MAESTRO AND HIS PUPILS: HISTORY OF A SCIENTIFIC PRODUCTION

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Francesco dell'Isola trained generations of scholars in the many subsets of Continuum Mechanics in which he himself fine-tuned his knowledge. In his scientific production, one can recognize various periods on the basis of the main interest emerging from his publications of the period in question.

The early production

The first problems that dell'Isola tackled date back to the late 1980s, when he pursued a master's degree in Physics under the mentorship of Antonio Romano. With Romano he studies interface and phase transition problems (1; 2).

This work formed the basis for the subsequent development of studies, carried out independently or together with his early colleagues, still concerning interface (3) or phase transition problems (4) in fluids. It is interesting to note how the young dell'Isola approached the main theme of his scientific production even today, the materials described by means of second gradient theories, through the study of fluids (5), finding himself at the very roots of second gradient theories, which took their origin from Pierre Casal's studies on capillarity (6).

These initial studies are mostly of a theoretical nature, but soon dell'Isola realizes how important it is to have practical feedback and it is to this need that the early work with Ugo Andreaus and others including numerics can be ascribed (7; 8).

Francesco dell'Isola finds in his fellow student from university days, Luigi Rosa, the closest collaborator of this period. With Rosa, he approaches the study of Saint-Venant cylinders (9; 10). He soon also extends his collaboration to other researchers, Giuseppe Ruta (Roma) and Romesh Batra (Rolla, Missouri), with whom he deals with topics still related to the Saint-Venant cylinders, but with peculiar characteristics (11; 12).

During this period, dell'Isola tackles various lines of research in parallel: with Rosa, Ruta and Batra Saint-Venant cylinders again, where he also introduces aspects of piezoelectricity (16; 13; 14; 15); with Czesław Woźniak (Warsaw) composite and microstructured materials, for which he refers to his early studies on interfaces (17; 18; 19; 20); with Kolumban Hutter (Darmstadt) application studies for different soil types (21; 22; 23; 24; 25). In addition, it is also during this same period that he begins his collaboration with Pierre Seppecher (Toulon) and the first germs of studies on the second gradient, contained in their work on edge contact forces (26).

The "piezoelectric years"

During these years, dell'Isola, who in the meantime has obtained a Ph.D. in Mathematical Physics (1992) and the qualification for Maitre de Conferences (1995), supervises the research of several Ph.D. students: Stefano Vidoli, Giulio Sciarra, Maurizio Porfiri and Corrado Maurini.

The core of the research conducted by dell'Isola and his Ph.D. students during this period concerns piezoelectric materials. Returning to the study of the Saint-Venant cylinder, he addresses the problem of a piezoelectric circular bar with Vidoli (27).

In addition to some works of various kinds with some colleagues, as his fellow student Ramiro Dell'Erba, (28; 29), in this period, as mentioned, dell'Isola focuses mostly on the study of piezoelectric materials and their use in problems of relevance in mechanics. With Vidoli he faces one-dimensional problems (35; 30; 31; 32; 33; 34); he also studies piezoelectro-mechanical control system for bidimensional problems (36; 38; 37); with Porfiri, on the other hand, the attention is placed on the problems of circuit synthesis and on the study of analogous circuits for Mechanics (39; 40; 41; 48; 47; 42; 43; 44; 45; 49; 46); finally, with Maurini different problems related to piezoelectro-mechanical systems are studied (50; 51; 52; 54; 53).

An interesting aspect of dell'Isola's scientific production consists in the fact that periodically the lines of research that he conducts intersect and influence each other: it is remarkable that, parallel to the study of the problem of the synthesis of circuits with Porfiri, dell'Isola approaches with Pierre Seppecher and Jean-Jaques Alibert (Toulon) the problem of synthesis in the mechanical field (55). The result of this collaboration is a work that still today opens new horizons in the synthesis of metamaterials.

During this period, dell'Isola also strengthens his familiarity with Gerard Maugin, from whom he was invited to Jussieu (Paris) in 1994 and through whom he met Paul Germain (see the Preface). As a result of his connection with Maugin and his group, in addition to the co-direction of Maurini,Äôs Ph.D. conducted with Joel Pouget, there are some works in the field of poroelasticity (56; 57). It is from these last works that the studies with Sciarra on poroelasticity develop (58; 59; 60; 61).

After a brief revival of the Sant-Venant problem (62), the piezoelectric years ideally conclude with three works concerning vibration control (63) and suppression (64) and damage detection (65).

The "variational" and "second gradient" years

As it is clear from scrolling through the list of his works, Francesco dell'Isola has always been a "variational man". Descending ideally from the school of Lagrange, as we mentioned in the Preface, dell'Isola could be nothing but variational. So the title of this section must be put into context: by the *variational years* we mean that during this period dell'Isola explicitly adopts the variational approach to the study of the problems he faces. This period logically precedes and intersects the development of the main theme of his research activity: second gradient theories.

During this period, a second generation of doctoral students replaces the first one, now autonomous. These new Ph.D. students are: Luca Placidi, Angela Madeo and Giuseppe Rosi. Like many of dell'Isola's pupils, Madeo and Rosi, once they have obtained their Ph.D., will also be employed in French universities.

The variational period is strictly linked to the previous one. In fact, as we have mentioned, with Sciarra dell'Isola has started a study on poromechanics. This study, to whom also Olivier Coussy (Paris) collaborates, finally produces some results, through variational approach, in the second gradient theory field (66; 69; 68; 67; 70; 71).

During this period one of the current main dell'Isola's collaborators joins the group: he is Ivan Giorgio (Roma), and he is involved in the studies about vibration control, as Rosi (73; 72).

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The variational approach can be fruitfully used also in biological field. This is the case of bone remodeling. In these years dell'Isola starts a deep collaboration with Tomasz Lekszycki, who is responsible for a biomechanical laboratory in Warsaw University. With Lekszycki and Madeo first, Giorgio later, dell'Isola studies bone mechanics (74; 75; 76; 77; 78).

With Placidi and Madeo, dell'Isola explores different properties of higher gradient continua, both from a practical point of view (through numerics) (79; 80; 81), and from a theoretical point of view, also in collaboration with Ali Javili (Ankara), Paul Steinmann (Erlangen), Felix Darve (Grenoble), Nicholas Auffray (Paris), Raffaele Esposito (Roma) and Mario Pulvirenti (Roma) (89; 90; 91; 82; 83; 84; 85; 86; 87; 88). We want to stress that Ref. (84) represents the first collaboration with Victor A. Eremeyev (Gdansk-Cagliari), who will become one of the principal scholars in dell'Isola's group.

A fundamental aspect in Francesco dell'Isola's personality is represented by his attitude to the search for the sources of mathematical and, in general, scientific theories. An important example is represented by Peridynamics, which only recently has become of main interest, although its germinal ideas can be found in Gabrio Piola's works. This has been stressed in Ref. (92). We cite the words of the authors (dell'Isola, Andreaus and Placidi), who well explain the problem of approaching history of Science:

> The authors question the concept of a 'historical method' especially when applied to the history of science and history of mathematics. We claim that there is not any peculiar 'historical method' to be distinguished from the generic 'scientific method' which has to be applied to describe any other kind of phenomenon, although the subject of the investigation is as complex as those involved in the transmission, storage and advancement of scientific knowledge.

The interest for Piola's work has a very important influence on dell'Isola subsequent investigation. The study of edge problems using variational approaches had previously led dell'Isola to the development of second gradient theories (26). At this point in his academic career, he enters into the fullness of his scientific maturity and is able to approach this topic in a comprehensive manner (93). A fundamental inspiration comes from reading the works of Gabrio Piola, which dell'Isola, assisted by a number of scientists, translates, in two volumes, completely into English for the first time (94; 95; 96; 97; 98; 99; 100; 101).

The "pantographic" years

In this period, the whole knowledge produced along the past years is employed for producing a practical realization of a second gradient material. In fact, one of the more frequent criticisms that dell'Isola receives when presents his ideas about second gradient materials at conferences and workshops is: "it's a good mathematical toy, but no practical applications are available because no second gradient material exists". His main purpose is then to realize a practical example of second gradient material. To this aim dell'Isola refers back to his paper with Alibert and Seppecher (55) and introduces the pantographic (micro)structure, which allows the realization, after a proper homogenization procedure, of the pantographic metamaterial. The first attempt to this purpose can be found in Ref. (102). In this paper numerical simulation are provided and compared to experiments. After it, many other works study the pantographic metamaterial and, more in general, fibrous second gradient metamaterials.

These years are characterized by many collaboration in experimental fields: again with Tomasz Lekszycki (Warsaw), Georg Ganzmüller (Freiburg) and Patrice Peyre (Paris), who

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offer the possibility to print samples via 3D printer in their laboratories using different materials, polymers and metals. This will be crucial for the subsequent developments. Also from the theoretical and numerical point of view, one can recognize different collaborations: David Steigmann (Berkeley), whose expertise in differential geometry helps in generalizing the bidimensional model for pantographic structure to 3D space (103; 104; 105; 106; 107); Victor Eremeyev (Gdansk) (108; 109; 110), Claude Boutin (Lion) (111), Pierre Seppecher (Toulon) (88), who analyze pure mathematical aspects at the foundations of pantographic metamaterial; Massimo Cuomo and Leopoldo Greco (Catania), whose *know-how* in numerics is crucial for calibrating the models (112; 113; 114; 115); Anil Misra (Lawrence, Kansas), who studies exotic phenomena emerging in this metamaterial (116; 117); Ugo Andreaus (Roma) and Nicola Rizzi (Roma), who introduce the pantographic metamaterial into their Engineering background (118); Antonio Cazzani (Cagliari) and Emilio Turco (Sassari), who propose different numerical approaches to discrete models (119; 120; 121); Wolfgang Müller (Berlin) (122), Jean-François Ganghoffer (Nancy) (123), Philippe Boisse (Lion) (124; 125; 126), who study different aspects relevant for possible generalizations of pantographic structure; Ivan Giorgio, who deals with different aspects of the pantographic substructure, such as dynamics, identification of constitutive parameters for second gradient models, three-dimensional deformations (127; 128; 129; 130); François Hild (Paris), who introduces the powerful tools of Digital Image Correlation in the analysis of metamaterials (131).

An already remarked aspect of dell'Isola's research style is represented by the interest in the source of scientific theories. Also the *pantographic years* are characterized by this style: with Simon Eugster (Stuttgart) an "exegesis" on the Hellinger's work is approached and presented in Refs. (132; 133; 134); other works in the field of History of Science are (135; 136; 137).

This very large amount of collaborations fully emerges in two papers published in 2019 (138; 139): on the one hand, in Ref. (138) all the obtained results on pantographic metamaterial are recalled within the main contributions given by a large part of "old" dell'Isola's collaborations; Ref. (139), on the other hand, presents the first results of the new lines of research on the field of this metamaterial. Most part of the themes referred in this last paper will be the main topics of the subsequent years and still constitute a map for future developments.

The mentioned collaborations make a trend topic the pantographic metamaterial: a huge amount of publications concerning this topic and resulting from such joint efforts can be found in the literature (140; 141; 142; 144; 145; 143; 146; 147; 148; 149; 150; 151; 152)

The third generation of Ph.D. students is composed by: Alessandro Della Corte, Antonio Battista, Mario Spagnuolo, Emilio Barchiesi and Michele De Angelo.

With Alessandro Della Corte the main contributions concern the nonlinear beam theory (153; 154; 155). Antonio Battista is guided to the study of swarm systems in describing Continuum Mechanical problems (156; 158; 157). With Mario Spagnuolo (159; 160), Emilio Barchiesi (162; 161) and Michele De Angelo (163) the main efforts are in the field of pantographic metamaterial.

Current times: deep investigations in Generalized Continua

Francesco dell'Isola is currently engaged in the study of the many aspects related to Generalized Continua. Specifically, with a large number of the collaborators mentioned in the previous sections, he is working on:

i. pantographic metamaterial (164; 165; 166; 167; 168; 169; 170)

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ii. micromorphic materials (171; 172; 173; 174; 175; 176; 177)
iii. granular materials and metamaterials based on this concept (178; 183; 180; 181; 182; 179)
iv. fiber-reinforced materials (185; 186; 184)
v. Digital Image Correlation applied to the study of metamaterials (187; 188; 189)
vi. Dissipation in Continuum Mechanics (190)
vii. Piezoelectric materials (a revival of) (191)
viii. History of Science Investigations (a revival of) (192; 193; 194)

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