The figure and work of Riccardo Felici in the 200th anniversary of his birth

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Abstract: Riccardo Felici (1819-1902) was Professor of Experimental Physics at the University of Pisa from 1859 to 1893. However his main scientific contributions go back to the Fifties of the XIX century, when he studied the electromagnetic induction phenomena both from an experimental and a theoretical point of view. His formulation was very rigorous, probably the best of his time, and it was quite appreciated also by J.C. Maxwell. His school of physics was the most important and influential in Italy for the best part of the XIX century, and he gave also a substantial contribution to the formation of the Italian Physics community, especially through his direction of the journal *Il Nuovo Cimento* and his participation in founding the Italian Physics Society.

Keywords: Riccardo Felici, Pisa school, electromagnetic induction

1. A short biography

In the official documents Riccardo Felici was born in Parma on June 11, 1819, but the circumstances of his birth are somewhat uncertain, since there is no trace of his birth in original Parmesan documents, while there is an act of baptism, requested from Felici himself, attesting the birth in Pisa, on that same date, of "Rinaldo Felice", son of unknown parents. Some circumstances lead us to believe that Felici was the illegitimate son of the Pisan noblewoman Isabella Roncioni, whose stormy biography would make the hypothesis plausible. Certainly, there is a "fraternal", albeit cautious, correspondence of Felici with Enrichetta Bartolommei, Isabella's daughter, and the choice of Isabella's name for Felici's only daughter does not seem casual either (Ferrero 2014).

Certainly, however, he spent his apparently uneasy childhood and adolescence in Parma, and he enrolled first, on November 30, 1838, at the local University, where he followed, among others, the teachings of Elementary Mathematics, Sublime Mathematics and Elements of Astronomy, Mechanics applied to Architecture, Statics and Hydrodynamics, Theoretical and Practical Physics, Experimental Physics, until the day when Professor Michele Leoni (1776-1858), who had been a lover of Roncioni in the past, prompted him to move, the following year, to the degree course in Mathematical Sciences at the Faculty of Sciences of the University of Pisa, as a pupil of Filippo Corridi, Vincenzo Amici, Luigi Pacinotti, Ottaviano Fabrizio Mossotti and Carlo Matteucci.

In Felici's articulated study plan both Physics and Mathematics teachings appeared, together with various other technical and scientific subjects, up to his degree on July 12th 1843, achieved in just three years instead of the usual four of the ordinary course of studies.

In 1846, having already published some scientific works, Felici was appointed as assistant to the Chair of Experimental Physics held by Matteucci, as well as an examiner and preparer for the exams. From 1848 to 1849, he participated, with the rank of lieutenant, in the First War of Independence, fighting valiantly in Curtatone. On his return to Pisa, due to his political ideas, he was opposed by the Church in resuming his post as assistant at the university, and it was only through the intercession of Professor Silvestro Centofanti, with whom he shared many political ideas and maintained friendly relations, that he soon succeeded in recovering his previous academic role.

In 1852, he held both courses and seminars at the *Scuola Normale Superiore* in Pisa, and in 1853 he was appointed repeater. In 1854 he became adjunct professor and married Elisa Frullini, from Pisa; their only daughter, Isabella, was born in 1856. In 1859, due to the increasing political commitments of Matteucci, Felici became a full Professor and took over the Chair of Experimental Physics - also holding the annexed Cabinet.

In 1870/71 and in 1882/83, Felici was also Rector of the University of Pisa, taking on various other organizational and managerial positions, including the presidency of the Faculty of Mathematical, Physical and Natural Sciences and the position of councilor of the *Scuola Normale Superiore*, that brought him to abandon active physical research. Officially he left university teaching in 1893, and in 1894 he was appointed professor emeritus of the University of Pisa.

He held friendly relationships and collaborations with several contemporary Italian scientists, as well as with scientists from other European countries. In 1897, together with several other university professors (including Battelli, Ròiti, Blaserna, Righi and Beltrami) he proposed the establishment of the Italian Physical Society and was the director of its main magazine "*Il Cimento*" (founded in 1844, and later renamed "*Il Nuovo Cimento*").

Many were also the acknowledgments for his career: he was a member of various other Italian and foreign scientific societies and academies, including the *Accademia Nazionale di Scienze, Lettere e Arti* of Modena (1861), the *Physical Society* of London (1868), the *Accademia delle Scienze* of Bologna (1873), the *Physicalisch-Medicinische Gesellschaft* of Wurzburg (1874), the *Accademia dei Lincei* (1875), the *Istituto Veneto* (1875), the *Accademia delle Scienze* of Turin (1881), the *Istituto Lombardo di Scienze e Lettere* (1882), the *Accademia di Scienze, Lettere e Arti* of Lucca (1883), as well as various honors by chivalry orders and official invitations by Italian and foreign associations among which, in 1899, the *Royal Institution of Great Britain*.

He died in the locality of Sant'Alessio di Lucca, on July 20, 1902. His body was then buried at the monumental *Camposanto* of Pisa.

2. Riccardo Felici's scientific work

Felici was one of the best Italian researchers and professors of experimental physics in the second half of the nineteenth century, educated in Pisa at the first Italian school of physics in the nineteenth century, which had as its main masters Mossotti, Luigi Pacinotti and especially Matteucci, who was the first to give an experimental character to the school, also by his pioneering research work.

There is often a certain continuity of methods and views within a school of thought, even more so in the scientific field, but this this cannot be said of Felici with respect to his teacher Matteucci. In fact the peculiarities of Matteucci's character were undoubtedly at the origin of this many and rapid initiatives taken both in the political, organizational and institutional context as well as in the practice of research, where his trend was often towards the immediate experimental discovery, while he showed much less interest in the theoretical and mathematical formalization. Quite different was Felici's temper, described by Pochettino as

> [...] of a calm, modest, constant character; methodical spirit, crystalline, ingeniously sharp and disciplined, cautious, balanced, sometimes even skeptical, and balancing the experimental and the mathematical element in his research. A man of reasoning, Felici did not tie his name to a phenomenon he discovered; but his fundamental researches on the induction currents were conducted with such perfection of method that they deserved the honor of being included in the *Klassiker der exakten Wissenschaften* collection published by Ostwald. (Pochettino 1930)

His first physics works date back to the years immediately following his graduation, with a first memoir, dated 1844, in which he expressed his critical considerations, basically on theoretical grounds, regarding research conducted by the French physician, biologist and physiologist Henri Dutrochet on some hydrodynamic phenomena that he explained by introducing *ad hoc* a new force, while Felici brought them back to the action of capillary forces.

Appointed as Matteucci's assistant in 1846, Felici was immediately able to make use of direct experimentation, supported by the precious work of the laboratory technician Mariano Pierucci, in support of his theoretical considerations. He could then publish in 1846 a more experimental work on some thermoelectricity phenomena in mercury, showing that electrolytic conductivity could be established, not necessarily in the presence of a thermal gradient, but in any case in conjunction with phenomena of ionization of the conductive substance.

In 1847, carrying on his studies and research on electrochemical phenomena, he published a third work on electrical circuits formed by galvanic elements, while, in 1850, he produced a work on the propagation of electric current inside a spherical conductor. In 1851, in continuation of what he had already been done in the previous papers, he published another work on electrochemistry in which he studied also the effect of thermal phenomena on electrical conduction in liquids, coming to determine, for the first time, the mode of variation of the polarization EMF with the temperature. These were purely experimental works, with the addition of non-formal theoretical considerations.

In the same year 1851 he published also a first essay, focusing on the explanation of electrodynamic induction phenomena, that was later translated into French and republished in 1852 in the famous *Annales de chimie et de physique*, This work was also known to Maxwell. This publication marked the beginning of the main sequence of works on electrodynamic induction, which would end in the early 1860s, consecrating Felici among the great masters of the discipline.

In the early Fifties Felici undertook a study of electromagnetic phenomena according to an experimental approach similar to that used in the 1920s by André-Marie Ampère in studying the phenomena of attraction and repulsion between linear elements of electrical circuits. Felici began his research with a series of experiences in which he systematically investigated the possible variations in the intensity of inducing and induced currents with the variation of nature, dimensions, relative position and shape of inducing and induced electric circuits, thus reaching a new theory of electromagnetic induction that contributed much to complete the theoretical framework for electromagnetic induction, that had been studied mainly by M. Faraday, F.E. Neumann, W.E. Weber and H.F. Lenz, in addition to many others.

What most distinguishes Felici's work from the certainly noticeable contributions of other authors, is the method by which he came to the formulation of his theory. Indeed, the theories of Neumann, Lenz and Weber were based on particular *ad hoc* hypotheses, having more an *a priori* nature and justification than a reasonable physical motivation.
Instead Felici, on the preliminary basis of simple and elementary but crucial physical experiments, following Ampère's method arrived at the construction of a general theory of electromagnetic induction, avoiding recourse to artificial and not experimentally proven assumptions. His main experimental results are the following (Agastra Selleri 2012):

1. The induced electromotive force is proportional to the inducing current intensity;
2. The induction caused by n currents of intensity I/n is the same as that caused by a single current of intensity I ;
3. A conductor's effects is the same as the summation of the effects of the elementary cur rents into which it can be decomposed;
4. The induced electromotive force is proportional both to the number of coils of the inductor and to the number of the induced circuits;
5. The currents originated in a moving closed circuit is equal to the difference of the currents that would be induced in that circuit if, being open, it were closed in its original or final position;
6. The mutual induction of two identical, coaxial, circular circuits is proportional to their diameter,
7. The current induced in a closed circuit from a solenoid (or a magnet) depends only on the relative position of the circuit and of the solenoid (or magnet) extremities;
8. If the axis of a solenoid (or a magnet) forms a closed loop, then its induction is zero unless the circuit is concatenated with the axis.

Felici's law, according to which «it is possible to calculate the total charge that passes in a circuit subject to an induced current as the difference between the final flux of the magnetic field and the initial one divided by the electrical resistance of the circuit», was resumed by J.C. Maxwell in constructing his general theory of electromagnetism, and also by A. Roiti, L. Puccianti and G. Polvani, who further confirmed many aspects of Felici's work. Thanks to these important results, Felici became, in 1859, full professor of experimental physics.

Precisely during the period in which these pioneering researches on the induction currents were conducted, Felici published works in which he explained, through the delay of electromagnetic induction, the presence of certain lack of symmetry in mechanical actions

intervening between a given rotating conductive sphere and a magnet placed perpendicular to the axis of rotation of this solid conductor, in the case where the angular velocity increased considerably. And it is precisely from these studies, even admitting hypotheses not directly linked to experimental facts - and this was the only case of a mathematical rather than theoretical treatment of an empirical problem by Felici - he came also to an ingenious theory of diamagnetism.

From the early Sixties onwards, he directed his interests towards other questions of electromagnetism, acoustics and optics. In the years between 1862 and 1866, Felici prepared, on the basis of previous work on the subject, laboratory experiments for estimating the speed of electric current, succeeding, at the same time, in describing some details of the phenomenology of electric sparks, their nature and duration, through appropriate experimental apparatuses prepared by himself.

In the same years, on the basis of what his teacher Carlo Matteucci had already done, he published some works concerning some laboratory experiences - building, for this purpose, his own special electromechanical system based on a torsion balance - on the physical behavior of dielectrics in the presence of other electrified bodies, with special attention to the case of an insulating material inserted between the two conductors of a capacitor.

He published also other remarkable works on the possibility of having dielectric polarization phenomena, an hypothesis already advanced by Avogadro, and taken up and further developed by G. Belli, M. Faraday and above all by Mossotti, however from a more theoretical than empirical point of view, thus leaving many open questions to which Felici's experimental work, which lasted until the final years of his research activity, responded with acumen and originality, thus bringing the polarization of dielectrics from a simple *ad hoc* hypothesis to an experimentally assessable physical reality, confirming however many theoretical aspects of Mossotti's mathematical theory. One must also recall some memories, published between the Sixties and the early Seventies, on the determination of the geometric shape of some surfaces of liquids modeled by the action of capillary forces.

In the mid-Seventies for the purpose of studying the demagnetization law of certain ferromagnetic materials (a more complicated case than that of diamagnetic and paramagnetic substances), Felici conceived and realized, with the help of the laboratory technician Mariano Pierucci, a special switch that produced rapid intermission (at intervals of 1 / 20,000 seconds) in the currents induced between two concentric solenoids in which an iron cylinder was inserted. One of the solenoids was connected to a battery, and the other to a galvanometer, so that, by closing the circuit of the battery, the iron would magnetize, thus inducing an electric current in the solenoid connected to the galvanometer. The switch prepared by Felici, with the technical support of Pierucci, made it possible to adjust specifically the opening and closing times of these two circuits, so as to be able to estimate and adjust the magnetization and demagnetization times of the iron rod, and then to evaluate the intensity of the various currents in play, which obeyed laws having the form $A \exp(-\alpha t)$, where A and α are numerical constants. These experiences, which were also taken up and extended by some of Felici's students, can be considered historically as forerunners of subsequent research and theories on the demagnetization of ferromagnetic materials, which were mainly based on the use of alternating magnetic fields of decreasing intensity, made necessary by the occurrence of magnetic hysteresis phenomena.

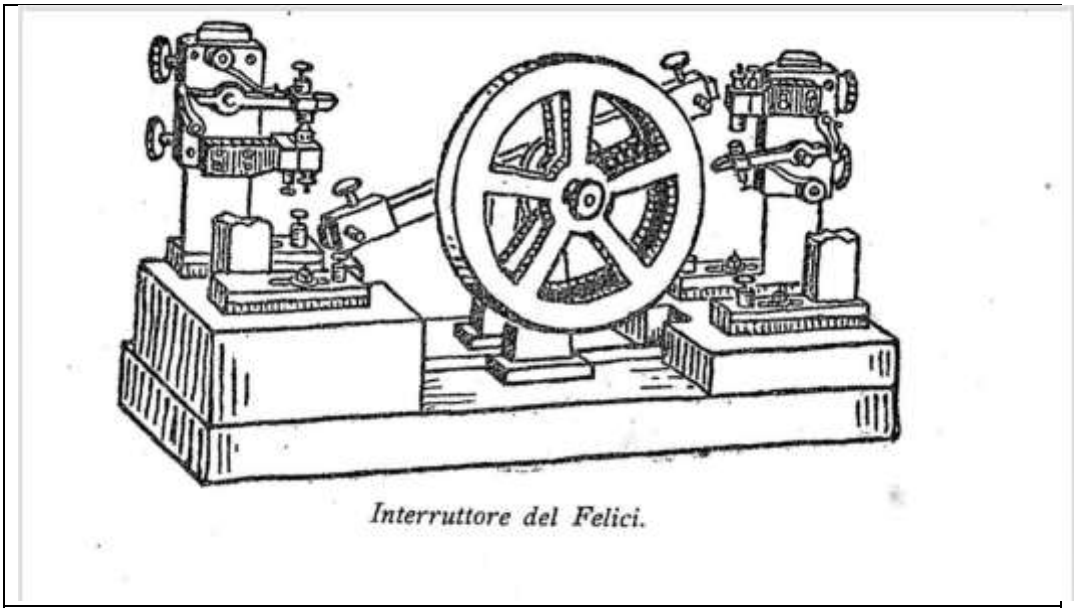

Fig. 1. Felici's switch (Occhialini 2014)

Finally we may recall some minor works, carried out between the Seventies and the Eighties, and related to laboratory experiences:

i) the study of the potential of a moving conductor under the influence of a magnetic field;
ii) the theory of the propagation of electricity in a homogeneous conductive sphere when the electrodes are placed on its surface;
iii) the investigation of phenomenological aspects of electromagnetic induction;
iv) the study of electromagnetic phenomena in moving fluids;
v) the "Amperian forces";
vi) the study of string vibrations;
vii) memoirs on thermodynamics, acoustics and optics, many of which constituted the thesis topic of his students.

3. Felici's view of physics and its impact

From a retrospective examination of the list of his works, we note that special attention was paid by Felici to the particular and indissoluble relationship between mathematics and physics, not seen from the axiomatic perspective typical of mathematical physics, such as it was taken for example by Neumann, Weber and Lenz in their research on electrodynamic induction, but rather from a theoretical physics point of view, starting from hypotheses having a clear and precise experimental basis and not being assumed a priori.

This epistemological position of Felici probably arose from a fruitful combination of the teachings received from Mossotti and Matteucci, from which he matured a sure, firm

and profound conviction on the necessary union between mathematics and physics, nearer to Galileo's prescriptions than to the typical attitude of mathematical physicists.

Felici renewed the Galilean tradition in its most typical methodological aspects of study, research and experimentation, starting above all from the work on electromagnetic induction, and with this he gave birth to a true school of Pisan Physics alongside the contemporary birth of a equally important school of mathematical physics - that of Enrico Betti and Vito Volterra, who were very much affected by Felici's influence.

Faced with the limited number of publications by Felici (almost all of them, however, having a character of completeness), one cannot certainly forget, alongside the figure of the researcher, that of a teacher: indeed for many years, as Pochettino wrote, in Italy

> [...] there was only one physical Institute, that of Pisa, directed by Felici, and the school could not have been better because from him, equally eminent both from the mathematical point of view and from the experimental point of view, the youth could come to know well the true way of working in the field of physics; that is, to balance the theoretical element with the experimental one in a proper measure, so that the inappropriate overdominance of one over the other does not lead to either abstruse metaphysics or disordered empiricism. (Pochettino 1930)

Despite this, Felici's pioneering work did not have a direct academic following in Pisa, partly due to Felici's own motives and dispositions, which led to a sort of diaspora of his students in many parts of the country. A complete list would be very long. Let's just recall here those who became full professors of Experimental Physics: E. Villari (in Bologna and Naples), A. Roiti (in Florence), L. Donati (in Bologna), G. Poloni (in Modena), A. Bartoli (in Catania and Pavia), G. Bongiovanni (in Ferrara), O. Murani (in Milan), not to mention mathematical physicists like E. Padova, G. Ricci Curbastro, C. Somigliana and V. Volterra.

This migration produced in the Pisa school of physics some discontinuity, that was in some way rectified only in 1917 with the call of Luigi Puccianti, who always held in great esteem the teaching of Felici, his studies and his researches. He explicitly attests that, with Felici, the school of Physics in Pisa reached the highest level of scientific research, thus renewing the great Galilean tradition. Recalling the famous maxim of Saggiatore ["philosophy is written in this great book ..."], Puccianti wrote that

> [...] perhaps no other modern physicist has ever conformed like him to the famous Galileo maxim with equal severity. [...] But if it is easy to admire the profound truth contained in this maxim, and to see in it a general and invariable norm of the method, it is very difficult to follow it rigorously, without being discouraged by the logical abstractness of those pure mathematical entities, or allowing oneself to be led to transform them with fantasy (as too often happened in the history of science) into fictitious physical entities, attributing to them an imaginary concreteness, which gives them the comforting illusion of handling real things by treating them: from which precisely repelled the mentality of R Felici, who [...] while sitting in the chair of experimental physics was no less a mathematician than an experimenter. (Puccianti 1939)

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