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THE EXAMPLES OF NUMERICAL SOLUTIONS IN THE FIELD OF MILITARY TECHNOLOGY

Reviewer: Josef TKÁČ

A b s t r a c t :

The paper is based on previous work of the authors, presented e.g. in [1]. The area of authors' interests is based on numerical solutions of electrical, magnetic or mechanical fields. The well known numerical methods are Finite Elements and Boundary Elements. Application of these can be successfully done in special technologies or special equipment as hightorque lowspeed machine suitable for manipulators or robots working in dangerous and aggressive environment, highspeed bearingless actuators designed for aggressive and explosive surroundings, as well as design and optimization of bridges, pontoons, etc. The bases of the Finite Element Method (FEM) and overview of the authors' most important results in this field of interest is presented in the following chapters. The used mathematical apparatus leads to identical a compatible results which are independent from the used platform of computer application software.

1. Introduction

The finite element method becomes popular in the second half of the 20th century when power and expansion of personal computers enlarged rapidly. The designers are able to predict the behavior of designed objects and technologies and their prediction is based on several common features: definition of potential, gradient of potential, material properties and field density. The previous statement is based on the supposition that the designers are looking for field distribution in different spheres: electrostatic problems, problems of current distribution, magnetostatic problems [3], and structural, thermal or gravitation problems. The analogy between quantities can be found e.g. in [1, 2]. Independent on the solved sphere, the base of problem can be defined as:

$$\nabla \cdot \kappa \nabla U = -Q \tag{1}$$

where κ describes the used material properties, U represents the required potential distribution, and Q the presence of field sources. However, even when the equation (1) seems to be very simple and easy-to-solve, the opposite is true. Respecting the material parameters (do not have to be constant!), boundary conditions, etc., the solution of (1) becomes more and more complicated and requires numerical (sometimes also called: inaccurate) solution. The equation (1) describes different physics through material properties κ and used source fields Q, but mathematical tools for numerical solution are quite the same with small difference in treating material properties κ, source fields Q and unknown potential U. One of useful consequences is, that we can prepare geometry Ω of the solved problems in the same CAD software package, independently on physical bases of the problem.

2. Finite Element Bases

The FEM is based on the Weighted Residual Method [2, 1], where the final distribution of the sought potential can be expressed as:

$$U = \sum_i N_i U_i \tag{2}$$

where the area of interest is divided into several subareas where U_i is the required solution of potential for subarea i, N_i is the properly chosen function, sometime called base function for subarea i. Inserting (2) into (1), multiplying by weight function w and integrating over the area of interest Ω, the following formula can be obtained:

$$\int_\Omega \left[w_i \left(\nabla \cdot \kappa \nabla \sum_i N_i U_i + Q \right) \right] d\Omega = 0 \tag{3}$$

The choise of weight function according to Galerkin [2] should lead to finite element formulation, where the basic results are the potential distributions on subareas (elements). Postprocessing of these primary results could lead to additional (secondary) results as forces, torques, etc., where the today's computer techniques can easily combine electrical, mechanical or magnetic fields and variables.

3. Examples Overview

The authors are interested in the design of a great variety of different special technologies, machinery and equipment; however, at the beginning of this chapter, two simple solutions will be introduced. The model of electromagnetic contactor has been built and the magnetic field distribution in this contactor has been solved. The primary result (magnetic potential distribution – see fig. 1) can be postprocessed and e.g. the required force can be computed [6]. After changing the model geometry, the force F vs air gap width δ can be obtained (fig. 2).

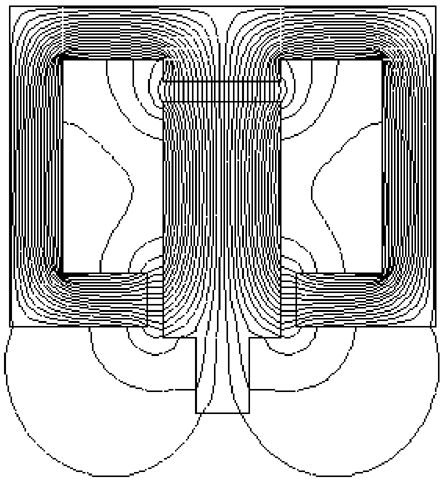

Fig. 1 – Field Distribution in Electromechanical Contactor

The second model is a model of a direct current machine. The field distribution for different rotor position can be seen in fig. 3, 5 and 7. Relevant flux density distribution in machine air gap can be seen in fig. 4, 6 and 8. Mechanical torque can be evaluated in postprocessing procedures in this case. The torque characteristic, as function of rotor position, can be seen in fig. 9.

One of the most important detections is the accuracy of the obtained solution. One of the authors has published the results e.g. in [7]. The principal criterion for accuracy in this case is the value of maximal static torque. Three different torque computation methods have been introduced, e.g. Maxwell Stress Tensor Method, Arkkio's Method and Coenergy Method, as well as different quality and density FE mesh has been used. The results are presented and discussed e.g. in [1]. Also the time consuming criterion has been presented, where the time necessary for precise mesh computation is 100%. Then, time needed for solution of medium quality mesh is 41% and coarse mesh

12.5%. The obtained maximal torque values, as well as necessary computation time, can be seen in tab. 1. It must be mentioned that the CPU time in tab. 1 includes only computation of primary results (does not include the time needed for postprocessing itself).

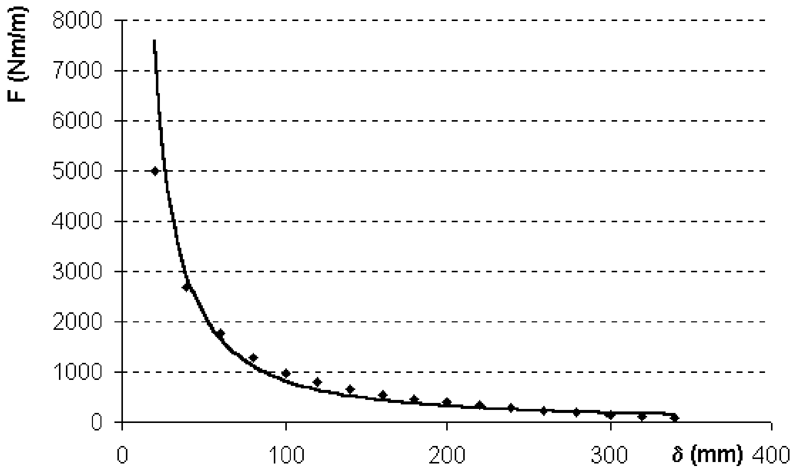

Fig. 2 – Force Characteristic of Electromechanical Contactor

Table 1 – Comparison of Computation Time and Obtained Maximal Torque Values.

	Torque by:			CPU time
	Maxwell stresses	Arkkio's Method	Coenergy Method	
Coarse mesh	90.5%	95.4%	88.5%	12.5%
Medium mesh	98.2%	98.5%	95.3%	41.0%
Fine mesh	100.0%	99.7%	98.6%	100.0%

From tab. 1 it can be concluded that the medium mesh (the definition of used terminology can be seen e.g. in [1]) is the optimal consensus between the required accuracy and necessary computation times. All three methods lead to acceptable results; even the Coenergy method with 95.3% of exact torque value. The recommended choose of torque evaluation method is the Arkkio's method (sometimes also mentioned as "Averaged Maxwell Stress Tensors"); since this method is the less mesh quality dependent from all three used methods.

The next example is a model of an asynchronous motor used in dieselelectrical traction. The analysis and design of a three phase four pole asynchronous actuator, used in dieselelectrical traction, is described in [8]. The rated power of the machine is 137.5 kW, rated voltage 600 V, rated current 140 A. The actuator is designed for rated speed 1470 rpm (equivalent to supply frequency 50 Hz, since the maximal frequency of supply voltage is 131.15 Hz). The actuator is supplied with constant ratio of U/f to 50 Hz, above this frequency the supply voltage does not exceed 600 V. The field distribution is influenced by slip of rotor (according to working principles of asynchronous machinery). An example of the field distribution can be seen in fig 10.

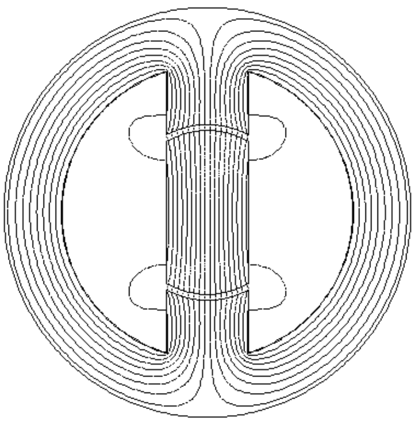

Fig. 3 - Field Distribution for Aligned Rotor

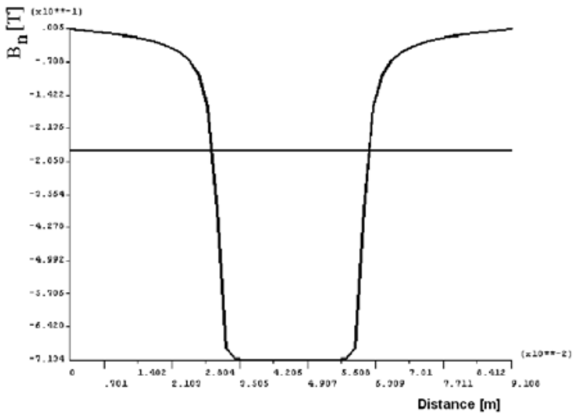

Fig. 4 - Flux Distribution in Air Gap for Aligned Rotor

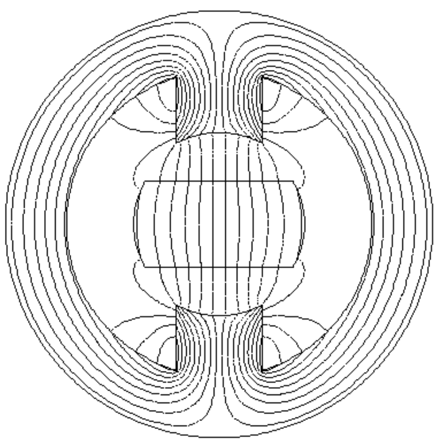

Fig. 5 - Field Distribution for Misaligned Rotor

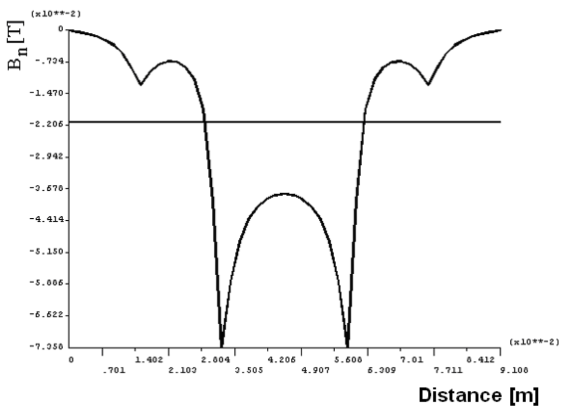

Fig. 6 - Flux Distribution in Air Gap for Misaligned Rotor

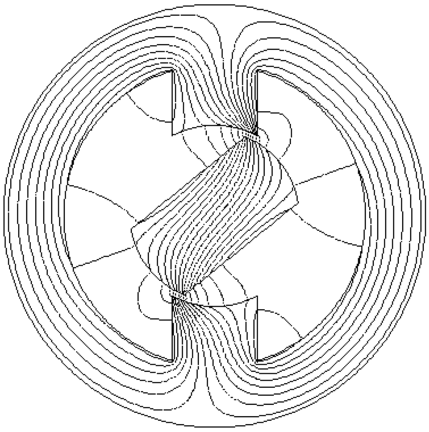

Fig. 7 - Field Distribution for Position of Maximal Torque

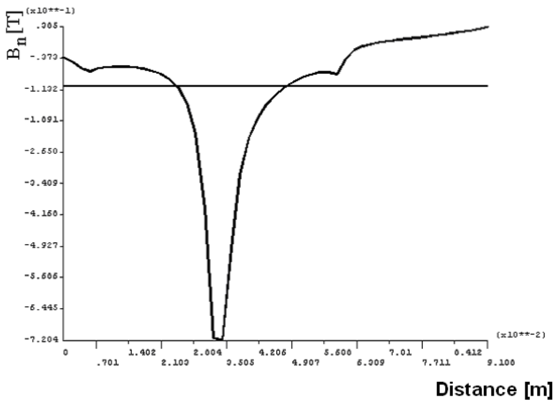

Fig. 8 - Flux Distribution in Air Gap for Position of Maximal Torque

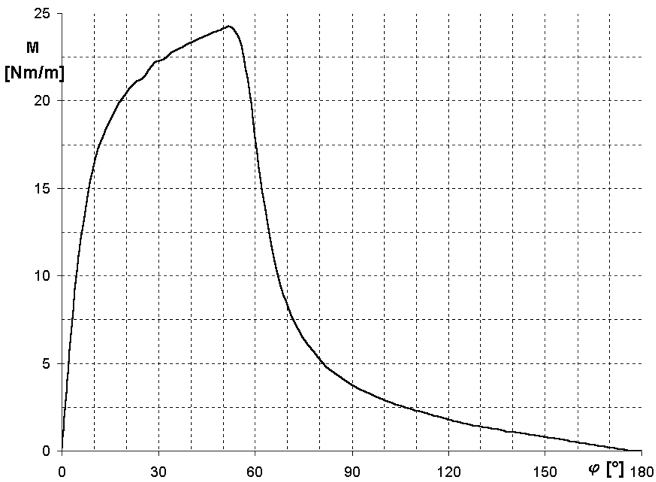

Fig. 9 – Torque Characteristic of DC Machine

One of the latest interests of the authors is the project of a bearingless actuator, introduced in [9]. The basic idea of using the bearingless actuators is in the skip of mechanical parts connecting the rotary and stationary parts of the machine. These parts should become critical especially in dangerous and aggressive environment or in cases when extremely high speed is required. Dusty or explosive stations, cooling conditions – these are the main factors in considering the use of the bearingless machinery (or magnetic bearings).The use of magnetic bearings, as well as the use of bearingless machinery, will cause a high quality magnetic field which allows the actuator rotor to levitate. The use of a magnetic bearings leads to additional windings, necessary to achieve the required strong magnetic fields, it also leads to the need of relatively fast and powerful control systems equipped with sensors and position probes. This system must be able to respond to the all eligible states of rotor and shaft loads. Only the first of the above mentioned demands can be eliminated – it is possible to redesign the existing windings of the machine, which will be supplied by two quasi independent supply systems. One part of the supply system will generate a rotary magnetic field, which will transport the rotor of the machine, while the second part will generate a levitation field necessary to retain the rotor position. Of course, in both cases, the "classical" bearing must be present in the machine, since when interrupting the power supply, the rotor must not crash the stator of the machine! These processes have been implemented into the FE system. According to the FE analysis, the required parameters of the control system have been defined. An example of field distribution in bearingless actuator can be seen in fig. 11.

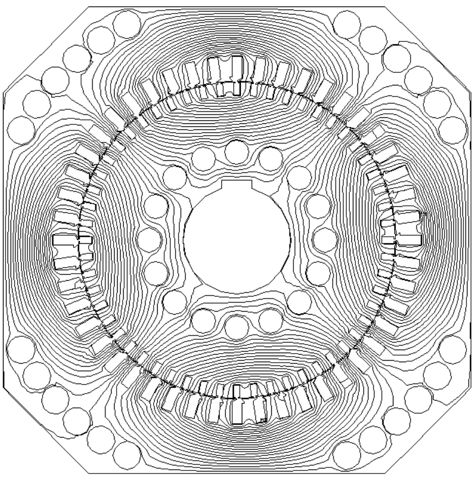

Fig. 10 – Field Distribution in Asynchronous Machine for Dieselelectrical Traction

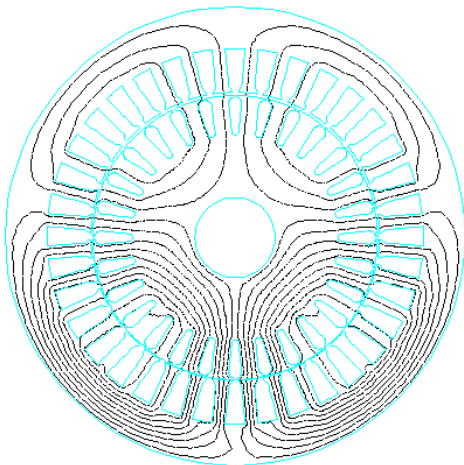

Fig. 11 – Field Distribution in Bearingless Electromechanical Actuator

One of authors' most important and complex works is the design and analysis of special lowspeed high torque electromechanical actuator (stepper). The "Megatorque" actuator is unique by its construction and parameters. The actuator consists of two stators and a rotor, which is in the form of a ring, placed between these two stators. According to its construction, the machine is able to produce extremely high torque (300 Nm) together with extremely low speed (0 – 60 rmp; when increasing the speed above 60 rpm, the torque will decrease rapidly). The big advantage of this construction are very precise positioning possibilities. The basic step of the machine is equal to

0,8°. This means, that without any feedback and special control system, the actuator is able to position the required technology within the accuracy of 0.8°. Of course, the control system is required and herewith the accuracy is even more precise. According to the coupled external load, the feedback could be omitted in many cases. Field distribution in the machine can be seen in fig. 12. The torque characteristic (fig. 13) has been also evaluated, as well as different current supply cases have been investigated and compared:

a, two phase supply, when two phases are supplied by rated current of the same polarity,

b, two phase supply, when both phases are supplied by rated current, though the second one of opposite polarity,

c, two phase supply, when one phase is supplied by rated current, second with half-size current of the same polarity,

d, one phase supply, when the phase is supplied by rated current.

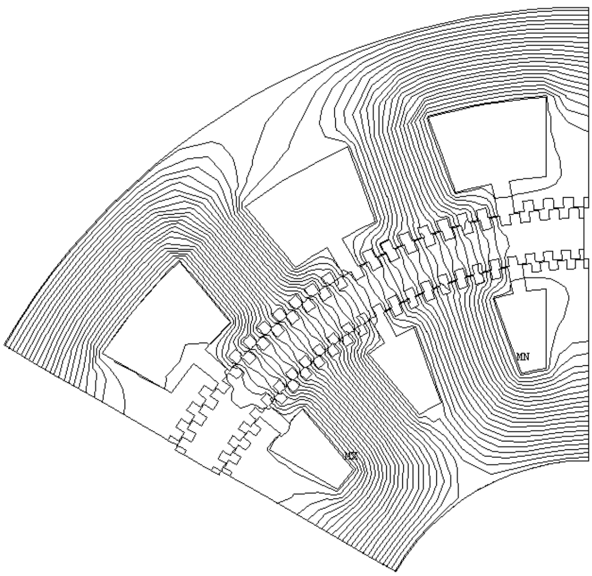

Fig. 12 – Field Distribution in "Megatorque" Actuator

The comparison of the obtained results can be seen in tab. 2. The results have been verified in the laboratories of Faculty on Mechatronics, ADU of Trenčín, Slovakia. A lot of other similar examples based on electrical machinery can be found e.g. in [11].

Table 2 – Comparison of Supply Cases of "Megatorque" Actuator

Supply case*	Torque	Percentage
a,	5233 Nm/m	124%
b,	5191 Nm/m	123%
c,	4441 Nm/m	105%
d,	4230 Nm/m	100%

* Description of supply cases can be found in the text above

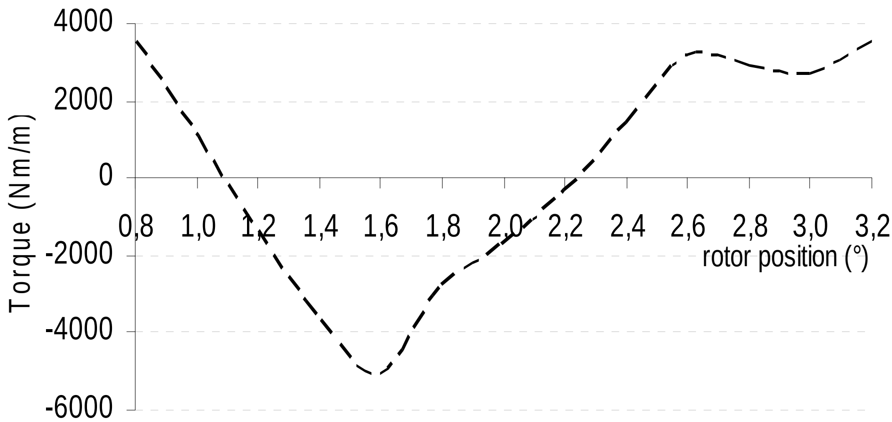

Fig. 13 – Torque Characteristic for "Megatorque" Actuator – Unsymmetrical Supply

FE principles are successfully used also in mechanical simulations. The basic formula which describes the given problem is always the same – as presented in (1). Analogy between quantities, described e.g. in [1, 2], should lead e.g. to certification processes of bridges and their construction, design, verification and optimization of mechanical parts according to specified demands and destination.

The request of verification and certification of bridge structures used by the Czech Armed Forces has appeared within the context of joining the NATO. One of these projects was "The certification of Floating bridge set PMS to NATO loading capacity". Numerical solution of a beam on elastic foundation is quite easy if bending stiffness is known and it is core of floating bridge problem. Therefore very precise computer model of one pontoon has been built (Fig. 14) to achieve bending and torsion stiffness, and, the computer simulation results have been again verified by measuring the relevant bridge constructions. The obtained results have been presented by one of the authors e.g. in [4, 5]. Mechanical stress and strain distribution in the upper part of a pontoon can be seen e.g. in [1, 4, 5]. The difference between numerical solution obtained from the FE model and the experimental measurement was under 5%.

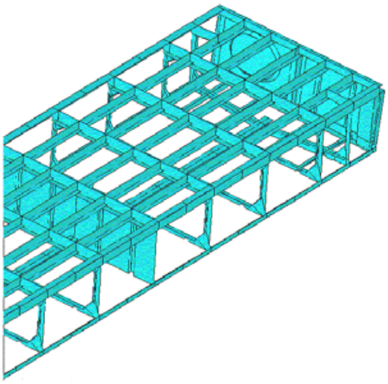

Fig. 14 – Model of pontoon bridge construction

Fig. 15 – Experimental measurement on floating bridge PMS

The loading capacity of the TMS provisional bridge construction (designed in the 50 and 60 of the last century in former Czechoslovakia for use in the military) according to modern codes and NATO standards has also been solved by FE. The measurement of loading capacity is an expensive and dangerous procedure – its costs could be reduced by predicting the results (this prediction is based on finite element analyses) and consecutive verification of the developed FE models only once, all the following analyses are based on a verified model.

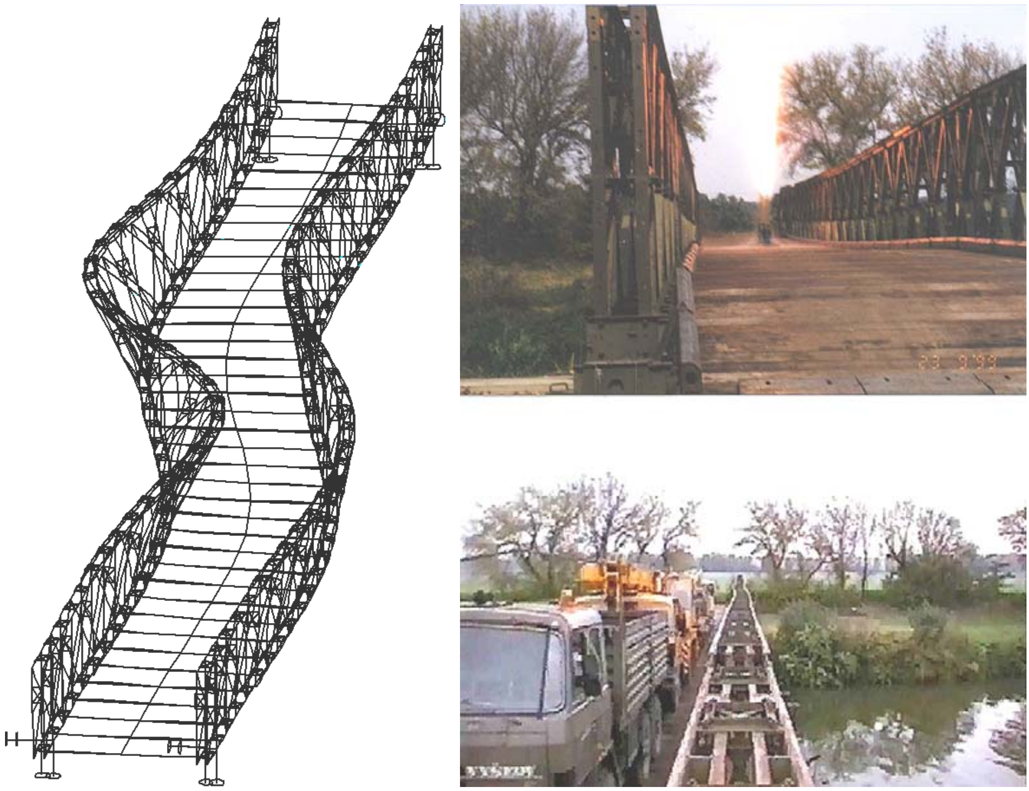

Fig. 16 – Natural shape of tested bridge and experimental measurement

4. Conclusion

The authors would like to present a modern view on numerical method - finite elements basis. Several common features in numerical background between different physical spheres (as magnetostatics or mechanics) have been assigned (however, the reader should follow the recommended references).

An overview of the authors' most important results based on finite elements has been presented in range as it has not been presented before. Except for the simple solutions, parts of complex analysis of special technology as the megatorque machine, bearingless actuator or asynchronous machine for dieselelectrical traction have been presented.

Special stress and strain analyses have been also carried out by one of the authors. The points of interest in this part are the bridge constructions as PMS and TMS bridges. The basic parts of the authors' most important results, including 3D shell and volume models, are presented in this paper.

All solved tasks have a common feature: mathematical aparatus in the background of the used computer software and methodology of use. Although, the software platform used by each author could be, and already is different, the results are compatible and should be easily compared and verified.

Any other information on the presented topics can be found in relevant references, which are listed at the end of this paper.

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