to the machine designer, and that the most rapid progress has usually followed when the inventor has broken away from this seductive but fettering idea, and has boldly and independently sought to attain a definitely known object, by the most direct and simplest of familiar mechanical devices.

Reuleaux's work concludes with a treatise upon the most important and highest—and naturally least developed—part of the newly constructed science: that of scientific kinematic *synthesis*, or the building up of a machine designed to do a specified work, and to have certain required motions. Reuleaux would substitute this for that blindly groping for, or guessing at, results which so generally leads to invention. He would make the process of invention a scientific one, and would thus raise the inventor to a higher plane, and give him the increased distinction which is due a higher order of intellectual work.

This may be illustrated thus: In the design of a cotton-combing machine, which once fell into the hands of the writer, certain objects were to be accomplished, and certain means were available. The uncarded cotton was to be received upon an apron, carried forward to a point where it could be seized by the mechanical fingers, which were to present it to the combs, holding it while one end of the mass of fibers was operated upon; this operation completed, another set of fingers were to seize the combed ends of the fibers, now released by the first set, and were to present the uncombed ends to the combs. Both ends of the fiber being finally combed, the cotton was to be deposited carefully and undisturbed upon the apron, to form the lap, which was then removed from the machine.

In designing this machine, each operation was studied with a view to determine what "kinematic chain" was best adapted to do that work, with the exact motion demanded, and this chain being obtained, it was located properly, and the next similarly worked out. When these combinations of motions were finally grouped in such manner that each succeeded its leader in correct order and in proper relation, the form of each piece or "element" was worked out; when all the elements had been given shape, and found to admit of the required cycle of kinematic changes without interference, the "centroids" of their motions were studied to obtain the best means of connecting all to a common fixed "link"—the frame of the machine. The aprons were sliding pieces; the feeding rollers were rotating elements; the mechanical fingers were vibrating pieces carried by parts themselves vibrating, and the combs were simple "sliding elements." The centroids determined by the motions of the nippers or fingers, gave the form of the cams needed to produce those motions; the cams actuating the other intermittently or irregularly moving pieces were laid out in the same manner. The machine now consisted of one extended kinematic chain, operated from one end. The fixed points in the chain, and those centroids which were themselves fixed in space, now gave location to parts of the frame of the machine adapted to their support, and the shape and proportion of the frame became readily determinable as soon as the lines of effort at these resistant points were laid down. The last part of this problem in machine design was solved when a frame had been fitted to the set of fixed points, having proper form and size to sustain all stresses coming upon them, and so arranged as to permit every motion to take place without bringing moving parts into collision with its own members. The frame was laid out in skeleton form, and when found suitable in all respects, was drawn in full and all details worked in.

Such a process of "kinematic synthesis" Reuleaux would adopt in all cases, and the construction of kinematic formulas would be the first steps to be taken in his method of "scientific invention." The other steps would follow as just indicatedt; the selection of the needed elements would be facilitated by that reduction to simplest terms of every proposed machine, which would become so easy when thus presented to the mind, uncomplicated by conceptions of conventional form.

The synthesis of a kinematic science, which we have been able to follow, must, in the opinion of the writer, ultimately prove of real service to the profession. Nearly all great advances of this character, like nearly all great mechanical inventions, are a generation, at least, in taking their place in the world; it is to be hoped that this may prove an exception to the rule. It will become evident at the first glance that the method of Reuleaux does not render valueless the work of Willis, of Rankine or of Redtenbacher.

The former should be studied as a basis for the detailed work of the others; it is a general science of machinery, which, once rendered familiar to the student, makes his later work easier and more fruitful of practical result. He should become familiar with this scientific basis, and should then study the relation of parts and of motions in detail with Willis and Rankine, and should finally make himself familiar with the complete machine, which he is likely to find useful in his professional work, and endeavor to become capable of designing them, and of synthetically producing new forms of mechanism.