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Electromagnetism for Mechatronics

Janusz Turowski
Grzegorz Zwolinski
Institute of Electrical Machines & Transformers, Technical University of Lodz, ul. Stefanowskiego 18/22, 90-924 Lodz, Poland
Zenon J. Pudlowski
UNESCO International Centre for Engineering Education (UICEE), Faculty of Engineering, Monash University, Clayton, Melbourne, VIC 3800, Australia

Electromagnetic theory is usually regarded as the most difficult subject in electrical engineering. Because of its wide application in electrical and mechanical systems, it has become an important subject. Therefore, special attention is given to the teaching of electromagnetic theory and application in mechatronics, a relatively new speciality in engineering. A special subject, dealing with the concepts, ideas and principles of electromagnetism has been designed and implemented. The paper presents a new approach to teaching electromagnetism, and the way in which the Reluctance Network Method (RNM) can be successfully used for the analysis of electromagnetic circuits and structures. Also, some comparisons between different methods of analysis are presented and discussed in the paper.

INTRODUCTION

Mechatronics is an interdisciplinary body of

> *…knowledge that was developed, to a great extent, in mechanical engineering departments and other non-electrical departments, as well as in the more non-electromagnetic university specialisations. It is considered as especially essential for the engineering environment of the next millennium* [1].

In a paper by Rizzo et al., the definition adopted by the International Federation for the Theory of Machines and Mechanism (IFTMM) is presented. It states that

> *…Mechatronics is the synergistic combination of precision mechanical engineering, electronic control and systems thinking in the design of products and manufacturing processes* [2].

As presented in Figure1a, this is not sufficient to describe the full development of this emerging discipline and specialisation. This approach does not take into account the inside of the structure of motors and many new electromechanical apparatus and devices. It is not possible to establish whether magnetic and electric circuits of such devices are optimal for a given job and a power supply without a thorough electromagnetic analysis. There are many examples that demonstrate that not only electronics and computers, but also the internal electromagnetic structure play a significant role in the assurance of optimal mechatronics system design and performance.

Electromechanical components of mechatronics are especially sensitive to their internal electromagnetic structures. Most impressive and popular examples of such structures are stepping, linear, switched reluctance and brushless motors of a large variety. Such mechatronics components can not exist separately

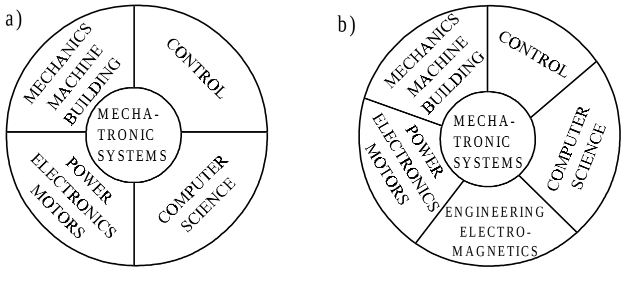


Figure 1: Two approaches to the definition of mechatronics: a) Formal *mechanical*, b) Considering the component design [2].

without any internal, inherent feedback of magnetic and electronic circuits.

Modern electrical machines are mostly *tailor-made* by manufacturers of components for aircraft, automobile, robotics and other modern mechatronic systems. Also, the modernisation of traditional components of automatics, like synchros, resolvers, magnesyns, microsyns, inductosyns, reductosyns, synchrotels, electromagnetic sensors, etc, is not possible without an electromagnetic analysis. From this point of view, the strictly *mechanical* definition (Figure 1a), indicated above, should be extended by saying that *engineering electromagnetics* is an inseparable element of education in Mechatronics (Figure 1b).

In light, it is necessary to look for an appropriate method for teaching electromagnetism, one that would be as easy and simple as possible, but without losing its accuracy, and which would be most user-friendly for non-electrical specialisations. This is the main objective of this work.

The most difficult problem for modern mechatronics is that for most engineers, electromagnetism is mistakenly thought to be too difficult. Also, they do not accept the fact that it is an effective and indispensable engineering tool. The solution is simple: it requires the selection of the proper method of analysis. The Reluctance Network Method (RNM) is extremely easy and user-friendly in this sense.

CHOOSING EASY AND USER-FRIENDLY METHODS OF ELECTROMAGNETIC DESIGN

At the beginning of 1980s, it was very popular to compare different methods of approximate numerical calculations of electromagnetic fields [3]. Such a comparison was too general as it was carried out on rather simple models. The contemporary approach to this problem involves carrying out such a comparison from the point of view of the usefulness of a particular method for the solution to a given problem or class of jobs, or for groups of users, rather than from a general point of view without strictly defined criteria.

For instance, the most popular Finite Element Method (FEM) is nowadays used widely to determine solutions to many problems, especially with 2-D and quasi 2-D configurations. Although the FEM method is by no means absolutely universal, it has been found that not every method is the best for any job. For example, in external, open boundary problems, the Boundary Element Method (BEM) is much better than the FEM. On the other hand, in cover-plates and bushing systems in transformers, the Analytically-Numerical (ANM) *Biot-Savart* approach is much better than all of the mesh methods mentioned above [4].

In many practical applications, the determination of an equivalent reluctance has proved to be the most simple and user-friendly method. It is the most understandable method for non-specialists because they can very easily accept the analogy between the water flow in pipes, the current flow in electric circuits, the magnetic flux flow in magnetic structures, etc. In this analogy, the pipes can be represented by resistances in an electric circuit and by magnetic reluctances in a magnetic circuit.

Fundamental circuit theory laws such as *Ohm's* and *Kirchhoff's* laws, as well as their magnetic analogies, can easily be used to analyse such circuits, as they are well taught in secondary school physics. Nevertheless, it is necessary to compare main numerical methods used for the numerical calculation of electromagnetic fields from various practical points of view.

Table 1 presents the comparison of different approximate numerical methods used for 3-D modelling and computation of electromagnetic fields. This comparison was carried out in order to illustrate the strengths and weaknesses of these methods from the most important practical points of view (criteria).

Some impressions in Table 1 can be considered to be more or less subjective, but they are based on long and numerous observations of publications, conferences as well as industry and personal experience.

From the analysis in Table 1, it follows that for the most popular and easy application, the equivalent reluctance method three-dimensional (RNM-3D) is the most recommended for non-electrical specialists. This has been confirmed by many practical applications [2][4-13]. More detailed description of the RNM teaching approach is given in papers [14] to [16]. After a student gains experience in RNM, it is possible to try to use a more sophisticated commercial package or FEM in 2-D and Quasi 2-D systems. Real FEM-3D is too complicated.

TRAINING OF MECHATRONICS STUDENTS IN ENGINEERING ELECTROMAGNETICS

A special subject dealing with the fundamental concepts of electromagnetic fields and electromagnetic circuit design has been developed and implemented.

The subject consists of fundamentals of the theory of electromagnetic fields, analytical exercises and calculation of definite engineering problems encountered in everyday practice (eg touch and step voltage), earthing resistance, capacitors, radiolocation fields, power losses in a round bar made of solid steel, induction dryers or heaters, solid steel elements of

Table 1: The comparison of cost, usefulness and simplicity of different approximate numerical methods for fast, 3-D interactive modelling, computation and design of electromagnetic fields, forces and losses in electromechanical converters.

No	Criteria	Method	Specifics Low	Specifics Medium	Specifics High
1	2	3	4	5	6
1	Degree of elaboration in literature	FDM	======	======	=
		FEM	======	======	====
		BEM	=====		
		RNM	======	=	
		ANM	======	=	
2	Cost of hardware and 3-D software	FDM	======	======	=
		FEM	======	======	===
		BEM	======	======	=====
		RNM	===		
		ANM	=====		
3	Cost and duration of complex 3-D computation of one design variant	FDM	======	======	=====
		FEM	======	======	=====
		BEM	======	======	=====
		RNM	===		
		ANM	======	==	
4	Cost and time of training of user	FDM	======	======	===
		FEM	======	======	=====
		BEM	======	======	=====
		RNM	===		
		ANM	======	======	==
5	Cost, difficulty and time of fulfilment of 3-D convergence conditions	FDM	======	======	===
		FEM	======	======	===
		BEM	======	======	=
		RNM	====		
		ANM	===		
6	Cost and time of fulfilment of boundary conditions	FDM	======	======	==
		FEM	======	======	==
		BEM	======	======	==
		RNM	=====		
		ANM	=====		
7	Stability of solution	FDM	=====		
		FEM	=====		
		BEM	======	=	
		RNM	======	======	====
		ANM	======	====	
8	Errors of approximation and rounding of a numbers with respect to computation time	FDM	======	=====	
		FEM	======	=====	
		BEM	======	======	=
		RNM	====		
		ANM	======	======	=====
9	Self-generation of errors and discontinuities (eg as an effect of differentiation)	FDM	======	======	===
		FEM	======	======	===
		BEM	======	=	
		RNM	====		
		ANM	====		
10	Cost and time of solution of internal 3-D problems in non-linear, conducting media, considering local heating	FDM	======	======	====
		FEM	======	======	==
		BEM	======	======	=====
		RNM	===		
		ANM	======	======	=====
11	Cost and time of solution of external 3-D problems in non-linear, conducting media	FDM	======	======	=====
		FEM	======	======	=====
		BEM	======	=	
		RNM	====		
		ANM	======	======	
12	Cost and duration of computation of 2-D and quasi 3-D models	FDM	======	======	=
		FEM	======	======	=
		BEM	======	======	==
		RNM	=====		
		ANM	======	==	
13	Possibility of hybrid co-operation with other methods	FDM	======	===	
		FEM	======	===	
		BEM	=====		
		RNM	======	======	===
		ANM	======	======	===
14	Quality of industrial verification confirmed	FDM	=====		
		FEM	======	=	
		BEM	=====		
		RNM	======	======	=====
		ANM	=====		
15	Usefulness of output data for direct, fast, interactive industrial design	FDM	======	=	
		FEM	======	=	
		BEM	=====		
		RNM	======	======	====
		ANM	======	=	
16	Implementation and sail applicable programs (Reference list)	FDM	====		
		FEM	======	===	
		BEM	====		
		RNM	======	======	====
		ANM	=====		

electrical machines and power transformers, screening (in power transformers, stealth aircraft technology, tanks, ships, etc), wave-guides, etc.

The practical part of the subject is enriched by laboratory demonstrations of applied computer methods, including the Reluctance Network Method (RNM), Tubes and Slices Method (TSM), Boundary Element Method (BEM) and Finite Element Method (FEM). All the methods use the same practical example and the same magnetic structure (electromagnet). It should be mentioned at this point that the use of the RNM-3D method by students in the laboratory experiments has been found to be the most efficient and easy.

EXERCISES IN COMPUTER LABORATORY

The subject was offered in the International Faculty of Engineering (IFE) at the Technical University of Lodz (TUL), Lodz, Poland, as EDT-LAB between 11 May and 5 June 1998, that is in the fourth semester of academic year 1997/98. The study speciality was *Mechatronics* and the subject name was *Engineering Electrodynamics*. Prof. J. Turowski supervised the subject, and there were several packages, dealing with modelling and computation of electromagnetic fields, power losses and forces used in the subject.

These included:

1. Zwolinski, G., Exercises on FINITE DIFFERENCE METHOD - **FDM**
   [a] Wiak, S. and Zwolinski, G., Selected computation problems of technological electrodynamics (in Polish). *Politechnika Lodzka*, Lodz (1997). FDM Suppl.No. 1, 2: Service Manual Program *MRS-ed*.

2 1. Sykulski, J., Exercises on METHOD OF TUBES AND SLICES - **TaS**
   [b] Hammond, P. and Sykulski, J.K.: Engineering Electromagnetism: Physical Processes and Computation. Oxford, New York, Toronto: Oxford University Press (1994), with program disk.

3. Turowski, J., RELUCTANCE NETWORK METHOD THREE-DIMENSIONAL **RNM-3D**
   [c] Turowski, J.: Computational Magnetics. Chapter 4. Reluctance Networks. New York, London: Chapman & Hall (1995), including files:
   c.1. **rekl-rnm. doc** - Information about the advantages and possibilities of the RNM-3D Program at the dedicated calculation of stray field and losses in power transformers.
   c.2. **uvw1.pcx** - Figure 3-D. To run, press: NC Enter; F3 Enter; Reduce/enlarge grey-/+; Esc
   c.3. **rnmdemo.exe** - To demonstrate calculation with the help Program **RNM-3D** of the stray field component and loss distribution in three-phase power transformer. To run: press: Enter ... Q - to quit.
   c.4. **rnmquest.doc** - The *Questionnaire*. To prepare data for three-dimensional (3-D) simulation and computation of leakage field, eddy current losses in tank wall and selection of electromagnetic and/or magnetic screens in three-phase power transformers on an IBM PC compatible computer, on below than 1 second CPU time for each structural variant.

4. Integrated Engineering Software, Canada. Boundary Element Method - **BEM**
   [d] BEM I, ELECTRO + MAGNETO and BEM II, ELECTRO + COULOMB demonstration diskettes. Hardware required: a) IBM PC/AT, PS/2 or compatible, b) DOS 3.3 or higher, c) IBM VGA or compatible, d) (1.44 MB) Floppy Drive, e) Fixed Disk.
   Vector Fields UK. Finite Element Method - **FEM.** *PC-OPERA* (demo disk).

Some practical exercises used in the subjects were as follows:

Exercise 18: Engineering Electrodynamics

Calculate the force $F = f(g)$ and the flux density $B_{max} = f\ (g)$ in a lifting electromagnet (Figure 2) with respect to the gap g = 3 to 1 mm. Dimensions in mm: a = 80, b = 20, c =10, d = 50, e = 30, f = 10, h = 10, g = 1, 2, 3. The magnetic core is made of laminated iron with an average relative magnetic permeability μ_r = 700 = const.

Use the following approximate numerical methods:

1. Finite Difference FDM
2. Reluctance Network RNM
3. Tubes and Slices TAS

Check the results obtained with other methods.

Solution

The field is described by the Poisson's Equation as follows:

$$\frac{\partial^2 A_z}{\partial x^2} + \frac{\partial^2 A_z}{\partial y^2} = -\mu_0 J_z$$

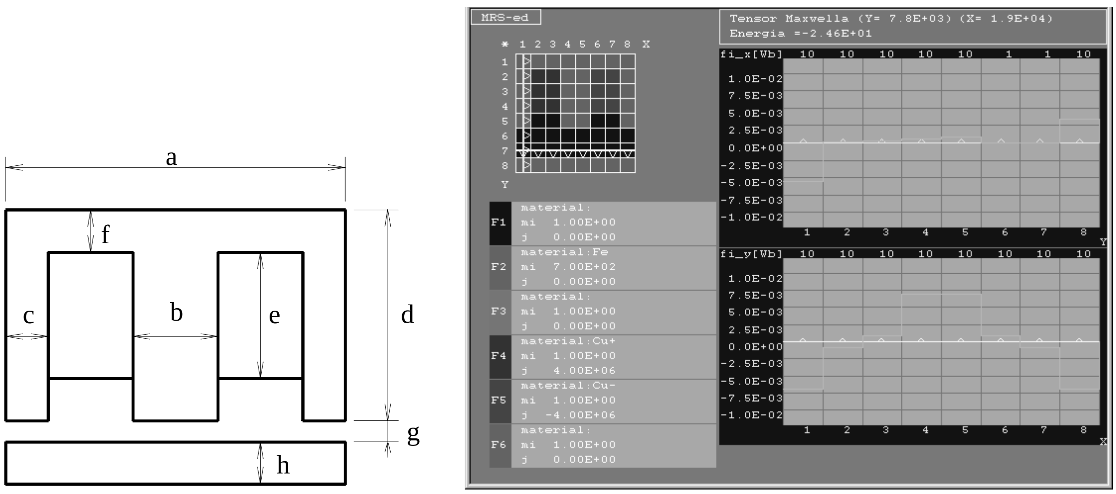


Figure 2: Modelling of the lifting electromagnet (FDM).

In order to solve any differential equation, boundary conditions should be applied. In electromagnetic problems they are usually: Dirichlet, including zero condition ($A=0$ or $H = 0$), and Neumann, including zero ($\frac{\partial A}{\partial n}$ = 0 or $H_t = 0$).

The electromagnetic forces can be calculated using the following three methods:

a) From the Ampere's law:

$$\mathrm{d}\boldsymbol{F} = I\,(\mathrm{d}\boldsymbol{l} \times \boldsymbol{B}) = \mathbf{n}I\,\mathrm{d}l\,B \sin \angle(\mathrm{d}\boldsymbol{l}, \boldsymbol{B}),$$

$$\boldsymbol{F} = \iiint_V (\mathbf{J} \times \mathbf{B})\,\mathrm{d}V = \boldsymbol{n}\,B\,I\,l \sin \angle(\boldsymbol{I}, \boldsymbol{B})$$

b) From the principle of virtual works (see: J. Turowski: *Teoria maszyn elektrycznych* Theory of elcetrical machines. TUL, 1984, p.17), we can see that:

$F_g = -\,(\partial\, W_m{}'/\partial\, g\,)_{\mathrm{i=const}}$, where F_g is the force in direction of g of motion of the moving part, $W_m{}'$ magnetic co-energy = energy when μ = const.

c) From the Maxwell's stress tensor:

$$F = \tfrac{1}{2}\,\mu_0\,\boldsymbol{n} \iint_s \left(H_n^2 - H_t^2\right)\mathrm{d}s + \mu_0\,\boldsymbol{t} \iint_s H_n H_t\,\mathrm{d}s$$

$$= \boldsymbol{n}F_n + \boldsymbol{t}F_t$$

Please note that in the method of virtual works, we use the total energy of the system, whereas in the Maxwell's stress tensor, we are looking only for the field on the surface of the moving element.

Flux linkage: Definition:

$$\psi = Li, \qquad \psi = N\Phi\ ;$$

$$\Phi = \iint \mathbf{B} \bullet \mathrm{d}\,\mathbf{s} = \frac{N\,i}{R_m}\ ;$$

$$R_{mi} = \frac{l_i}{\mu\, s_i}\ ; \quad W_m = \frac{L\,i^2}{2}$$

Flux density: $\int \mathbf{H} \times \mathrm{d}\,\mathbf{l} = Ni$;

$$\sum_{i=1}^{i=n} H_i\, l_i = Ni\ ;$$

$$\sum_i H_{Fe}\, l_{Fe} + \sum_i H_0\, g = Ni\ ;$$

At $\mu_{Fe} >> \mu_0$, $\quad \displaystyle\sum_{i=1}^{i=n} H_{Fe}\, l_{Fe} \approx 0$

and $\quad B_{0m} = \mu_0 H_{0m} \approx \mu_0 \dfrac{\sqrt{2}\,NI}{\Sigma g_i}$.

More detailed descriptions of the RNM-3D method applied in teaching is given in [15][16].

INDUSTRIAL ASPECTS

In simple 2-D examples used by students, all the methods (FDM, RNM, TSM, BEM and FEM) are practically equivalent in their complexity and the use of time.

However, when solving complex 3-D problems (Figure 3) the RNM-3D solution takes a few seconds on a PC, whereas the FEM-3D needs hundreds of hours of the CPU's time on an expensive computer and requires the use to be highly qualified to be able to use it.

CONCLUSION

It has been found that applied electromagnetics plays an important role in the teaching of mechatronics. The nature and complexity of electromagnetics require an extensive use of modern numerical methods, especially for electromagnetic field computation. However, many excellent numerical methods applied in electromagnetic field computation are too difficult when used in design and application by non-electrical specialists.

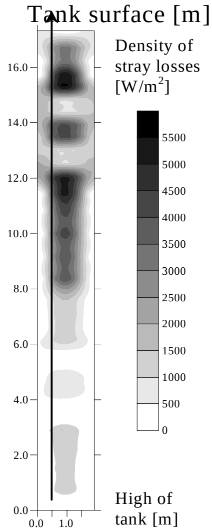
Practical experience shows that the RNM-3D method is an extremely simple tool, which provides the user with a user-friendly environment in electromagnetic field computation. Therefore, the use of this method should be strongly recommended to staff and students in mechatronics engineering education.

When using the RNM, students can even model 3-D fields, the process which is extremely difficult, time consuming and expensive in the FEM-3D, FDM-3D and BEM-3D.

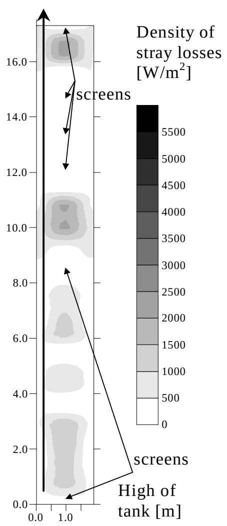
After students become familiar with all the basic ideas, notions and laws of electromagnetic fields, they can endeavour to use much more sophisticated and expensive methods like FEM, FDM, BEM and other commercial programs. Since electromechanical devices can often be modelled and calculated with the help of 2-D fields, then the FEM is much easier, as they can continue their analyses with FEM-2D.

The most difficult problem for modern mechatronics is that for most engineers, electromagnetism is mistakenly thought to be too difficult. Often it is very difficult to calculate certain electromagnetic structures. There is a simple solution by selecting the proper method of analysis. The Reluctance Network Method (RNM) is extremely easy and user-friendly in this sense.

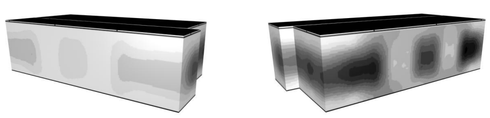
Furthermore, it is mostly engineers who do not accept that it is an effective and indispensable engineering tool.



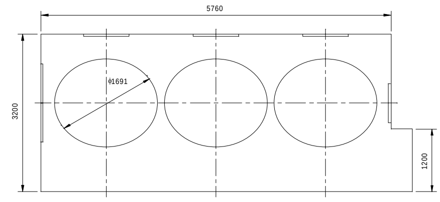
a) A model without screens (total stray losses 47.77 kW).



b) A model with screens (total stray losses 18.88 kW).



c) The density of stray losses on the tank surface.



d) Cross section of the transformer.

Figure 3: Transformer of 100 MVA, 220/132/11 kV, with results of calculations of stray loss with RNM-3D method (G. Zwolinski [11]).

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BIOGRAPHIES

Profesor Janusz Turowski was born in the former eastern territory of Poland and was deported by the Soviets to Siberia (1940-46). He graduated from the Technical University of Lodz (TUL), Poland with an MSc in Electrical Engineering in 1951. He received his PhD in 1958 and the DSc in 1963. He was appointed professor in 1964 and full professor in 1978. He received the degree of Doctor *Honoris Causa* from the University of Pavia, Italy, in 1998.

Prof. Turowski was Director of the Institute of Electrical Machines and Transformers, Technical University of Lodz (1973-92) and Vice-Rector of the TUL for International Co-operation (1990-96). He was a Member of the Supreme Council for University Education in Poland (1990-96). He has authored and co-authored about 230 scientific publications in Poland, UK, USA, France, Russia and other countries, including 43 books or chapters in books. Others have cited him over 766 times. He is Past President of the Polish Association of Theoretical and Applied Electrotechnics and is its Honorary Member. He is a Member (1978-) and Vice-Chairman (1999-) of the Electrical Committee of the Polish Academy of Science. Prof. Turowski is a Member of the UATI Administrative Board (1999-) and UNESCO International Committee of Higher Education of Technologies COMIEST-Paris (2000-). He is Chairman (1979-) of biennial *Internat. Symposium on Electromagnetic Fields in Elec. Eng.*, Member of CIGRE (Paris, 1964-), Senior Member IEEE (USA 1988-), SEFI (Paris 1992-96), *Alliance Universities for Democracy* (USA), *International Compumag Society* (1996-) and of the New York Academy of Science (1994-95). He was also a Member of the International EC/PHARE Higher Education Steering Committee (1996-97), Chairman of Polish UNISPAR Working Group Soc. (1996-), a Member of the Baltic Sea Innovation Network BASIN Steering Committee (1999-), plus others.

He has supervised 17 PhD theses and is a Consultant to the Ministers and Transformer Works in Poland, India and China. He has received several scientific awards of Polish Academy of Science and the Ministry of National Education. He received two State Crosses, and is cited in 15 Who's Who world publications. He is married, with two sons.

Grzegorz Zwolinski was born in Lodz, Poland in 1967. He attended the Technical University of Lodz from 1987 to 1992 were he received the degree of MSc degree in the Institute of Electrical Machines and Transformers in 1992 and a PhD in 1999.

Since then he has worked as a Teaching and Research Assistant at the same Institute. Since 1993 he has worked on the modelling of electromagnetic fields in transformers and machines using 3-D Reluctance Network Analysis Methods. He is married, with two sons.

Zenon Jan Pudlowski graduated Master of Electrical Engineering from the Academy of Mining and Metallurgy (Cracow, Poland), and Doctor of Philosophy from Jagiellonian University (Cracow), in 1968 and 1979 respectively. From 1969 to 1976 he was a lecturer in the Institute of Technology within the University of Pedagogy (Cracow). Between 1976 and 1979 he was a researcher at the Institute of Vocational Education (Warsaw), and from 1979 to 1981 was an Adjunct Professor at the Institute of Pedogogy within Jagiellonian University. From 1981 to 1993 he was with the Department of Electrical Engineering at The University of Sydney where, in recent years, he was a Senior Lecturer.

He is presently Professor and Director of the UNESCO International Centre for Engineering Education (UICEE) in the Faculty of Engineering at Monash University, Clayton, Melbourne, Australia. He was Associate Dean (Engineering Education) of the Faculty of Engineering between 1994 and 1998. His achievements to date have been published in books and manuals and in over 250 scientific papers, in refereed journals and conference proceedings.

In 1992 he was instrumental in establishing an International Faculty of Engineering at the Technical University of Lodz, Poland, of which he is the Foundation Dean and Professor (in absentia)(1992-99). He was also appointed Honorary Dean of the English Engineering Faculty at the Donetsk State Technical University (DonSTU) in the Ukraine in 1995.

Professor Pudlowski is a Fellow of the Institution of Engineers, Australia. He is a member of the editorial advisory boards of many international journals. He was the 1st Vice-President and Executive Director of the AAEE and the Editor-in-Chief of the AJEE since its inception in 1989 until 1997. Currently he is the Editor-in-Chief of the *Global Journal of Engineering Education*, and is the Foundation Secretary of the International Liaison Group for Engineering Education (ILG-EE).

Professor Pudlowski has chaired and organised several international conferences and meetings. He received the inaugural AAEE Medal for Distinguished Contributions to Engineering Education (Australasia) in 1991 and was awarded the Order of the Egyptian Syndicate of Engineers *for Contributions to the Development of Engineering Education on both National and International Levels* in 1994.

In June 1996, Professor Pudlowski received an honorary doctorate from the Donetsk State Technical University in the Ukraine in recognition of his contributions to international engineering education, and in July 1998 he was awarded an honorary Doctorate of Technology from Glasgow Caledonian University, Glasgow, Scotland, United Kingdom. In 1997, he was elected a member of the Ukrainian Academy of Engineering Sciences.