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Original scientific paper

REQUIRED PARAMETERS IN THE THERMAL PROCESSES CONDUCTED FOR RICE QUALITY IMPROVEMENT

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A b s t r a c t: An investigation was realized to obtain information on paddy parboiling conditions and parboiled rice drying conditions. Parameters required in the processes of paddy thermal treatment were reviewed and compared with research results. Field tests on parboiling autoclaves and mixed-flow rice dryer were made at the parboiling rice factory in Kočani. Three autoclaves with functional capacity of 3000 kg paddy/h and one mixed-flow parboiled rice dryer with capacity of 2500 kg parboiled rice/h were included in the examination. The paddy behavior in the parboiling process was controlled by measurements. The processes of paddy soaking in hot water, steaming, pre-drying, milling and parboiled rice drying were included in the measuring programme. The study was conducted on three local paddy varieties, Monticelli, Saint Andrew and RS76. The range of the required parameters for the processes of paddy parboiling and parboiled rice drying was determined.

Key words: rice, paddy parboiling, parboiled rice drying

БАРАНИ ПАРАМЕТРИ ВО ТЕРМИЧКИТЕ ПРОЦЕСИ СПРОВЕДЕНИ ЗА ПОДОБРУВАЊЕ НА КВАЛИТЕТОТ НА ОРИЗ

А п с т р а к т: Реализирано е истражување со цел да се добијат информации за условите на витаминизирање оризова арпа и за условите на сушење на витаминизиран ориз. Бараните параметри во процесите на термичка обработка на оризова арпа се прегледани и споредени со резултатите од истражувањето. Направени се теренски истражувања на автоклави за витаминизирање на ориз и сушилници за ориз со мешан протек во фабриката за витаминизиран ориз во Кочани. Во истражувањето беа користени три автоклави со работен капацитет од 3000 kg оризова арпа/час и една сушилница со мешан протек за витаминизиран ориз со капацитет од 2500 kg витаминизиран ориз/час. Однесувањето на оризовата арпа во процесот на витаминизирање е контролирано со мерења. Во листата на мерење беа вклучени процесите потопување на оризова арпа во топла вода, обработка со пареа, претсушење, лупење и сушење на витаминизиран ориз. Проучувањето беше спроведено на три локални сорти оризова арпа, Monticelli, Saint Andrew и RS76. Одреден е опсегот на потребните параметри за процесите витаминизирање на оризова арпа и сушење на витаминизиран ориз.

Клучни зборови: ориз; витаминизирање на оризова арпа; сушење на витаминизиран ориз

1. INTRODUCTION

World rice production is about 500 million tonnes [1]. Over 95 % of the world rice production is used for human food [2].

Rice quality is evaluated according to grain size, shape uniformity, color, translucency, milling yield, cooking characteristics, cleanliness and soundness.

Rice quality depends on: rice variety, environmental conditions during the growing period, time and system of harvesting, postharvest treatment, storage practices and transport procedures [3].

The postharvest treatment is the phase in which the thermal engineers intervene.

Rice is harvested at moisture contents that are too high for safe storage. Immediate drying is essential to prevent grain quality deterioration. Drying of rice is the most widely practiced preservation method [4].

Parboiled rice is exposed to thermal treatment even before its drying.

Rice in the husk, paddy, which has been soaked in water steamed and dried, after removing its husk, is parboiled rice.

About 50% of the world paddy production is parboiled.

Rice is parboiled to improve its nutritional value, to reduce grain breakage during milling and to increase the storage period [5].

In the rice parboiling technology, heat energy is needed two times:

1) for the parboiling autoclave, where the paddy is soaked and steamed,

2). for the heat exchanger in the dryer.

Of all cereals, rice is probably most difficult to process without quality loss [6].

The purpose of this paper is to summarize the available data in the analysis of thermal processes: paddy parboiling and parboiled rice drying.

2. THERMAL PROCESSES OF RICE PARBOILING AND DRYING

For the both thermal processes the following parameters were considered: used equipment, capacity for processed product, characteristics of working medium, thermal state in the working room, needed period for process realization and final moisture content of treated product.

The production of parboiled rice consists of: 1) paddy soaking in hot water, 2) paddy steaming, 3) paddy drying, 4) paddy husk removing, and 5) parboiled rice drying.

Field tests on parboiling autoclaves and mixed-flow rice dryer were made to control the improvement of rice quality.

The paddy behavior in the parboiling process was followed by measurements. These parameters were included in the measuring programme: 1) soaking in hot water (water temperature, paddy moisture content, time), 2) steaming (steam pressure and temperature, paddy moisture content, time), 3) paddy drying (air temperature, paddy moisture content, time), 4) paddy husk removing (whole-kernel yield), and 5) parboiled rice drying (air temperature, airflow, rice moisture content, time).

In the phase of preparation of dryer for planned tests two interventions were made at the dryer: 1) The augers and the modules were fitted with sampling tubes. 2) Air inlet duct was completed with a measuring duct.

In the last decades there has been remarkable development in the rice parboiling technology. Some improvements were introduced to rise up the quality of edible rice and to increase the energy efficiency of the equipment. The attention is concentrated to the basic functional element of a parboiling plant, the autoclave.

For the actual investigation, three autoclaves were included in the test process. They are built as double wall rotary containers (Figure 1).

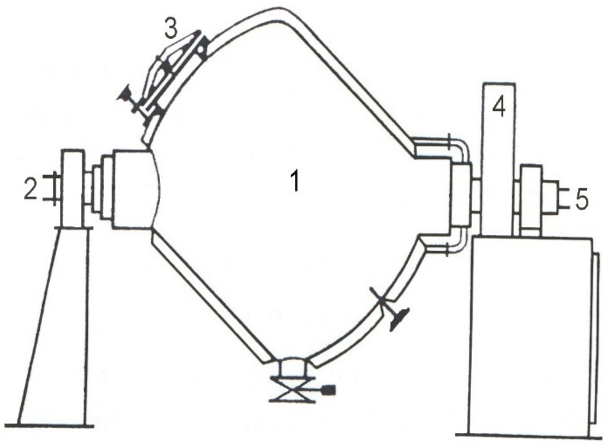

Fig. 1. Paddy parboiling autoclave
1 – parboiling room, 2 – vacuum tube, 3 – autoclave lid, 4 – autoclave drive, 5 – heating tube

Through the left axle of the autoclave the drying room is in connection with the vacuum pump. At the end of the process of paddy steaming, a partial vacuum is created in the autoclave and the process of parboiled paddy drying is started. For the period of about three hours the paddy moisture content ought to be lowered at 17 %.

The right axle of the autoclave is used as filling tube for the heating medium.

At the test procedure 6000 kg of paddy, in one charge per autoclave, were treated with hot water and steam. Before parboiling the paddy mass was carefully cleaned and all organic or inorganic impurities were eliminated.

The quality of potable water for soaking was also controlled, because the content of minerals or other substances in the autoclave may affect the results of the process.

About 1200 liters potable water is needed for soaking of 1000 kg paddy.

For deciding how long soaking must be practiced, four factors are important: paddy variety, cultivation conditions period of storage and water temperature [7, 8]. The process can be speeded by the use of physical and chemical means: air vacuum, hydrostatic pressure and wetting agents.

For the soaking process is desirable to avoid the husk opening as far as possible. Incorrect water temperature and period of soaking can cause solubilization of substances in the rice, change of color, smell and taste [9].

The efforts to define the correct soaking conditions resulted in data shown in Table 1.

Table 1

Basic parameters for paddy parboiling process

Parameter	Process		
	Soaking	Steaming	Drying
Equipment	Parboiling autoclave	Parboiling autoclave	Cascade dryer
Capacity, paddy (kg/h)	1000	1000	1000
Working medium	Water	Steam	Air
Working medium maximum temperature (°C)	60	110	40
Period (min)	35–45	60–80	180
Final moisture content dry basis (%)	35	60	17

Steam injection in the parboiling room of the autoclave is the second phase of paddy parboiling process. Thus the paddy is heated at the temperature of 110 °C.

The use of steam for gelatinization of paddy starch is the most preferable method. The steam is normally sterile, has no smell and it is easy to pipe.

At the tests, duration of the steaming process of 60 to 80 minutes was satisfactory for the varieties Monticelli, Saint Andrew and RS76.

After the soaking and steaming operations, the edible portion of the paddy is enriched with substances from the covering structure, the husk, but the paddy is carried to very high moisture content dry basis, up to 60 %. Such moisture content is not encountered in any other rice treatment. Therefore, a long period of rest or "tempering" before removing the husk is used, so that the moisture content of the paddy may be even. At the end of the process the paddy moisture content dry basis reaches 17 % [10].

When the paddy is parboiled in the correct manner, milling will give maximum yield of edible rice with the minimum content of broken grains.

There are no difficulties in removing the husks of parboiled paddy, as the husks split to some extent when the grain swells. Husks are removed in shelling machines with rubber rollers. The next step is whitening of parboiled rice. To get a good polishing degree, the parboiled rice must pass through more polishers than the ordinary rice. Five polishers with five different regulations are used.

Paddy husk removed in the milling process is stored in silos. In the applied parboiling technology the husks are used for fuel. Stored husk is transported, in the needed quantities, to the boiler grate for burning. Combustion of husks has the advantage of consuming this secondary product at the same location where it is produced.

The tests of parboiled rice drying were realized on the industrial type mixed-flow rice dryer [11].

The dryer is composed of drying room, air ducts, heat exchanger, fans and augers.

Drying process is crucial for rice quality. One of the most important criteria for rice quality is milling yield. Unbroken rice kernels or head rice, are preferred for human food and their market value is greater than that of broken kernels. Therefore, it is important to minimize any kind of stress that may result in kernel breakage. To avoid thermal stress, the maximum rice kernel temperature in the dryer, ought to be 38 °C. Rice, unlike corn and wheat, cannot be dried in high temperature drying systems.

The parboiled rice drying conditions are presented in Table 2.

Table 2

Basic parameters for parboiled rice drying

Parameter	Process: Drying
Equipment	Mixed-flow dryer
Capacity, parboiled rice	2500 kg/h
Capacity, heated air	40000 m^3/h
Working medium	Air
Working medium maximum temperature	42 °C
Dried product maximum temperature	38 °C
Final moisture content, dry basis	12 %

Initial, internal and final moisture content of parboiled rice are inspected by taking representative samples in the rice filling auger, all six modules of the dryer and in rice unloading auger. In the dryer, the moisture content dry basis of parboiled rice is reduced from 17 % to 12 %.

The whole-kernel yield was registered by electronic whole kernel separator. The amount of broken kernels was less than 5 %.

3. CONCLUSION

Drying conditions were established in the mode based on field tests.

The data presented in this paper are for local rice varieties, under a specified range of conditions.

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Original scientific paper

THERMOCHEMICAL CONVERSION OF WASTE HYDRAULIC OIL TO GASOLINE AND DIESEL FUEL

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A b s t r a c t: Waste hydraulic oil is environmental problem because the contents of solvents, heavy metals, suspended solid particles, polycyclic aromatic hydrocarbons (PAHs), chlorinated paraffins and polychlorinated biphenyls (PCBs). Energy recovery with combustion the oil is not practical method and reusing with filtration and vacuum distillation is a cost effective process. Also, blending waste hydraulic oil with diesel fuel is not possible because the higher density and viscosity comparing with diesel fuel and causes reduction of volatility of fuel and higher exhaust emission. Pyrolysis is a promising catalytic thermochemical process that can easy convert the waste hydraulic oil into valuable liquid fuel. The aim of this work is pyrolysis of waste hydraulic oil in semi-batch reactor using Al_2O_3 as a catalyst and characterization of obtained liquid fuel. The compounds of pyrolytic oil were identified using Fourier Transform Infrared Spectroscopy (FTIR). Analyzing obtained results it can be conclude that the composition of obtained pyrolytic oil is between the gasoline and diesel fuels.

Key words: pyrolysis; semi-batch reactor; waste hydraulic oil; fuel; Fourier Transform Infrared Spectroscopy

ТЕРМОХЕМИСКА КОНВЕРЗИЈА НА ОТПАДНО ХИДРАУЛИЧНО МАСЛО ДО БЕНЗИН И ДИЗЕЛ-ГОРИВО

А п с т р а к т: Отпадното хидраулично масло претставува проблем за околината поради присуството на растворувачи, тешки метали, суспендирани цврсти честички, полициклични ароматични јаглеводороди (PAH), хлорирани парафини и полихлорирани бифенили (PCB). Енергетското искористување на маслото со негово согорување е непрактичен метод, а неговата повторна употреба со филтрација и вакуум-дестилација претставува скап процес. Исто така, мешањето на хидрауличното масло со дизелско гориво не е можно поради неговата повисока густина и вискозитетот споредено со дизелот, што предизвикува намалување на испарливоста на горивото и поголема емисија на отпадни гасови. Пиролизата е надежен термохемиски каталитички процес со кој може лесно да се конвертира отпадното хидраулично масло до корисно течно гориво. Целта на овој труд е пиролиза на отпадно хидраулично масло во полушаржен реактор со користење на Al_2O_3 како катализатор и карактеризација на добиеното течно гориво. Соединенијата на пиролитичкото масло беа идентификувани со примена на Фуриеова трансформна инфрацрвена спектроскопија (FTIR). Од анализата на добиените резултати може да се заклучи дека составот на добиеното пиролитичко масло е помеѓу бензин и дизелско гориво.

Клучни зборови: пиролиза; полушаржен реактор; отпадно хидраулично масло; гориво; Фуриеова трансформна инфрацрвена спектроскопија

INTRODUCTION

Hydraulic oils are the wide range of liquids, different in composition, used at the mobile equipment, automobile automatic transmissions, industrial and hydraulic machinery. They are viscosity liquids between 15 and 100 $mm^2 s^{-1}$ at 40 °C, with light color, and contains 99% base fluids. The density and viscosity of the hydraulic fluids are little higher than the commercial diesel fuel but lower than engine oils. [1–3]. The most of the hydraulic oils are non-renewable mineral base oils and after lifecycle they are environmentally hazardous waste especially due to the content of polychlorinated biphenyls. Also, disposing is a high cost process. Reusing hydraulic oil is complicated process because it is very sensitive to presence of contaminants [3]. Blending diesel fuel with hydraulic oils the combustion characteristics of the fuel are changed due to the higher viscosities of the hydraulic oils and reduction of volatility of a mixture when injected into combustion chamber. Also, burning hydraulic oil and conventional diesel fuel blends lead to higher exhaust emission such as hydrocarbon, carbon monoxide and particulate matter [4]. Pyrolysis is a thermochemical process of conversion hydraulic oil to gasoline and diesel fuel at high temperature and inert atmosphere. Obtained pyrolytic oil has a high hating value due to the low oxygen content and can be used as engine fuel without any problem.

The subject of this study is analyzing the pyrolytic oil obtained from waste hydraulic oil. The main functional groups of pyrolytic oil will be determinate using Fourier transform infrared spectroscopy.

EXPERIMENTAL

Materials and methods

The pyrolysis of hydraulic oil is performed in a semibatch reactor (volume $0.4\ 10^{-3}\ m^3$) in presence of commercial Al_2O_3 (BASF 92.7% Al_2O_3) as catalyst. Waste hydraulic oil was with light yellow color and 0.8800 g cm^{-3} density, purchased at the car service station. Composition of pyrolysis oil was analyzed using FTIR Spectroscopy (Thermo Scientific Nicolet 6700 spectrometer) and compared with commercial diesel and gasoline purchased from the petrol station A.D. Makpetrol, Skopje.

Procedure

The waste hydraulic oil (120 g) was putted into reactor and after that the catalyst Al_2O_3 (180 g) was added. Equipment for pyrolysis contents semi-batch reactor, three separators (condensers) at constant temperatures ($T_1 = 70$°C and $T_2 = T_3 = 0$°C) and PID controller for controlling heating rate and temperature into reactor. Heating rate and reaction temperature were 10°C min^{-1} and 400 to 600°C, respectively. The reactor was isolated with glass wool and produced pyrolysis oil was filtered and conducted to FTIR analyzing.

RESULTS AND DISCUSSION

In this study, we analyzed the influence of temperature and catalyst on the rate of pyrolysis to produce the greatest yield of liquid oil. The process of pyrolysis starts at 345°C with slaw intensity and increasing at 405°C. Fast pyrolysis process was carried out between temperatures 405°C and 410°C when the greatest yield of liquid oil was obtained. Slaw intensity of pyrolysis continued to 590°C. Lower temperature of pyrolysis, comparing with another researchers 525 °C [5], is due the presence of catalyst and fluid catalytic cracking of hydraulic oil. The pyrolytic oil was with light yellow color with characteristic smelt on gasoline and diesel fuel. The density of pyrolytic oil was 0.8092 g cm^{-3}.

Identification of the functional groups of obtained pyrolytic oil was performed using FTIR spectroscopy by infrared absorption at different frequencies (Figure 1). There is no presence of alcohols and phenols (O–H vibrations of hydroxyl groups with wave length 3200 to 3400 cm^{-1}) and aldehydes, ketones and carboxylic acid (C=O stretching vibrations between 1700 and 1750 cm^{-1}). The biggest peaks are at 2922, 2852, 1460 and 1377 cm^{-1} and belong to alkanes (C–H stretching vibrations with wave range between 2750 and 3000 cm^{-1} and also 1375 and 1454 cm^{-1}). There are lower peaks at 721 and 813 cm^{-1} (wave range from 675 to 850 cm^{-1}) and 908 cm^{-1} (wave range from 860 to 945 cm^{-1}) characteristic for C=C streching vibrations that represent group of alkenes. Single ring aromatics are present with two low peaks in a wave range from 675 to 850 cm^{-1}. Comparing FTIR spectrograms for pyrolytic oil and comercial gasoline (Figure 2), can be concluded that the alkanes are in higher percent in pyrolysis oil than in the commercial gasoline and alkenes are in higher percent in commercial gasoline than in the pyrolysis oil. Single and polycyclic aromatics were in higher percent in a gasoline than in pyrolysis oil. Pyrolysis oil has almost the same percent of alkanes comparing with commercial diesel fuel, lower percent alkenes and higher percent of single and polycyclic aromatics contents (Figure 3). The composition of pyrolysis oil is between the diesel and gasoline, similar with the pyrolysis oil obtained from waste engine oil [6, 7].

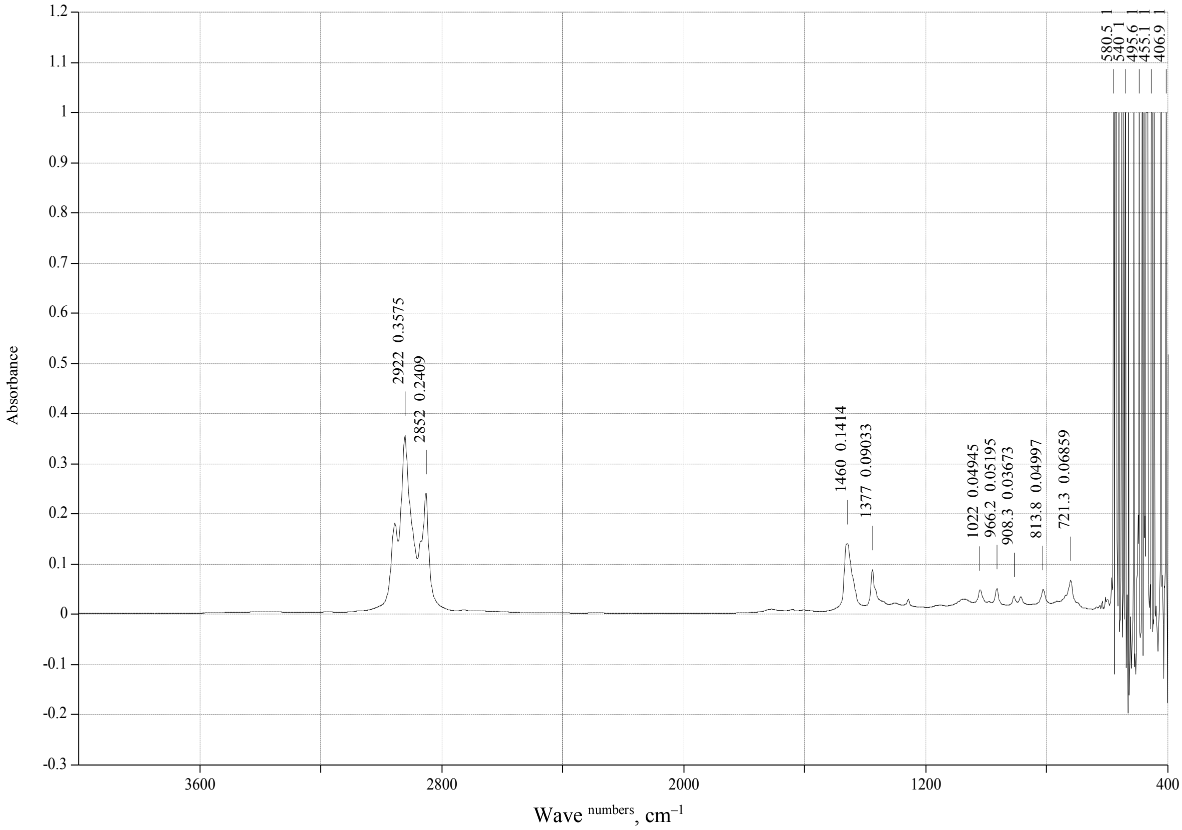

Fig. 1 FTIR spectrum of pyrolysis oil

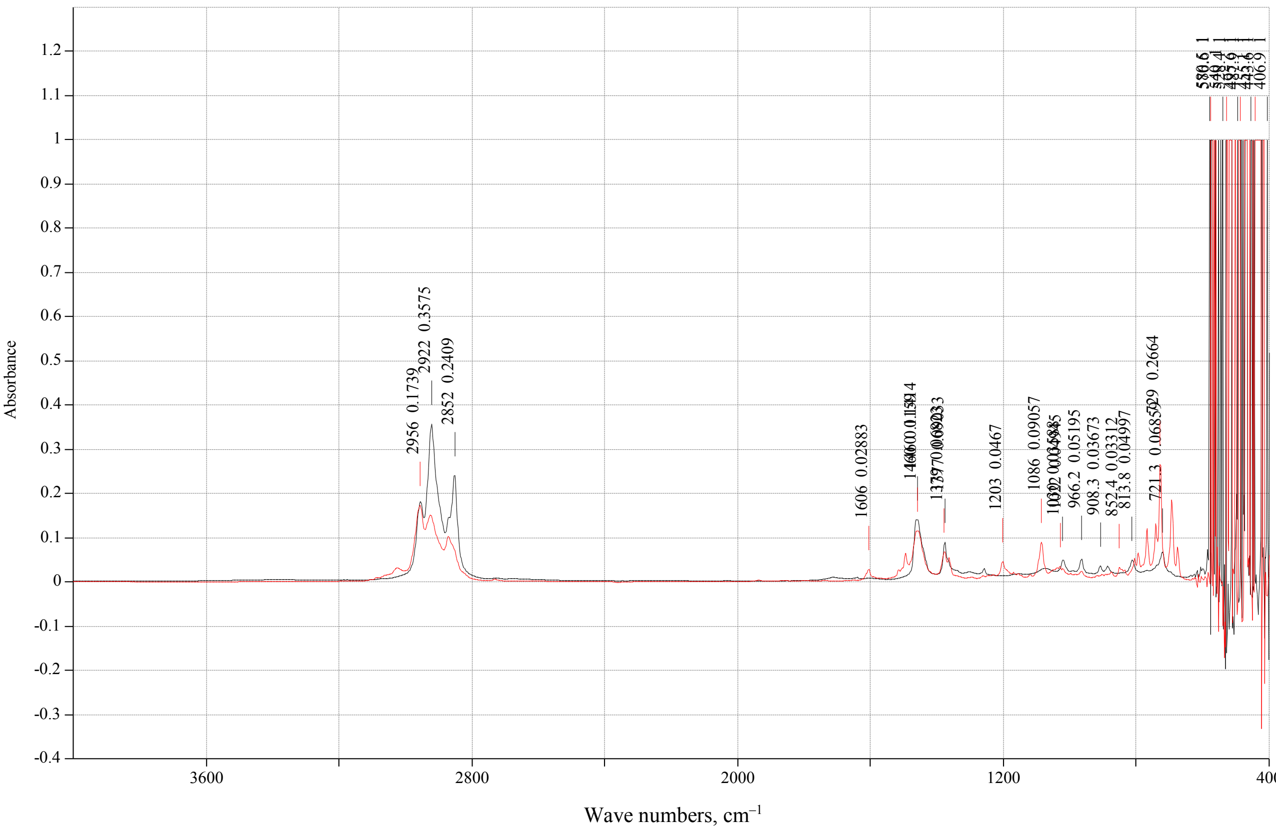

Fig. 2. FTIR spectrum of pyrolysis oil (black) and commercial gasoline (red) color

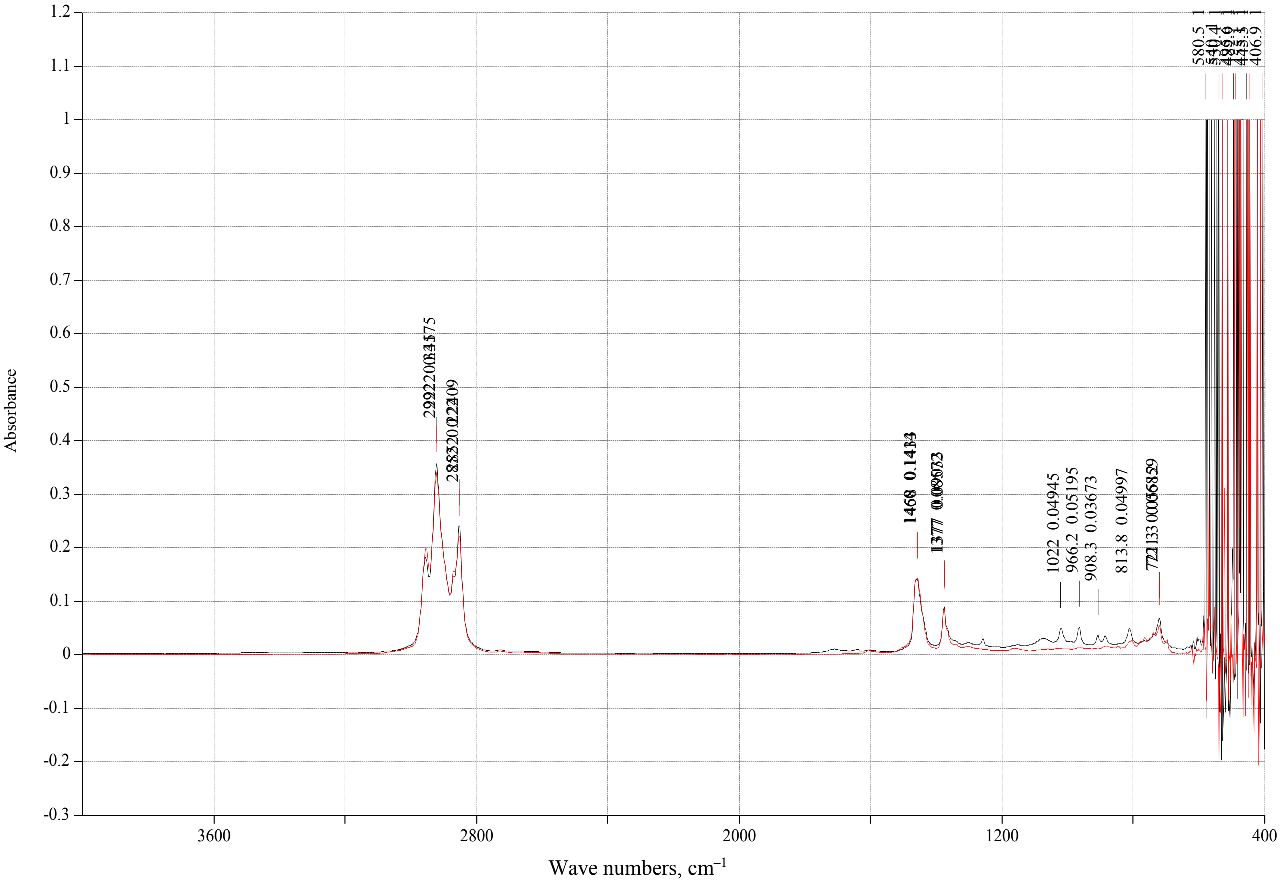

Fig. 3. FTIR spectrum of pyrolysis oil (black) and commercial diesel (red) color

Fast pyrolysis of the hydraulic oil is adequate method for valorization the waste oil to gasoline and diesel fuel. Obtained oil can mixed with commercial diesel fuel or fractionated on diesel and gasoline. Process of pyrolysis should be conducted between temperatures 405 and 410°C, and heating rate 10ºC min^{-1}. Al_2O_3 is efficient catalyst for fast conversion of hydraulic oil to diesel and gasoline. Using FTIR spectroscopy, the main functional groups in the pyrolysis oil can be rapid determinate.

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Original scientific paper

ANALYZING AND APPLICATION OF REVERSE ENGINEERING FOR DESIGN AND DEVELOPMENT OF MECHANICAL PARTS

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A b s t r a c t: The reverse engineering has already found an extensive application in industry and other different fields. Reverse engineering (RE) is a process of taking the existing physical model and reproducing its surface geometry in three-dimensional (3D) data file on a computer-aided design (CAD) system. This paper will analyze the real situation in one industrial plant and provide comparative analysis of the application of current measuring methods and possibility of incorporating digital measurement. The reverse engineering (RE) is based on a method of reducing the time of dimensioning and modeling of mechanical parts which can be complex by geometry or dimensionally very accurate. In this paper we can give some practical examples of parts that are really produced in one manufacturing factory. Recommendation for digitalization will be of crucial importance for every company in its measurement and quality control activities.

Key words: reverse engineering (RE); manufacturing; CAD; measurement; digitalization

АНАЛИЗА И ПРИМЕНА НА РЕВЕРЗИБИЛНОТО ИНЖЕНЕРСТВО ЗА ДИЗАЈНИРАЊЕ И РАЗВОЈ НА МЕХАНИЧКИ ДЕЛОВИ

А п с т р а к т: Реверзибилното инженерство веќе има голема примена во индустријата и други различни области. Реверзибилното инженерство е процес кој зема постоен физички модел и ја репродуцира неговта површинска геометрија во тридимензионален (3D) фајл на систем за компјутерски помогнат дизајн (CAD). Овој труд ја анализира фактичката ситуација во еден индустриски погон и обезбедува компаративна анализа на примената на тековните мерни техники и можноста за инкорпорирање на дигитални мерења. Реверзибилното инженерство е базирано на методот за намалување на времето за димензионирање и моделирање на механички делови кои можат да бидат со комплексна геометрија или димензионално многу прецизни. Во овој труд се дадени практични примери на делови кои реално се произведуваат во една фабрика. Препораката за дигитализација е од круцијална важност за секоја компанија и нејзините активности во областа на мерењето и контролата на квалитетот.

Клучни зборови: реверзибилно инженерство (RE); производство; CAD; мерење; дигитализација

1. INTRODUCTION

Global competition in the world industry today is very high. So the companies are trying continually to be competitive on global market by looking for new ways to reduce production times and develop new products to meet all the consummers requirements. Mostly, the investments of the manufacturing companies are concentrated on Reverse Engineering (RE), CAD / CAM, Rapid Prototyping (RP) and a large number of new technologies that offer greater production, business benefits and greater profit.

Reverse engineering (RE) is now considered as one of the new technologies that provides bigger business benefits using shortening the product development cycle.

Reverse engineering has been associated with the copying of an original product design for competitive purposes. In the manufacturing world today, however, the concept of reverse engineering is being legally applied for producing new products or variations of old products. The term reverse comes from the concept of bi-directional data exchange between the digital and physical world [12].

Its application is already proven in many areas of engineering and every day life. There are many reasons why it should be used.

Some of the reasons for using reverse engineering are given below:

- The original manufacturer no longer exists, but a customer needs the product.
- The original product design documentation has been lost or never existed.
- Creating data for renewing or manufacturing a part for which there is no CAD data, or for which the data have become unusable or lost.
- Inspection quality control – comparing a fabricated part to its CAD description or to a standard item.
- Some bad features of a product need to be eliminated.
- Strengthening the good features of a product based on long-term usage.
- Exploring new ways to improve product performance and features.
- Architectural and construction documentation and measurement.
- Fitting clothing or footwear to individuals and determining the anthropometry of a population.
- Generating data to create dental or surgical prosthetics, artificial engineered body parts, or for surgical planning.
- Creating 3D data from a model or sculpture for animation in games and movies.
- Creating 3D data from an individual, model or sculpture to create, scale, or reproduce art work.

The above list is not exhaustive and there are many more reasons for using reverse engineering, than documented above [1].

Classic machining process begins from CAD model and ends by component production. Reverse engineering process is opposite. At the beginning is real component and it ends with digital model (Figure 1) [2].

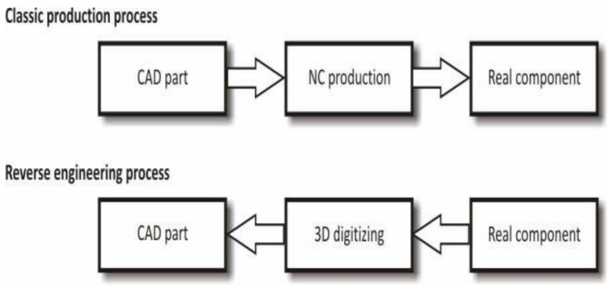

Fig.1. Comparison of reverse engineering and classic production processes [2]

2. DEVELOPMENT AND APPLICATION OF REVERSE ENGINEERING

Reverse engineering covers a variety of approaches to reproduce a physical object with the aid of drawings, documentation, or computer model data. In the broadest sense, reverse engineering is manual work or use of computer and some kind of software to reproduce something.

Reverse engineering is one of the methods used by companies in order to accelerate their product design process and this method is desire for access to the new technologies with minimum cost, risk and time [11]. This method in the developing countries that are not so advanced in terms of product and technology design knowledge, compared to the developed countries, is a logical response to increase designing capability and accelerate the design and manufacturing process.

Reverse engineering is no longer used just only for bringing again the old technology back to life. It is also for using existing or old technology as a launch pad directly into the future [3].

Reverse engineering techniques are being used in a wide range of applications and it is not restricted only to the industry. The type of reverse engineering that will be discussed in this paper is a technique where the physical dimensions of a part are being captured in order to be produced a detailed drawing of the part. In the Computer Aided Manufacturing (CAM) world, this is referred as part to CAD conversion, where the geometry of the physical objects is captured as digital 3D CAD data [4].

The generic process of reverse engineering is a three-phase process shown in Figure 2. The three phases are: scanning, point processing, and development for the particular application specific geometric model [1].

Scanning phase: This phase is connected with the scanning strategy. Its include: selecting the correct scanning technique, preparing the part to be scanned, and performing the actual scanning to capture information that describes all geometric features of the part such as steps, slots, pockets, and holes.

Point processing phase: This phase involves importing the point cloud data, reducing the noise in the data collected, and reducing the number of points. A wide range of commercial software are available for point processing. The output of the point processing phase is a clean, merged, point cloud data set in the most convenient format.

Application – Geometric model development phase: The generation of CAD models from point data is probably the most complex activity within reverse engineering. Sophisticated surface fitting algorithms are required in order to be generated surfaces that accurately represent the three-dimensional information described within the point cloud data sets.

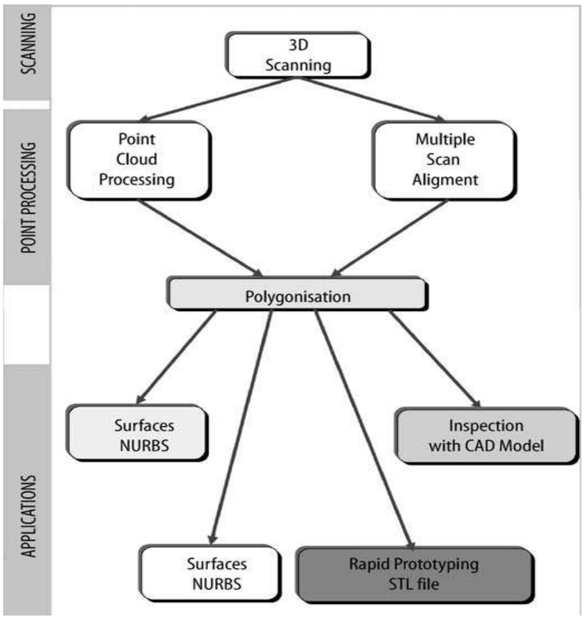

Fig. 2. Reverse Engineering – the generic process [1]

Reverse engineering strategy must consider the following:

• Reason for reverse engineering of a part.

• Number of parts to be scanned – single or multiple.

• Part size – large or small.

• Part complexity – simple or complex.

• Part material – hard or soft.

• Part finish – shiny or blurry.

• Part geometry – cylindrical or prismatic and internal or external.

• Accuracy required – linear or volumetric.

Computer-Aided Reverse Engineering (CARE) relies on the use of computer - aided tools for obtaining the part geometry, identifying its material, improving the design, tooling fabrication, manufacturing planning and physical realization. The structure is shown in Figure 3.

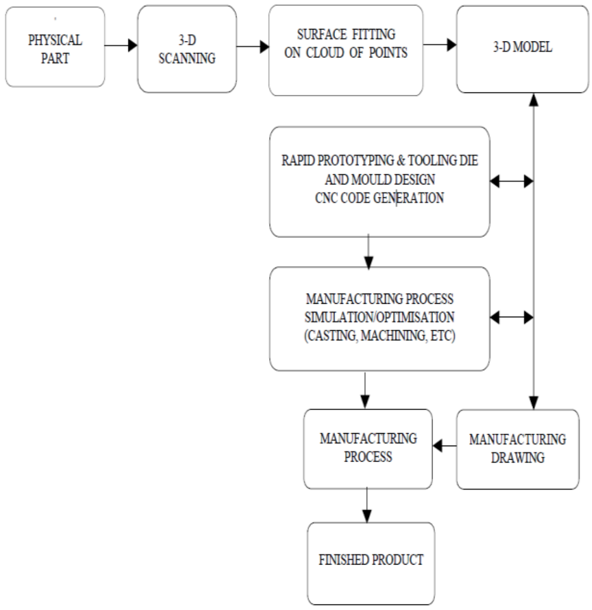

Fig. 3, Computer-aided reverse engineering framework [5]

A solid model of the part is the backbone for computer-aided reverse engineering. The model data can be exported from or imported into CAD/CAE/CAM system using standard formats such as IGES, STL, VDA and STEP. The three most important sets of data in reverse engineering activities are related to the CAD model generation, material identification, and manufacturing [5].

Reverse engineering (RE) is generally defined as a process of analyzing an object or existing system using hardware and software, to identify its components, their interrelationships and to investigate how it works in order to redesign it or produce a copy without access to the design from which it was originally produced.

Reverse engineering hardware is used for reverse engineering data acquisition, which for 3-D modeling, is the collection of geometric data that represent a physical object. There are three main technologies for reverse engineering data acquisition: contact, noncontact and destructive. Outputs of the reverse engineering data acquisition process are

2D cross-sectional images and point clouds that define the geometry of an object (Figure 4).

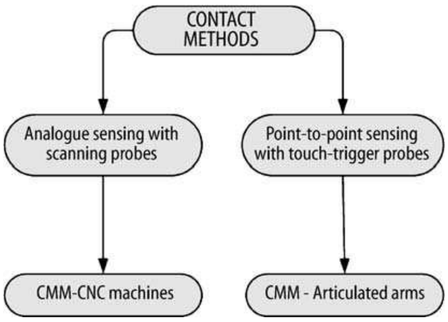

Fig. 4. Reverse engineering hardware classification [1]

Reverse Engineering software is used to transform the reverse engineering data produced by reverse engineering hardware into 3D geometric models. The final outputs of the reverse engineering data processing chain can be one of two types of 3D data: (i) polygons or (ii) NURBS (no uniform rational B-splines). Polygon models, which are normally in the STL, VRML, or DXF format, are commonly used for rapid prototyping, laser milling, 3D graphics, simulation, and animations. NURBS surfaces or solids are frequently used in computer-aided design, manufacturing, and engineering (CAD-CAM-CAE) applications [1].

Except the advantages obtained by the use of reverse engineering, during the implementation, we encountered some barriers that are necessary to be overcome for its wider acceptance. As can be seen from Figure 5, this study proposes a three-phased factor analysis approach in order to determine the critical factors that effects the adoption of reverse engineering technologies.

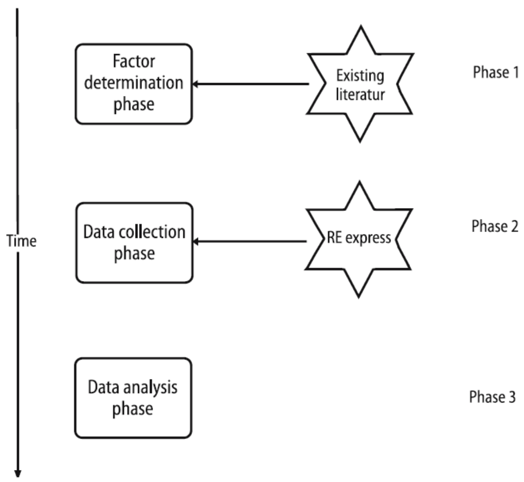

Fig. 5. Factor analysis approach [1]

Factor determination phase is a hypothetical research model and it uses a multidimensional model to represent the organizational, environmental, and project dimensional factors. Using of a such dimensional model allows clustering the factors, and also facilitates a logical data collection and analysis study.

Data collection phase offers a qualitative approach using interviews with experts in the field of reverse engineering. The data collection was carried out by reverse engineering expert and a qualified coordinate measuring machine (CMM) operator. Both of them analyzed the collected data. Face-to-face interviews, approximately 50 minutes longm were conducted. The number of interviewees was determined during data collection. The interviewing was stopped in the moment, when no new information was obtained from interviewees and saturation was reached.

Data analysis phase is closely aligned with the empirical phase. After data are collected, the data are prepared for analysis. The quantitative data are typically entered into a statistical program and qualitative data are often transcribed in order to facilitate data analysis.

As we know with reverse engineering, for an existing mechanical part we make the technical drawings in order to make a production of it. Because the original part already physically exists, some people believe that reverse engineering and duplicating are the same.

But this is not true, because duplicating process is based on expected short time benefits in order to make profit through manufacturing of products which will provide less of the properties and functional specifications compared with the original products. Duplicating differs from reverse engineering in sense that products made with duplicating will result in products on low level technology. In case of complicated products, duplicating will not result in adoption of technology of manufacturing. Instead of that, the reverse engineering will result in preparing production technology, similar or better, than previous used for manufacturing the original part. Manufacturing of products with reverse engineering approach is based on a long term benefits and innovations. Application of updated standards, manufacturing of optimized products and working on products development and improvement is the best scheme in adopting reverse engineering methods [3].

3. TECHNIQUES AND TOOLS FOR CASE STUDY

Main techniques used by reverse engineering for our case study are calipers used for measurement, Autodesk Inventor software used for CAD modeling and CNC milling machine that it used for realizing the physical part. The current situation in the factory offers the above mentioned possibilities. The production is mainly individual with different quality requirements. So the application of the reverse engineering is not continuous, but it depends on every specific case.

A) *Calipers*

Using the calipers as device of measurement is considering as (reverse engineering) manual process for taking the dimensions from different mechanical parts. Then, from these measurements, we could manually define a 3D computer model using CAD primitives. There are different constructions of calipers, but in principle there are not very big differences between them. All of them have a purpose of reducing the measuring error and increasing the accuracy of the reading. The Figure 6 shows standard vernier caliper.

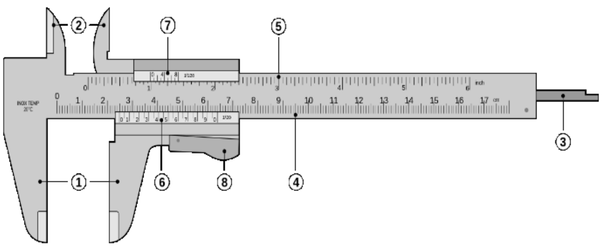

Fig. 6. Vernier caliper [6]

The parts of the caliper include:

1. **Outside large jaws**: used to measure external diameter or width of an object.
2. **Inside small jaws**: used to measure internal diameter of an object.
3. **Depth probe/rod**: used to measure depths of an object or a hole.
4. **Main scale**: scale marked every mm.
5. **Main scale**: scale marked in inches and fractions.
6. **Vernier scale** gives interpolated measurements to 0.1 mm or better.
7. **Vernier scale** gives interpolated measurements in fractions of an inch.
8. **Retainer**: used to block movable part to allow the easy transferring of a measurement.

B) *CNC milling machine*

CNC is the abbreviation of computer numerical control. The working principle of these highly flexible machines is based on converting the CAD (Computer Aided Design) of the part with CAM (Computer Aided Manufacturing) software in cutting tool trajectory (in coordinates). These Computer Numerical Control (CNC) machines made revolution in manufacturing, enabling production of different complex parts, with different accuracy and different materials.

CNC milling machines are the most widely used type of CNC machines. Typically, they are grouped by the number of axes simultaneously operating. Axes are labelled with various letters [7].

The machine shown in Figure 7 was taken from the factory where the mechanical parts presented in this paper, as case study, were produced.

Fig. 7. CNC milling machine [8]

4. PRACTICAL ANALYSIS

Damage of machine parts is a serious problem in production. It affects production efficiency and causes financial losses due to machine(s) malfunction. Most threatened are components like transmission parts, tools or electronics. Our examples show cases of a damaged: tool part (precision) and mechanical part (complex geometry).

A) *Tool part (precision)*

Figure 8 shows tool part which has some damage or cracks along the channels and holes.

For this part, which has to be produced again, first must be estimated the costs and required time for manufacturing. The precision and the type of tool material are the two main components necessary for the measurement and reconstruction procedure.

Fig. 8. Tool (original version) [8]

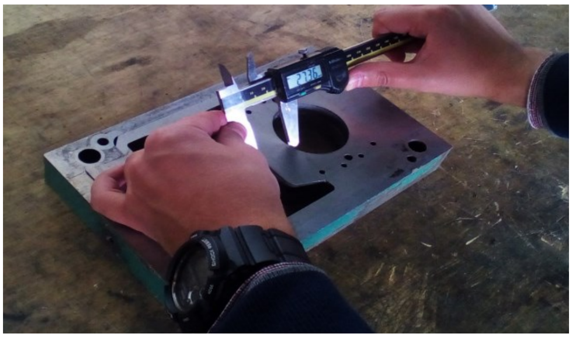

Fig. 9. Measurement of tool part [8]

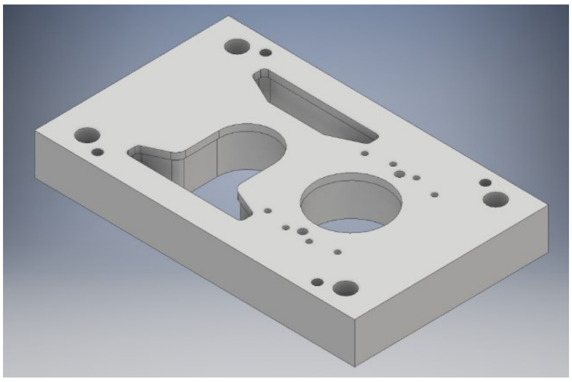

Fig. 10. CAD model of tool part

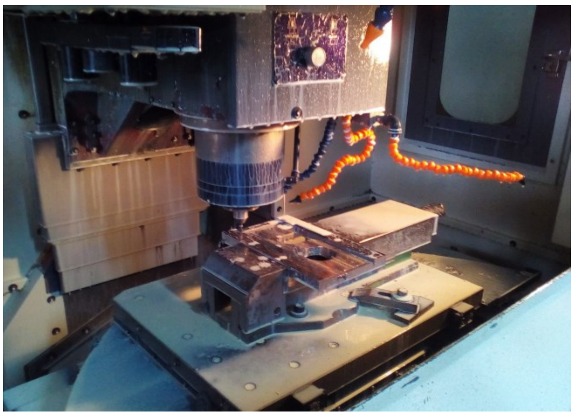

Fig. 11. Production of tool part with CNC Milling machine [8]

Based on the damages that exist on the tool, we have recommended that it should be produced a completely new part. In this case it is possible to apply reverse engineering to eliminate possible machine damage due to the tool damage. The tool part was measured with calipers and we made a CAD model of the part (tool) with autodesk inventor (Figure 9).

After we have made the measurements of the existing work piece and created a 3D model through the software (Figure 10), the next step was the machining the part on the respective machine (Figure 11).

The tool part was drawn in 1:1 ratio, so its conversion in required different forms was very easy.

The software used in this case (Autodesk INVENTOR 2017) is very professional and provides many opportunities for designing and correction of parts.

B) *Mechanical part (complex geometry)*

The mechanical part shown in Figure 12 is used like housing for holding shafts with bearings and it makes an assembly with bolts with an others part. This broken mechanical part should have been manufactured again with previous estimation of costs and necessary time for production. The complex geometry of this mechanical part was very difficult to be measured and to be created a 3D geometrical model.

The requirement was to compare the original part produced with casting, with the part made of construction steel manufactured by milling. We made some optimization in geometric shape of the mechanical part in order to obtain easier manufacturing, but the functionality remained still unchanged, the same like in the original part.

Based on the damages that are presented in the Figure 12, we recommended that mechanical part should be produced as a new one. In this case it is also possible to apply reverse engineering in order to eliminate the part damage. The part was measured with calipers and we made a CAD model of the mechnaical part with Autodesk Inventor.

After we have made the measurement of the existing work piece and creating the 3D model through the software, the next step was the manufacturing on the milling machine (Figure 13).

The used software (Autodesk INVENTOR 2017) provides many opportunities for design of parts complex geometry (Figure 14).

Fig. 12. Mechanical part (original version) [8]

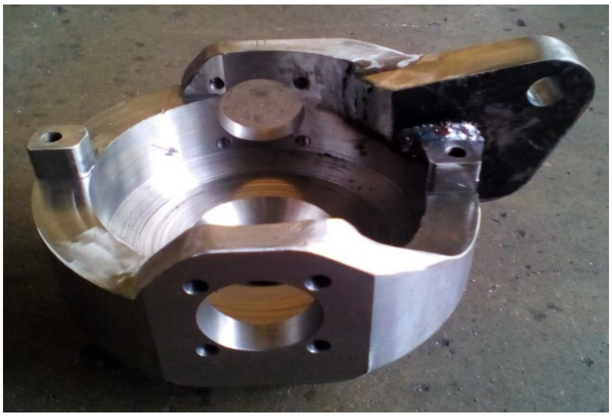

Fig. 13. New mechanical part produced with milling and welding

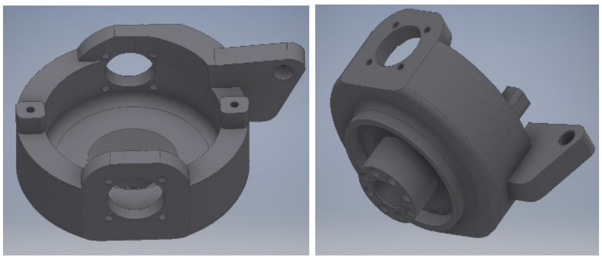

Fig. 14. CAD model of the mechnical part

Applying reverse engineering (RE) techniques in our case gives us great opportunities for preliminary analysis before real production. On the created CAD model we could compare the dimensions with the real part and have possibility to make easy changes and improvements. .

5. RECOMMENDATIONS FOR IMPROVEMENT

Analyzing the current situation in the factory which was given as a practical example, it could be mentioned that the measurement of the machine parts with calipers affects on continuous loss of time during the measurement process and reduces the reliability for accurate measurements.

Error criteria set by the parts orderer for rejection of mechanical parts was 0.1 mm. Parts with errors above 0.1 mm were considered as a scrap.

The above given examples, show us that the application of coordinate measuring machine (CMM) technology would be much better, because the accuracy will be higher and the ability to make corrections will be much faster.

Coordinate measuring machine (CMM) consists of a probe supported on three mutually perpendicular (*x*, *y*, and *z*) axes (Figure 15).

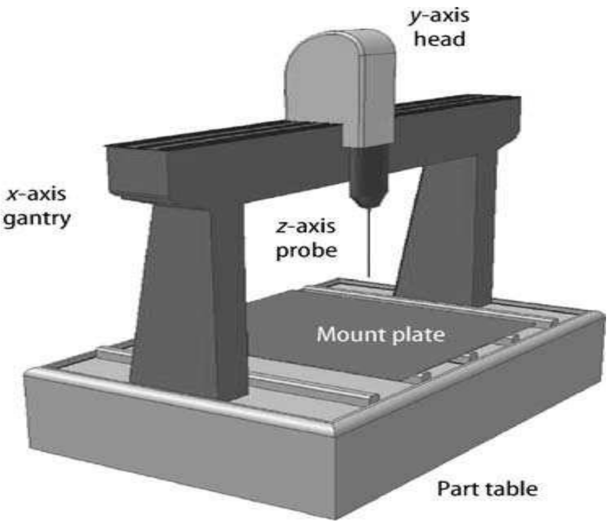

Fig. 15. Conceptual view of a coordinate measuring machine (CMM) [1]

Coordinate measuring machine (CMM) generates 3D coordinate points, as the probe moves across the surface of the part. Operators may run coordinate measuring machine (CMM) in a manual mode where they move the probe around an object and collect coordinate measurements, or they may program the probe to move automatically around the part [1].

The coordinate measuring machines (CMM) can be divided into mainly two major types: with contact-type measurement system and with non-contact measurement system [9].

Reverse engineering using 3D digitizing is a potential methodology to make virtual prototype models for analysis and 3D visualization of the products [10].

Applying reverse engineering will be essential for the technical and economic development of the analyzed factory in general.

6. CONCLUSION

In this paper, the mechanical parts that have been selected for analysis were: tool part (precision) and mechanical part (complex geometry).

The form used for measurement the mechanical parts was through the calipers, which is currently the only opportunity in the factory used as an example. Drawing of the parts and creating their CAD models was on computer using Autodesk Inventor software.

Taking into the account the analysis that were made, we can conclude that digital scanning is indispensable and irreplaceable for application to minimize errors and reduce the time of measurement.

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Original scientific paper

AN INNOVATIVE APPROACH IN PRODUCTS' SIZE ADJUSTMENT INSPIRED BY NATURE

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A b s t r a c t: The research presented in this paper is based on an interdisciplinary approach where the possibilities of ergonomic and bionics methods are integrated. The main goal of the research is a verification of the advances and possibilities of our recently established six-step bio-inspiration strategy. The applied strategy resulted with recognition of a natural phenomena – layering, which became an inspiration for proposing of an innovative solution for products' size adjustment. The efficiency and quality of the proposed principle were verified on a certain design problem – a bicycle seat for children transportation. Extensive anthropometric survey was applied for providing precise dimensioning of the seat layers in order to accommodate the children of different ages. An ergonomic analysis was performed for assessment of the seating comfort with pressure sensors, and important guidelines for the design process were obtained. The results were applied on three proposed concepts and detailed design of the selected one.

Key words: bionics; biologically inspired design; ergonomics; product design; products size adjustment

ИНОВАТИВЕН ПРИСТАП КОН ПРИСПОСОБУВАЊЕТО НА ГОЛЕМИНАТА НА ПРОИЗВОДИТЕ ИНСПИРИРАН ОД ПРИРОДАТА

А п с т р а к т: Истражувањето презентирано во овој труд е базирано на интердисциплинарен пристап во кој се интегрирани можностите на ергономските и бионичките методи. Главна цел на истражувањето е верификација на стратегијата за извлекување инспирација од природата преку шест чекори, која ја воспоставивме неодамна. Примената на стратегијата резултираше со препознавање на природниот феномен – слоевита градба, кој претставуваше инспирација за предлагање на иновативен пристап кон решавањето на ергономскиот проблем приспособување на големината на производите. Ефикасноста и квалитетот на предложениот принцип беа верификувани преку решавање на конкретен дизајнерски проблем – велосипедско седиште за превоз на деца. Заради прецизно димензионирање на слоевите на седиштето, со цел тоа да одговара на деца од различна возраст, беше применето опсежно антропометриско истражување. Заради определување насоки во врска со удобноста на седиштето беше извршена анализа на распределбата на притисоците на постојни детски седишта. Резултатите од анализите беа применети во три предложени концепти и во детална разработка на еден од нив.

Клучни зборови: бионика; биолошки инспириран дизајн; ергономија; дизајн на производи; приспособување на големината на производите

1. INTRODUCTION

Bionics is an interdisciplinary science, which synthesizes the knowledge of biology and other sciences. Industrial designers, architects and engineers find the application of principles and methods of bionics efficient for deriving inspiration and improving their creative thinking.

Designers explore natural systems by adopting one of the two main bionic strategies: solution-driven or problem-driven approach. The first one deals with abstraction of the principle in biological systems as an inspiration for application in the product design process. The second one searches for a solution in natural systems for already recognized design problems.

Many researchers worked on developing strategies and methods for practicing biologically inspired design. Helms, Vattam and Goel [3, 4] propose an organizing framework for practicing of biologically inspired design, which could be applied on both problem – driven process and solution-driven process.

Versos and Coelho propose the bi-directional bionic design method [1, 2], which suggests a series of steps in the design process that could be practiced in one of the two alternative orientations considered for the bionic design process. The common steps in both directions of analysis consist of the same activities, contain the same description and are applicable for the two orientations.

The research presented in this paper is based on an interdisciplinary approach where the possibilities of ergonomic and bionics methods were integrated. The main goal of the research was verification of the advances and possibilities of our recently established six-step bio-inspiration strategy for improvement of creativity [5], based on the advances of the bi-directional bionic design method proposed by Versos and Coelho [1, 2]. We offered a strategy of six steps in the process of exploration of natural systems followed by identification of important natural solutions and a structured way of documentation in order to become more noticeable and observable to attract an attention of designers and engineers. The recognized natural solutions could become a trigger for inspiration for various design solutions.

The applied strategy resulted with recognition of a natural phenomena – layering, which was an inspiration for proposing of an innovative solution for products' size adjustment. The efficiency and quality of the proposed principle were verified on a certain design problem – a bicycle seat for children transportation. An extensive anthropometric survey was applied for providing precise dimensioning of the seat layers in order to accommodate the children of different ages. An ergonomic analysis was performed for assessment of the seating comfort with pressure sensors, and important guidelines for the design process were obtained. The results were applied on three proposed concepts and detailed design of the selected one.

2. THE PRINCIPLE OF LAYERING DISCOVERED IN NATURE

The main intention of our research was to verify our recently established six-step bio-inspiration strategy as an efficient tool for deriving inspiration from nature in the design process.

Step 1 – exploration of nature. Nature is everywhere around us. Observation and direct interaction are the best ways to recognize an inspiring object and become familiar with its characteristics.

Step 2 – attraction of attention. Product designers are usually attracted by the visual features of the object – shape, material, texture, colour, as well as structure, functionality and multi-functionality, space organization, effectiveness and optimization of the shape and the material. Our attention was triggered by the structure of onion.

Step 3 – identification of an inspiring natural phenomena. The phase of solution identification is based on perception and observation as exploration methods. The outcome is one or more identified exceptional solutions, documented with a collection of photos, videos, sketches and textual explanations, description of the identified natural solutions with ordinary language (Table 1).

Table 1

Description of the identified natural phenomena with ordinary language

Natural object / phenomena – onion	Description
	Onion has rounded shape of the body, consisted of several layers

Step 4 – exploration of the identified natural phenomena. The phase of exploration points towards a complete explanation of the identified natural solutions from all necessary aspects and with all necessary means in order to become clear and recognizable for their possible application in the phase of concept generation (Table 2).

Table 2

Documentation for explanation of the principles

Natural object / phenomena – onion	Description
	• Several layers • Fractal design of the layers • The layers are placed one over the other, from inside to outside • Solid body

Step 5 – reformulation of the identified natural phenomena. The reformulation of the identified natural phenomenon is an important step for recognition of the possible design solution for a new product creation or improvement of existing one. The reformulation means application of the deduction method in order to transform the description into a set of specific keywords or short explanations (Table 3). The main intention is the description to become comparable with possible design problems.

Table 3

Reformulation of the identified natural phenomena

Natural object / phenomena – onion		
What?	Purpose?	How?
Body shape	Shape into shape principle	Fractal design
	Step by step growth of the body	Layers placed one over another from inside to outside
	Rising of the body strength	Layers placed one over another from inside to outside
	Optimization of the volume	Rounded body

Step 6 – recognition of the design problems where the identified natural phenomena could be applied. The reformulation of the identified natural phenomena already points to the possible design solution(s). Layered structure of onion is associated with the growth of the body volume, as well as with the rising of the body strength. The deduction method is useful to be applied again in order to reach closer to the possible design problem(s) with appropriate questioning and answering (Table 4).

Table 4

Questions and answers for reaching closer to the possible design problems

Question	Answer
Which products need enlargement or reducing of the size?	Products that are used by different users that change their body size very fast
Which users change their body size very fast?	Children
Which products are used by different users?	Seats, chairs, skiing boots, heats
Which seats are used by children?	Especially designed car seats, bicycle seats
What features are important for those products?	Strong, safe, adjustable size
What is the benefit of the possibility for size adjustment?	The product could be used of different users and for a longer period

At the end of the step 6 the possible design problem was already recognized: the principle of layering would be very useful to be applied for solving of an ergonomic problem products' size adjustment.

The six-step bio-inspiration strategy was an efficient guide trough the process of inspiration where the discovered natural phenomena became a model for an innovative approach in solving of a regular ergonomic problem.

3. PRODUCTS' SIZE ADJUSTMENT WITH APPLICATION OF THE PRINCIPLE OF LAYERING

The application of ergonomic principles is an imperative for the design of contemporary products and their success on the market. The main goals of the ergonomics in product design are to provide directions how to obtain more comfort, safety, intuitive and easy managing and handling. Mass production imposes products to be designed to accommodate as many users as possible. The solution for this necessity is application of the principles of adjustability, modularity, as well as different sizes of products.

According to the results of inspiration process presented in the previous chapter, we decided to apply the principle of layering and to offer an innovative approach for solving of the ergonomic problem products' size adjustment.

We adopted the principle of layering for adjustment of products' sizes and applied it in solving of a particular design problem – a bicycle seat for children transportation. The results of this phase were necessary for verification of the efficiency and quality of the proposed principle of layering for products' size adjustment.

A} *Anthropometric analysis for children seats design*

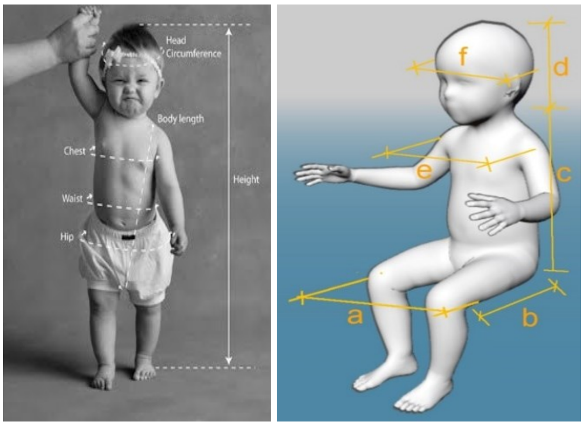
Due to the fact that children change their body size very fast most of the products that are necessary for their everyday lives need successive replacement with products of higher sizes. This fact means a huge burden of the home budget for their families. Because of this fact it is a great challenge for the designers to invent more durable and adjustable products. The principle of layering offers a possibility to make products that could be used in a longer period of time of the same user, as well as of different users. The process of layering is reversible, which means that the layers could be add or removed in accordance of the particular necessity.

The application of the concept of layers in the design of a bicycle seat for children transportation requires a detailed analysis of child anthropometry to obtain regular and precise dimensioning of the layers depending on the children age.

After the extensive study of the available anthropometric data for children between 6 months and 5 years we decided to design a seat consisted of three layers, appropriate for three age ranges:

- Layer 1 – the smallest size – suitable for children of age under 12 months (1 year).
- Layer 2 – the middle size – suitable for children of age between 1 and 3 years.
- Layer 3 – the biggest size – suitable for children of age between 3 and 5 years.

In the first stage of the survey the anthropometric measurements relevant for the design of a bicycle seat for child transportation were recognized (Figures 1, 2). According to the available anthropometric data for children [6] a table with extracted measurements for different children ages was determined (Table 5).



Figs. 1, 2. Anthropometric measurements relevant for the design of a bicycle seat for child transportation

Table 5

Anthropometric measurements for children of three different ages

Necessary children measurements (mm)	Layer 1	Layer 2	Layer 3
Width of the hips (a)	159	190	213
Buttock lenght (b)	194	284	358
Body lenght (c)	319	371	442
Distance between the shoulders and the top of the head (d)	161	174	191
Width of the shoulders (e)	208	243	278
Width of the head (f)	116	136	139

The method of fractals was adopted for the layers design. The extracted anthropometric measurements were applied for assessment of the relations between the layers dimensions:

- relation between the layer 1 and layer 2 is 1:1.092,
- relation between the layer 1 and layer 3 is 1:1.163.

B) *Comfort analysis of the existing children seats*

In order to obtain the relevant information about the seating comfort for the seat design an appropriate analysis of the pressure distribution was performed with three different existing children seats (Figures 3–5) and a group of 10 children of different age and sex. The experiment was performed 10 times with 10 children seating consequently on all of the three selected seats, covered with the pressure pillow. After the experiment an evaluation of the seating pressure distribution diagrams and detailed comparison of the results was performed.

Fig. 3–5. Three existing children seats selected for the experiment

The analysis of the pressure distribution between the children and the seats was performed with XSENSOR pressure measurement system. The results are presented with diagrams of the pressure distribution where the maximal and average pressure in mm Hg (transformed latter in kPa) and seating area in mm^2 are visualized with different colours in several levels, according to the pressure intensity. The areas with the highest pressure intensity are visualized with red colour, the areas with lower pressure with orange, the next level of pressure with yellow, than – light blue and the areas without pressure are presented with dark blue colour.

The diagrams of the experiment with the seat No. 1 (Figures 6, 7) represent very high pressure with average range 3.68 – 4.9 kPa (27.6 – 36.76 mm Hg) and maximal range 17.99 – 34.13 kPa (134.96 – 256 mm Hg). Very high pressures on unexpected places (pressure "jumps") are evident, as well as irregular distribution of the seating area (28870.97 – 55161.29 mm^2). Conclusion – the shape of the seat is extremely uncomfortable.

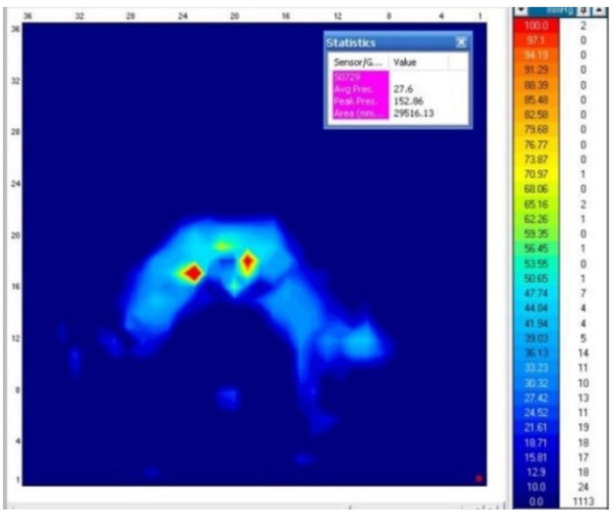


Fig. 6. Pressure distribution of the seat No. 1 with child No. 1

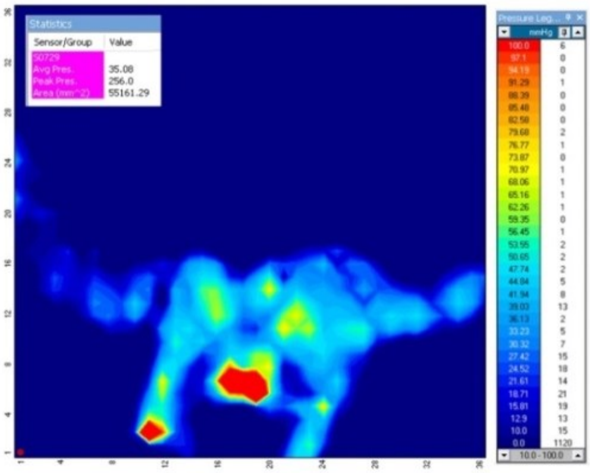


Fig. 7. Pressure distribution of the seat No. 1 with child No. 10

The diagrams of the experiment with the seat No. 2 (Figures 8, 9) represent pressure with average range 5.85 – 33.38 kPa (25.38 – 43.85 mm Hg) and maximal range 17.93 – 34.13 kPa (134.52 – 256 mm Hg). The effective seating area is in the range 29032.26 – 38548.39 mm^2. The seating surface is too flat which results with minor "jumps" of the pressure. Conclusion: the shape of the seat is more comfortable than the previous one, but still not enough.

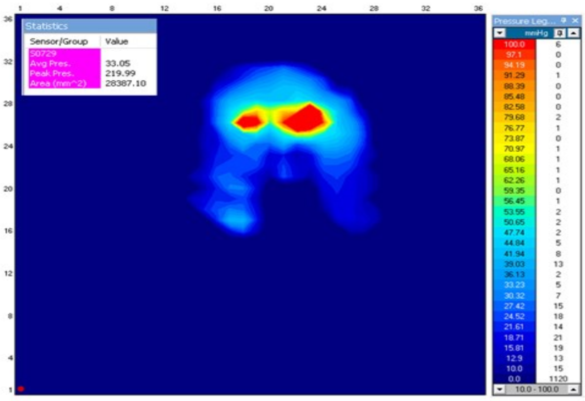


Fig. 8. Pressure distribution of the seat No. 2 with child No. 1

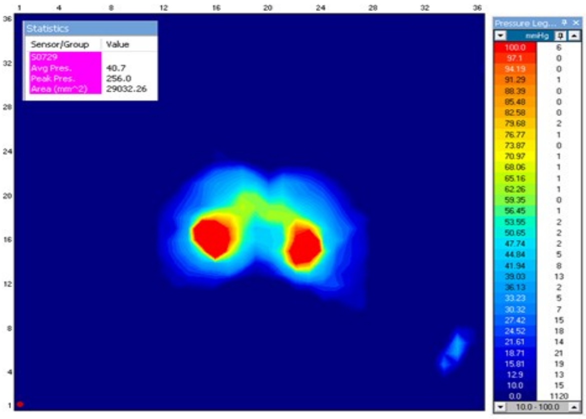


Fig. 9. Pressure distribution of the seat No. 2 with child No. 10

The diagrams of the experiment with the seat No. 3 (Figures 10, 11) represent pressure with average range between 5.85 and 33.38 kPa (25.38 – 43.85 mm Hg) and maximal between 6.58 and 30.67 kPa (49.35 – 230.06 mm Hg). The effective seating area is between 29677.42 and 65322.58 mm^2. It is evident that the seat No. 3 is more comfortable than the previous two as a result of more anatomic shape. The pressures are distributed more smoothly and logically related to the pelvis. The pressure "jumps" are very rare and with minor values.

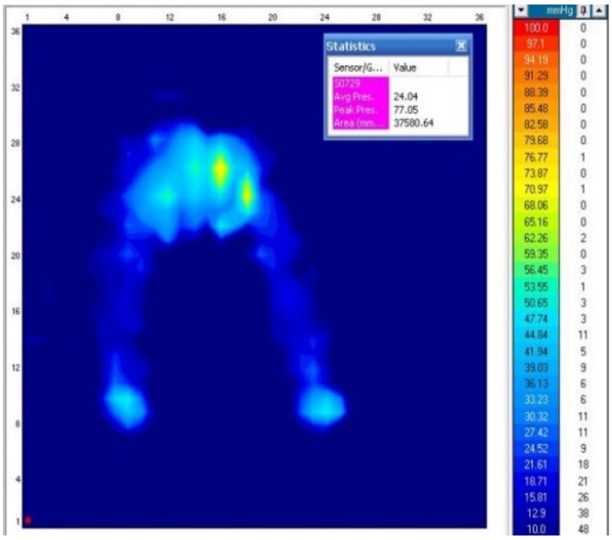


Fig. 10. Pressure distribution of the seat No. 3 with child No. 1

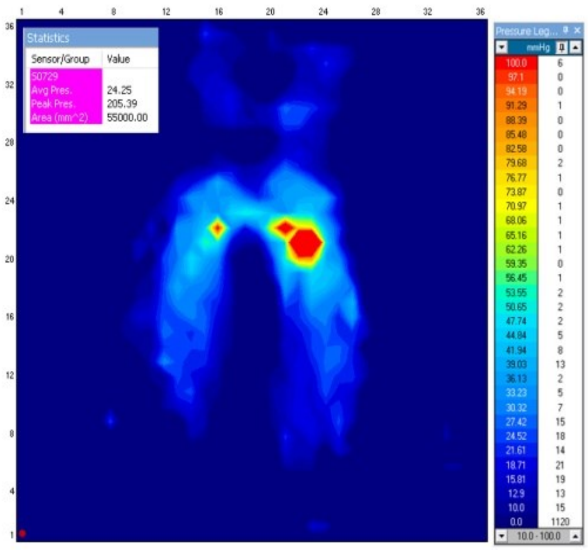


Fig. 11. Pressure distribution of the seat No. 3 with child No. 10

According to the presented results of the experiment, several useful conclusions were extracted for further implementation in the process of design of bicycle seat for children transportation:

- an anatomic surface of a seat is better than a flat surface from the aspect of pressure distribution;
- an anatomic surface of a seat obtains better protection of the child body;
- the centre of gravity has to be lower in order to obtain stability of the child body;
- the angle between the seat and the back rest has to be in the range between 90 and 110 degrees in order to obtain more comfortable seating.

4. DESIGN OF A BICYCLE SEAT FOR CHILDREN TRANSPORTATION

The design process always starts with precise definition of design requirements. In order to obtain as much as possible information an extensive review of the existed bicycle seats for children transportation on the market was performed, as well as a survey among the representatives of the recognized target group. According to the results of the review and the survey the most important requirements were adopted as guidelines for the design process:

1. child safety,
2. light weight,
3. adjustable size,
4. reduced number of parts,
5. easy mounting on and removing from the bicycle,
6. easy manipulation – placing of the child on and removing it from the seat,
7. comfortable seating,
8. attractive appearance,
9. affordable price,
10. compact shape.

A) *Concepts generation*

The next step in the design process was generation of concepts. According to the specified guidelines and principles three different concepts were proposed (Figures 12, 13, 14).

The presented concepts were evaluated with application of the spider mesh diagram (Figure 15), where the adopted requirements were used as evaluation criteria. The rating was performed with grades between 0 and 3.

Fig. 12.. Concept 1

Fig. 13. Concept 2

Fig. 14. Concept 3

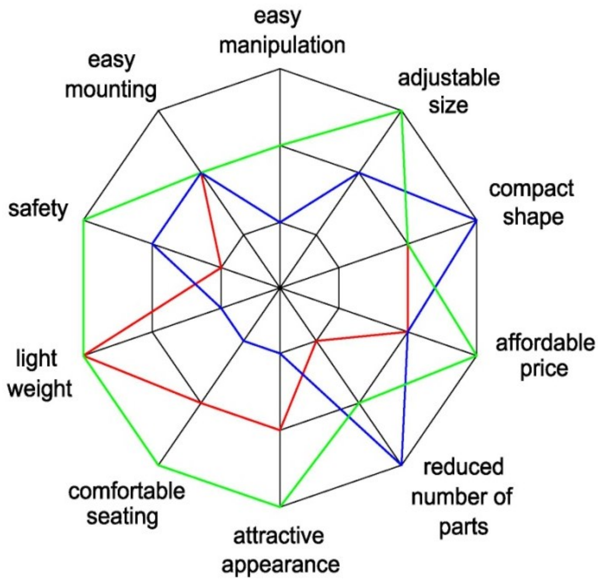


Fig. 15. Concepts evaluation with the spider mesh diagram

After the evaluation process of the proposed concepts the third one was selected for further development. The selected concept offers the best ergonomic and seating comfort, as well as better safety for the children.

B) *Final design of the selected concept*

The selected concept of a bicycle seat for children transportation is build of two main parts: the seat and the leg holder. The leg holder is necessary for obtaining of legs safety during the drive and has to be used for the children over 12 months. The seat could be utilized without the leg holder for the children younger than 12 months.

The seat and the leg holder are designed as assembles of four layers (Figure 16). The outside layers are responsible for the strength of the seat and the leg holder, as well as for the children safety. They should be produced of a strong material, for example ABS or polypropylene. The three additional layers should be more flexible in order to obtain better seating comfort during the utilization and easy maintenance (handling) in the phase of size adjustment. EVA polymer is the most suitable material for their production (Figure 17).

The layers are dimensioned and designed according to the precise results from the phase of anthropometric and ergonomic survey, presented in the chapter 3. They are responsible for size adjustments for different children ages (Figure 18).

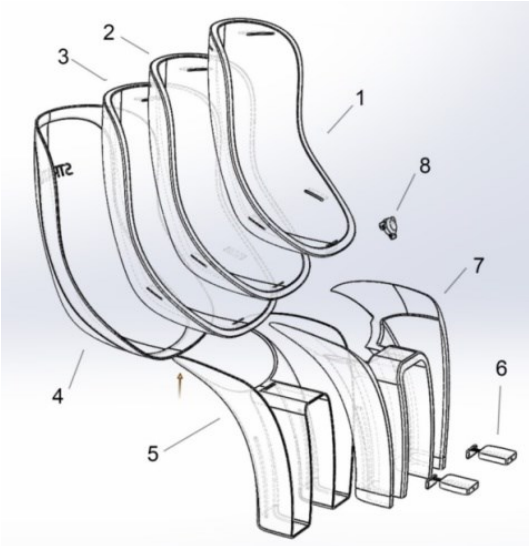


Fig. 16. Exploded view of the final design of a bicycle seat for child transportation

Fig. 17. Components of a bicycle seat for child transportation

Fig. 18. Visualization of the possible utilization of the seat of the children of different ages

5. CONCLUSIONS

The presented research is based on an interdisciplinary approach where the possibilities of ergonomic and bionics methods were integrated. The main goal of the research was verification of the advances and possibilities of our recently established six-step bio-inspiration strategy for efficient of identification of natural phenomena in order to become an inspiration for solving of a specific design problem.

At the end of this research we can confirm that the application of the six-step bio-inspiration strategy is evidently very efficient. The applied strategy resulted with effective recognition of a natural phenomena – layering, which became an inspiration for proposing of an innovative solution for products' size adjustment.

The efficiency and quality of the principle of layering for products' size adjustment were verified on a certain design problem – a bicycle seat for children transportation. It could be further be applied for solving of other similar design problems where the size adjustment is necessary: different kinds of seats for children or adults (baby car seats, office chairs). It could also be applied for design of other products or devices where the topography and configuration are important for obtaining of safety and possible medical cure.

The applied anthropometric and ergonomic analysis, especially the assessment of the seating comfort with pressure sensors, mean valuable experience which could be further be applied for other similar products.

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Original scientific paper

FUZZY LOGICS MODEL FOR DIMENSIONING OF TRANSPORT CAPACITIES IN RAILWAY FREIGHT TRANSPORT

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A b s t r a c t: As any transportation system, the railway system is based on significant capital and is an important national and economic potential. In same time the economy and society need to enable efficient, massive, environmentally friendly, fast and quality transport. On the other hand, is engaging directly and indirectly a significant part of the work force in a society and an important part of national resources. Therefore, the transport by rail must be cost effective, operationally flexible and followed by reliable and high quality service in order to make the balance of the requirements that arises during the planning of transportation facilities and the opportunities which are determined by the capacities. The available capacity of the rail freight and the market demand are determining their planning and allocation. The planning and allocation is a very complex process that directly affects the efficiency and effectiveness of the rail transport, and by that, the efficiency and effectiveness of the economy. Worldwide, despite the analytical and graphical methods, different models based on queuing theory, special mathematical and statistical models as inputs are using statistics. Within this paper in order to achieve the objective, which is efficient and effective operation of the railway system, through proper planning of the capacities, a fuzzy model was designed based on the theory of artificial intelligence, such as Model for dimensioning capacities in freight transport by using Fuzzy Logic (FL). Produced model will alow delivering operational (capacity planning by demand for transport market) and strategic decisions (predicting demand for transporting facilities in the future). The testing of the models is applied to the example of Macedonian Railway Transport JSC (MRTJSC) railway operator which core business is the transportation of passengers and goods in domestic and international markets.

Key words: modeling; dimensioning; railway freight wagons; fuzzy logic

МОДЕЛ НА ФАЗИ ЛОГИКА ЗА ДИМЕНЗИОНИРАЊЕ ПРЕВОЗНИ КАПАЦИТЕТИ ВО ЖЕЛЕЗНИЧКИОТ ТОВАРЕН ТРАНСПОРТ

А п с т р а к т: Како и секој транспортен систем, и железничкиот систем се базира на значителен капитал и е важен национален и економски потенцијал. Истовремено, економијата и општеството имаат потреба од ефикасен, цврст, еколошки, брз и квалитетен транспорт. Од друга страна, тој директно и индиректно ангажира значителен дел од работната сила во едно општество и важен дел од националните ресурси. Затоа железничкиот сообраќај мора да биде рентабилен, оперативно флексибилен, а истовремено сигурен и висококвалитетен сервис правејќи баланс на побарувањата што произлегуваат од планирањето на транспортните капацитети и можностите кои се одредени од капацитетите. Расположливиот капацитет на железничкиот товарен транспорт и побарувачката на пазарот го одредуваат неговото планирање и распределба. Планирањето и распределбата претставуваат многу сложен процес кој директно влијае на ефикасноста и ефективноста на железничкиот превоз, а со тоа и на ефикасноста и ефективноста на економијата. Во светот, покрај аналитичките и графичките методи и разни модели базирани на теоријата на редови, специјалните математички и статистички модели како појдовна вредност ја користат статистиката. Во рамките на овој труд, со цел да се постигне ефикасно и ефективно работење на железничкиот систем, преку правилно планирање на капацитетите е дизајниран модел базиран на теоријата за вештачка интелигенција, каков што е моделот за димензионирање на капацитетите во товарниот транспорт со користење на фази логика (FL). Добиениот модел ќе овозможи донесување на оперативни (планирање на капацитетите по потреба на транспортниот пазар) и стратешки одлуки (предвидување на побарувачката за транспорт на стоки во иднина). Тестирањето на моделите е применето на примерот на железничкиот оператор Македонски железници – Транспорт (МЖТ), чија основна дејност е превозот на патници и стоки на домашниот и на меѓународниот пазар.

Клучни зборови: моделирање; димензионирање; железнички товарни вагони; фази логика

1. INTRODUCTION

The railway system with its huge capital is a significant national and economic potential, which needs to enable efficient, massive, environmentally friendly, fast and quality transport to the economy and to the citizens. On the other hand, engage directly and indirectly a significant part of the work force in a society and an important part of national resources. Therefore, transport by rail must be cost effective, operationally flexible and followed by reliable and high quality service in order to make the balance of the requirements which are arising in the process of planning of transportation facilities which are directly determined by the capacities.

The transport capacites of the railway undertaking mostly are planned based on intuition, based on partial facts relating to the prospects of transport in the future, based on industry trends and based on partly outdated analytical methods which are less used in the process of planning capacities.

Since all systems can not be modeled based on statistical data, the use of modern techniques for definition of specific inputs is increasing. The theory of artificial intelligence is most applied. Some of the techniques which are used are the techniques of Fuzzy logic, Neural networks, Swarm intelligence (ant colony, bee colony), CBR [1].

There is lack of established models which can enable efficient, effective and technologically optimal allocation of limited transportation facilities and resources in the everyday functioning of a company that deals with rail transport, but also for those companies who rent capacity of railway undertakings. The establishment of that kind of model would allow better financial and economic functioning of the companies and would improve the services offered to the market.

Rail transport is part of the logistics chain, and therefore part of the complete logistic service. This means that the implementation of a high quality model for planning and allocation of the capacites in the rail transport can directly affect the performance and the logistics chain as a whole.

The rail freight transport and market demand of rail transport services are determining the planning and allocation of available capacities. The planning and allocation is a very complex process that directly affects the efficiency and effectiveness of rail transport, and thus the efficiency and effectiveness of the economy. On the one hand, insufficient capacity of rail transport may affect the choice of transport modality, or ultimately the inefficiency of the economy, and on the other hand the oversized and irregularly structured facilities affect the efficiency and effectiveness of the railway undertaking (loss of transport, costs of "tied" capital, maintenance, loans, etc.).

The scope and the structure of the capacity increase the complexity in the planning process. The market claims which from day to day are more different and more specific in terms of the types of cargo that would be transport, also affect the planing. Although the opinion that the use of unified transport units would reduce the problem complexity of planning capacity is increasingly govern, yet that such transport units can not fully meet the various requirements of the economy. Until the man and his uniqueness are existing, there will be different requirements for different types of products with different sizes, color, conditions, types, etc., therefore the need for different types of vehicles.

According to the previous in terms of exploitation of the capacity in rail transport, the problem of (un)rational exploitation is identified exactly and the need to be solved by quantitative and qualitative planning and determination (dimensioning) is foreseen.

2. RESEARCH OBJECTIVE

In order to provide the needed level of quality of transport services in rail transport, it is necessary to determine the necessary facilities and to set the correct organization. This means, above all that it is necessary to know what transport facilities are needed what kind of capcaities for which types of goods as the way of organizing transport etc. will be applied. These are a basic prerequisite for the rational use of vehicles. While forecasts and decisions relating to the future are high risk despite its large number of possible detailed data analyzis, that can be made from the previous period in terms of planning and use of the structure and size of transport facilities.

An important element in decision making and planning is choosing [2], and the decision is a choice of one share of the group of available alternateves [3]. The decision must be operational, tactical and strategic.

There are also cases when the problem can not be solved by analytical way or that solution is too complex. In those cases, different techniques of simulation can be used.

Considering the types and amount of information on which a decision for the allocation of capacity should be reached, their mutual incorsistancy and comparison, then it is the model that would allow dimensioning to be based on the application of mathematical methods and techniques. This model should take into account the availability of capacity and market demand for a solution that will enable the adoption of correct and incorrect decisions.

3. PREVIOUS RESEARCH

The transport capacity of the railway systems is directly proportional to the volume and structure of available vehicles. For successful management of the rail transport service, the securing enough rail vehicles it is needed, which structure must suit the type of goods intend to be transported. When it comes to rail transport, this issue is not sufficiently processed in the scientific and professional literature. As a result there is an established and widely used scientific method for dimensioning the transport capacity of the railway traffic based on multidimensional involving multiple factors that determine the real needs and capacities which enable efficient and effective rail transport.

Specific planning and design capacity in the rail transport in the available literature can find a limited number of models, but some of them will be presented.

Authors Etezadi and Beasley studied the problem of determining the optimal structure of the fleet and its optimal size [4]. Given that the decision of these tasks is the long term, they have presented a model that is based on integer linear programming. In the same paper the authors suggest that the problem may more accurately be solved by using simulation.

One of the first papers concerning the sizing of the fleet but in the maritime sector is published in 1954 by the authors Dantzig and Fulkerson [5]. They have presented the problem of determining the minimum number of tankers to carry out the timetable. While Kirby [6] in 1959 had one of the first attempts concerning optimization of the fleet of the railways. He deals with the problem of increasing the degree of utilization of wagons owned by the small rail system and reduces the level of rental cars by determining the relative cost of own and leased cars per day.

Bojović and other authors [7] in 2010 worked out the problem of determining the optimal composition of the freight wagon fleet. The problem is divided into two parts, determining the optimal mix and determine the optimum size of freight wagon fleet. The first part is processed through the method multicriteria decisioning and solves the application of Fuzzy-analytical hierarchical process. The solution of this section consists of the most appropriate types of wagons for the carriage of goods. The second part of the solution to the problem of the size of the fleet is obtained through model Fuzzy multiple-layer linear programming. Same author [8] in 2002 addressed the problem of optimizing the size of the fleet through meeting demand and minimize the total cost.

Lima and other authors [9] in 2004 have described a mathematical algorithm to solve the problem. This algorithm is a hybrid of genetic algorithm and local search based on GENIUS algorithm.

Wu and other authors [10] in 2005 addressed the problem of dimensioning fleet in road traffic. Operational and tactical decisions for heterogeneous fleet explicitly designed by the model of linear programming in order to determine the optimal size and mix of the fleet. Demand is assumed as known while travel time is stochastic parameter.

Choi and Tcha [11] in 2007 represent approach based on generating columns to resolve the problem. The authors propose an integer programming model whose LP relaxation is dealt with the method of generating columns.

Song and Earl [12] in 2008 represent an integrated model for determining the optimal management policy of the allocation of empty wagons and sizing the fleet in the system comprising two depots. The times of arrival of the vehicles and the times of travel of empty wagons accepted as stochastic variables. Under this approach the optimal strategy for allocating vehicles in homogenous fleet is based on the management of the limits in terms of minimizing the expected discount cost consisting of the cost of maintenance, rent and moving vehicles in an empty condition.

Sayarshad and Ghoseiri [13] in 2009 suggested the formulation and procedure for solving optimization of fleet size and allocation of wagons with demand and travel times for freight wagons being treated as deterministic. The authors assume that unfulfilled demand becomes zero at the end of the planning period. The calculation tests on small examples can be solved with an exact procedure for a short period of getting results, while for medium and large instances this is not possible. For this reason these authors propose an algorithm of simulated problem solving.

Sayarshad and other authors [14] in 2010 proposed formulation and procedure for solving optimization size of freight wagon fleet and allocation of wagons for the case of stochastic demand. The authors propose a two-phase procedure based on the algorithm of simulated problem solving.

Loxton and other authors [15] in 2012 have considered the problem of forming a heterogeneous fleet with the presence of stochastic demand. The problem is based on determining the number of vehicles to be purchased for each type of vehicle specifically so that the total expected cost of the fleet to be set to minimum. These authors developed an algorithm that combines the dynamic programming method and the golden section to resolve the problem.

Models of optimization based on the behavior of swarms (colonies) named by Teodorović "swarm intelligence" is partly inspired by the behavior of ants and bees in nature. They solve problems of combinatorial organization. It is a problem that occurs in the dimensioning of capacity in railway transport [16].

Overall the models pertaining for sizing and planning of transport facilities in railway transport newer generation are related to the analysis and determination of transport capacity on the basis of historical data and predict future needs. Based on that information, a model that can provide facilities that will satisfy the needs of the company and customers is defined. It is therefore necessary to take into account factors such as: types of facilities, types of goods, industry trends, uses of facilities, costs etc.

The model should be able to include more factors commonly with different sizes and values. To avoid mixing of different sizes and values or the linguistic variables as the most appropriate method that can measure and compare differences represent the method of artificial intelligence – "Fuzzy logics" (fuzzy logic). This method allows measuring, comparing and synthetizing different variables that are hard to be quantified to carry more qualitative features, as well as simplifying the uncertainty regarding the input data and parameters in terms of uncertainty, subjectivity, inaccuracy and ambiguity.

4. FUZZY LOGICS

Fuzzy sets, as an entirely new concept, defined in 1965 (Lotfi Zadeh,) were introduced with the main objective of formalized mathematical way to present and modeled uncertainty in linguistics.

Great application of fuzzy logic (FL) is found in the situations where there is an adequate mathematical model for display in a complex process that is necessary to use the knowledge of experts. By using different modeling techniques based on fuzzy logic allows solving a wide range of problems and enables making the right conclusions. Fuzzy logic uses the experience of experts in the form of linguistic rules and mechanism of aproximative reasoning can give an appropriate decision on a particular case.

Fuzzy logic has occurred as a result of trying to model human thinking, experience and intuition in the process of making decisions based on inaccurate data. Suitable for expressing uncertainty, application of fuzzy logic proved excellent in those models in which intuition and assessment are the primary elements.

It is important to recognize that the essence of fuzzy logic is quite different from the essence of classical logic that strengthened since Aristotle. Conventional logic is based on clear and precise rules established and is based on the theory of sets, a respective element can belong or not to belong to a specific group (set). If it mathematically present, then the degree of belonging to that element is 1 if it belongs to a set, or 0 if it does not belong to the set.

5. MODEL FOR DIMENSIONING CAPACITIES IN FREIGHT TRANSPORT USING FUZZY LOGIC

The main problem in the process of forming the model by applying fuzzy logic to the transport capacity dimensioning is based on determining the fuzzy rules and parameters of membership functions. For defining the rules have been used data obtained by polling experts for rail transport. Knowledge of experts in the process of determining the type, the amount of transport capacity is expressed by a number of linguistic variables.

The choice of the type and the parameters of the function of belonging is implemented on the basis of the positive experiences of certain authors and subjective estimates of the authors. With literature review, it was determined that the application of the origin function with Gaussian shape achieves utmost precision outputs. Therefore, in this model this type of curve is generated. Its parameters are determined on the basis of subjective evaluation. The interval of size of the input and output variables are defined on the basis of the amounts of real values within the system Macedonian Railways Transport JSC (MRTJSC). Only the values of the turnover of cars, and the level of immobilization of the same where not taken into account. These two criteria for each series and subseries of wagons have a different value of these two criteria and affect only the increase in capacity needs from the specified series of wagons.

The model is based on a system of Mamdani fuzzy logic and min-max method of direct locking, while for the process of defuzzification the method of centroids was applied. The model has been tested for the most common series and subseries of freight wagons in groups (open, closed, plateau and special) that are obtained on the basis of a matrix consisting of correspondence "type of goods - type of wagon" of Macedonian Railways Transport JSC. The observed series and subseries in groups of wagons are typical in other major rail carriers (17).

6. ASE STUDY: FUZZY MODEL FOR DIMENSIONING A GROUP OF OPEN FREIGHT WAGONS AS TRANSPORT CAPACITIES (MODEL FL)

The fuzzy model for dimensioning the group of open wagons (Eas, Eanos, Fad) has five input variables: coal / lignite, ores of nonferrous metals, wood, scrap metal and ballast. Each variable fuzzy model has three linguistic values. Also the output variables for each series of open wagons has three values (Figure 1).

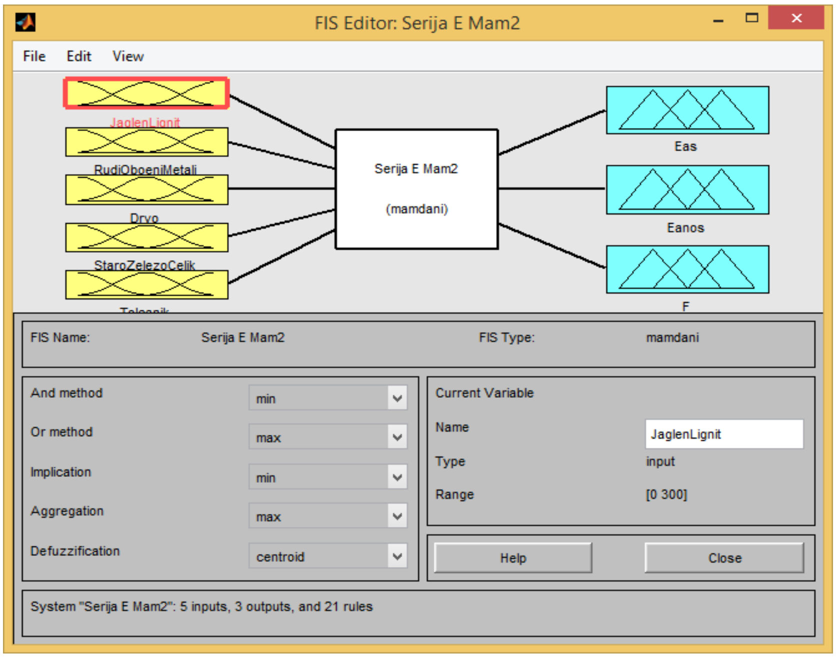


Fig. 1. Fuzzy system FL for dimensioning of open wagons of series Eas, Eanos and F

The input variable coal / lignite has the following values: a small amount of coal (MKJ), medium amount of coal (SKJ) and a large amount of coal (GKJ). The values of the input variables relating to ores of non-ferrous materials are presented as: a small amount of ore (MKR), medium amount of ore (SKR) and a large amount of ore (GKR). When questioned variables relating to wood as a commodity, they have the following linguistic values: a small amount of wood (MKD), medium amount of wood (SKD) and a large amount of wood (GKD). The same goes for scrap metal and ballast: a small quantity of scrap iron (MKS), medium amount of scrap metal (SKS) and a large amount of scrap metal

(GKS), and a small amount of ballast (MKT), medium amount of ballast (SKT) and a large amount of ballast (GKT).

With the fuzzyfication of the actual values that over the last five years occurred annually, are reflected in the membership functions in the following intervals (in 1000 tons) of coal / lignite [0 – 300], ores of nonferrous metals [0 – 700], wood [0 – 100], scrap [0 – 100], and ballast [0 – 100]. Interval all output variables Eas, Eanos and F is [0 – 50] wagons.

The input and output variables have Gaussian membership functions defined as:

$$\mu_A(x) = e^{\frac{-(x-c)^2}{2\sigma^2}} \quad (1.1)$$

The Gaussian stage number is described with two parameters $A = (\sigma, c)$. The first number represents the left and right distribution bell curve length of both the abscissa and the second number represents the value at which the Gaussian curve has a value of 1 on the abscissa. While the bell curve combined with dual center is described by four numbers and in which the first two are describing the left side of the function and the other two right side of the function.

Functions belonging to fuzzy input variables coal and lignite in 1000 tonnes are defined by the following parameters: MKJ [50 – 15 50 15], SKJ [50 125 50 175] and GKJ [50 285 50 315] for x ε [0, 300] (Figure 2a).

$$\mu_{\mathrm{MKJ}}(x) = e^{\frac{-(x-15)^2}{5000}}$$

$$\mu_{\mathrm{SKJ}}(x) = e^{\frac{-(x-125)^2}{5000}}$$

$$\mu_{\mathrm{GKJ}}(x) = e^{\frac{-(x-285)^2}{5000}} \quad (1.2)$$

Membership functions of the fuzzy input variables ore for ferrous metals in 1000 tonnes are defined by the following parameters: MKR [100 –35 100 35], SKR [100, 315, 100, 385] and GKR [100, 665, 100, 735] for x ε [0, 700] (Figure 2b):

$$\mu_{\mathrm{MKR}}(x) = e^{\frac{-(x-35)^2}{20000}}$$

$$\mu_{\mathrm{SKR}}(x) = e^{\frac{-(x-315)^2}{20000}}$$

$$\mu_{\mathrm{GKR}}(x) = e^{\frac{-(x-665)^2}{20000}} \quad (1.3)$$

Membership functions of the input variables to the tree 1000 tons are defined by the following parameters: MKD [10 –5 10 5], SKD [10 45 10 55] and GKD [10 95 10 105] for x ε [0, 100] (Figure 2c):

$$\mu_{\mathrm{MKD}}(x) = e^{\frac{-(x-5)^2}{200}}$$

$$\mu_{\mathrm{SKD}}(x) = e^{\frac{-(x-45)^2}{200}}$$

$$\mu_{\mathrm{GKD}}(x) = e^{\frac{-(x-95)^2}{200}} \quad (1.4)$$

The functions of belonging of the input variables for scrap in 1000 tonnes are defined by the following parameters: MKS [10 –5 10 5], SKS [10 45 10 55], GKS [10 95 10 105] for x ε [0, 100] (Figure 2d):

$$\mu_{\mathrm{MKS}}(x) = e^{\frac{-(x-5)^2}{200}}$$

$$\mu_{\mathrm{SKS}}(x) = e^{\frac{-(x-45)^2}{200}}$$

$$\mu_{\mathrm{GKS}}(x) = e^{\frac{-(x-95)^2}{200}} \quad (1.5)$$

The functions of the input variables belonging to ballast in 1000 tonnes is defined by the following parameters: MKT [10 –5 10 5], SKT [10 45 10 55], GKT [10 95 10 105] for x ε [0, 100] (Figure 2e):

$$\mu_{\mathrm{MKS}}(x) = e^{\frac{-(x-5)^2}{200}}$$

$$\mu_{\mathrm{SKS}}(x) = e^{\frac{-(x-45)^2}{200}}$$

$$\mu_{\mathrm{GKS}}(x) = e^{\frac{-(x-95)^2}{200}} \quad (1.6)$$

The functions of the output variables belonging to the series Eas, the amount of car, are defined by the following parameters: MKEas [9 3 9 –3], SKEas [9 9 23 28], GKEas [9 9 48 53] for x ε [0, 50] (Figure 2 f):

$$\mu_{\mathrm{MKEas}}(x) = e^{\frac{-(x-3)^2}{162}}$$

$$\mu_{\mathrm{SKEas}}(x) = e^{\frac{-(x-23)^2}{162}}$$

$$\mu_{\mathrm{GKEas}}(x) = e^{\frac{-(x-48)^2}{162}} \quad (1.7)$$

The functions of the output variables belonging to the series Eanos, the amount of car, are defined by the following parameters: MKEanos [9 3 9 –3], SKEanos [9 9 23 28], GKEanos [9 9 48 53] for x ε [0, 50] (Figure 2e):

$$\mu_{\mathrm{MKEanos}}(x) = e^{\frac{-(x-3)^2}{162}}$$

$$\mu_{\mathrm{SKEanos}}(x) = e^{\frac{-(x-23)^2}{162}}$$

$$\mu_{\mathrm{GKEanos}}(x) = e^{\frac{-(x-48)^2}{162}} \qquad (1.8)$$

The functions of the output variables belonging to the series F, the amount of car, are defined by the following parameters: MKF [9 3 9 –3], SKF [9 9 23 28], GKF [9 9 48 53] for x ε [0, 50] (Figure 2h):

$$\mu_{\mathrm{MKF}}(x) = e^{\frac{-(x-3)^2}{162}}$$

$$\mu_{\mathrm{SKF}}(x) = e^{\frac{-(x-23)^2}{162}}$$

$$\mu_{\mathrm{GKF}}(x) = e^{\frac{-(x-38)^2}{162}} \qquad (1.9)$$

On Figure 3. the presented graph is for output variables for different batches of wagons depending on the input variables.

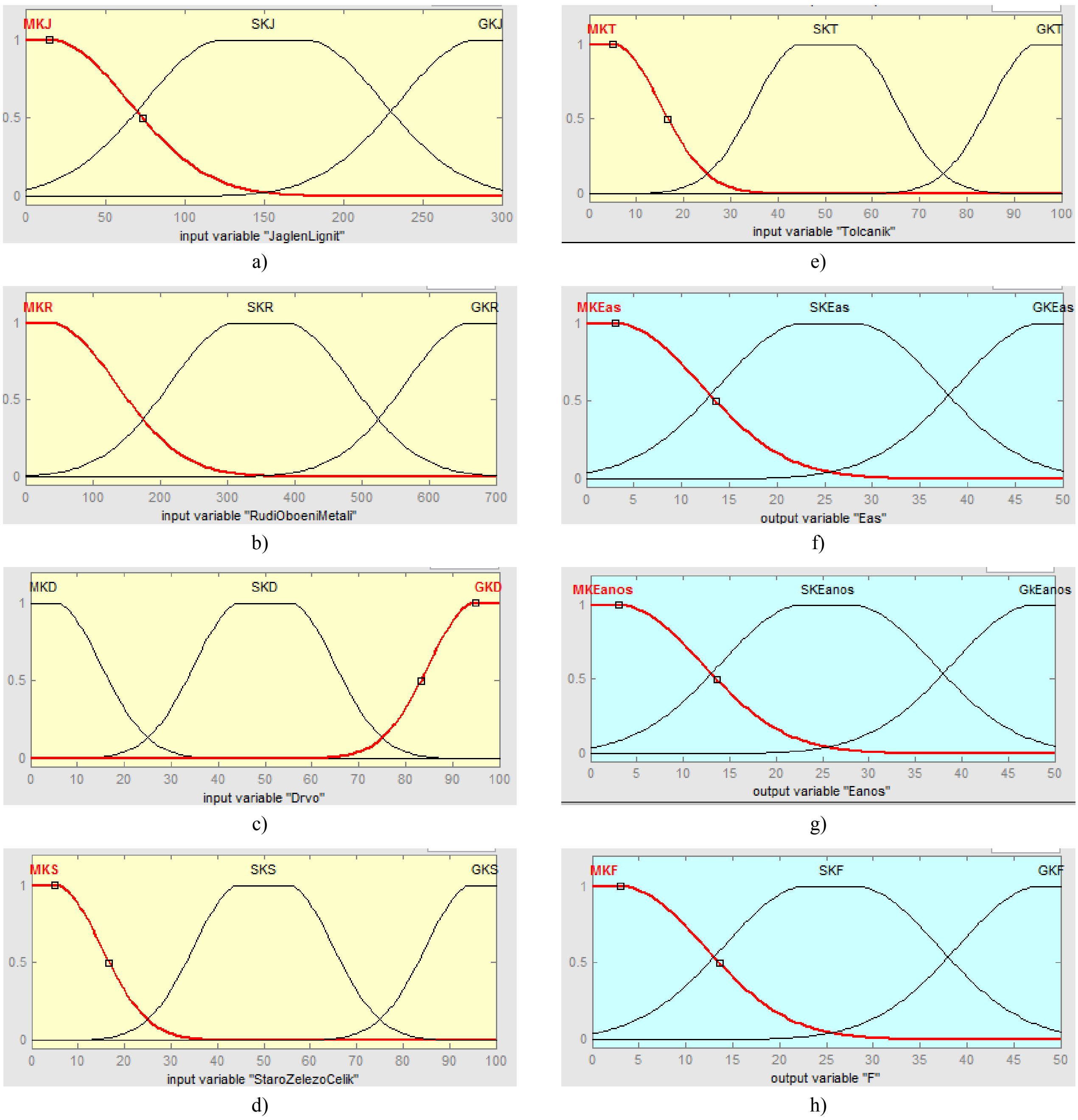
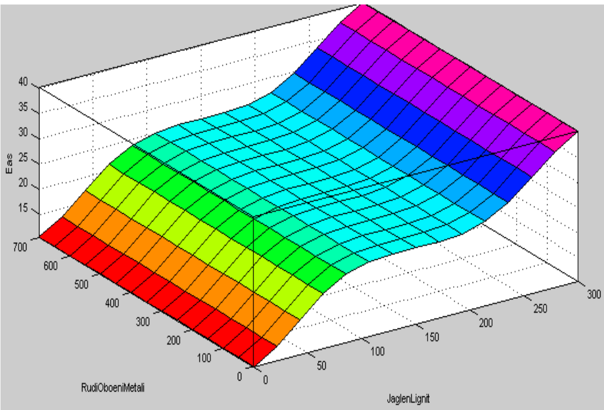
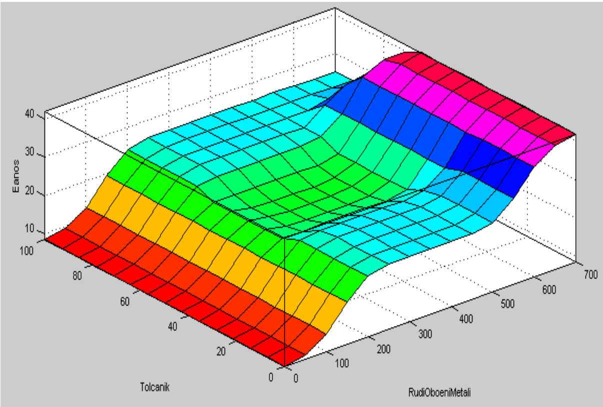


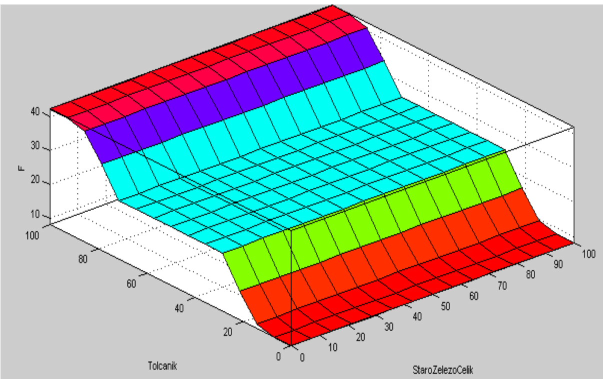
Fig. 2. Membership functions of fuzzy sets:
a) Coal / lignite; **b)** Ores of ferrous metals; **c)** Wood; **d)** Scrap metal; **e)** Ballast; **f)** Eas; **g)** Eanos; **h)** F



a)



b)



c)

Fig. 3. Graphic display of output variables for transport capacities as an open group of wagons depending on: **a)** Ores of colored metals and coal for Eas; **b)** Ballast, ores and non-ferrous metals for Eanos; **c)** Ballast and scrap for F

7. ANALYSIS OF MODEL TESTING RESULTS

The FL model for open group of wagons has been tested on 10 samples (10 monthly data) from the statistical report of MRTJSC as known input values. Big difference between the results of operating decisions and results obtained with FL model can be noticed.

The analysis of the validity of the model FL results for group of open wagons is runed on the basis of the average relative error of the results in comparison with the actual results from the real system. Based on the testing of 10 samples of data from statistics of MRJSC obtained average relative error for Eas wagons is 39.5%, for Eanos wagons is 27.8%, while the F wagons 5.8%. Based on this analysis we can conclude that the expert system for dimensioning of capacity using fuzzy logic shows significant statistical error that can not be rejected.

8. SENSITIVITY ANALYSIS OF MODELS FL

One of the basic requirements in the modeling process is achieving satisfactory sensitivity of the model. This means that during small changes in input variables, the output of the model must also have a small change of values. It is common procedure for verification of the models.

Sensitivity analysis of the expert system using fuzzy pattern FL is conducted by changing the shapes of membership functions of input and output variables (Table 1). Instead Gaussian curve which is applied to the base model, now triangular, trapezoidal and bell curve were tested. The analysis method used "prod" (product of array elements) operator and method "probor" (probably) for the operator "or". The sensitivity analysis model at this point is shown for two series and subseries of the group of open wagons.

Table 1

Sensitivity analysis of the fuzzy model FL for group of open wagons (17)

	FL		
	Membership function		
	Triangular	Trapezoidal	Bell
	19	16	13
	14	9	9
Eas	22	20	19
	22	19	19
	21	12	20
	12	8	10
	9	8	9
Eanos	9	8	9
	9	8	9
	10	8	9
	9	8	8
	9	8	8
Fad	9	8	8
	9	8	8
	9	8	8

9. CONCLUSION

The FL model for all groups of wagons was tested comparing to the statistical reports of MRTJSC, for which a significant difference between the results of operating decisions and results obtained with FL model was noticed.

Analysis of the results in the process of verification and validation of the model FL for all groups of wagons regarding the higher relative error of the results obtained from the results of the real system derived from the data of MRTJSC often shows a significant statistical error that cannot be rejected. However, also noteworthy is that the application of this model gives satisfactory results when it comes to modeling and design of facilities where there is no historical data or has a very small base. In this case, the application of fuzzy logic provides very satisfactory results.

The analysis of the sensitivity of the defined expert system of the fuzzy model (FL), was carried out by changing the shapes of the membership functions of input and output variables. The obtained results were with the same or similar values with negligible differences and show that expert model was shaped as it was expected.

The FL model showed it is more appropriate for the planning of transport facilities for new types of transport, where there are no historical data based on which the model can be based.

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19.5 M ANTENNA MAST COLLAPSE ANALYSIS

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A b s t r a c t: In long-term usage of the steel antenna, masts corrosive processes occur that are especially manifested at the welded joins and joins with bolts. Combined with the irregular renewal of the anticorrosive protection these processes may become a dominant cause for disaster, especially at the sections where critical tensions stresses occur. These constructions are exposed to wind forces that are by their nature variable in intensity and frequency. In this paper is given an analysis of the causes for disaster of an antenna mast.

Key words: antenna mast; corrosion; welded joints; tension stress

АНАЛИЗА НА ПРИЧИНИТЕ ЗА ПАЃАЊЕ НА АНТЕНСКИ СТОЛБ СО ВИСИНА ОД 19,5 МЕТРИ

А п с т р а к т: При долгогодишна експлоатација на челични антенски столбови настануваат корозивни процеси кои посебно се изразени кај заварените врски и врските со завртки. Во комбинација со нередовното обновување на антикорозивната заштита, овие процеси можат да станат доминантна причина за хаварија посебно во пресеците каде што се јавуваат критичните напони. Овие конструкции се изложени на оптоварувања од ветер кои по природа варираат по интензитет и зачестеност. Во овој труд е дадена анализа на причините за хаварија на еден антенски столб.

Клучни зборови: *а*нтенски столб; корозија; заварени споеви; напонска состојба

1. INTRODUCTION

Antenna masts and towers are often manufactured in the form of steel constructions in various shapes. One of the most common form of antenna mast is tubular. Tubes with different or same diameters are joined together via welding and combination of joint flanges with bolts in the form of segments. At certain heights of the mast, antennae are mounted for receiving and transmitting of signals. Antenna masts are found at various locations and terrains on altitudes often higher than 800 meters. At such locations dominant are significant loads by wind. Occasionally, because of longer period of usage, irregular maintenance of anticorrosive protection, defects happen that are combination of the corrosion of the welded joints and material fatigue. These defects in some cases can cause minor or severe disaster of the supporting structure of the mast.

2. TECHNICAL DESCRIPTION OF THE MAST

In this paper was done an analysis of the causes of a disaster of antenna mast, manufactured with construction tubes using welding and bolts. The outline of the antenna mast is on Figure 1.

Fig. 1. Outline of the antenna mast before the disaster

The total height of the mast is 19.5 m. The mast is composed of four segments with diameters: Ø273, Ø168, Ø168, Ø88.9 mm, and heights of 4.5, 6.0, 6.0 and 3.0 meters respectively. The mast is additionally fastened with three guys. The point of fastening of the guys is at height of 12.5 meters.

On Figure 2 is shown the joint between the first and the second segment of the mast. The first segment of the mast is a tube with diameter of Ø273 mm and wall thickness of 5.0 mm. The second segment is a tube with diameter of Ø168.3 mm and thickness of the wall of 4.0 mm. The first and second segments of the mast are connected with flanges having diameter of Ø403 mm and wall thickness of 10 mm. The joint between the first and second segment is of dismantling type using 6 M16 bolts (Figure 2).

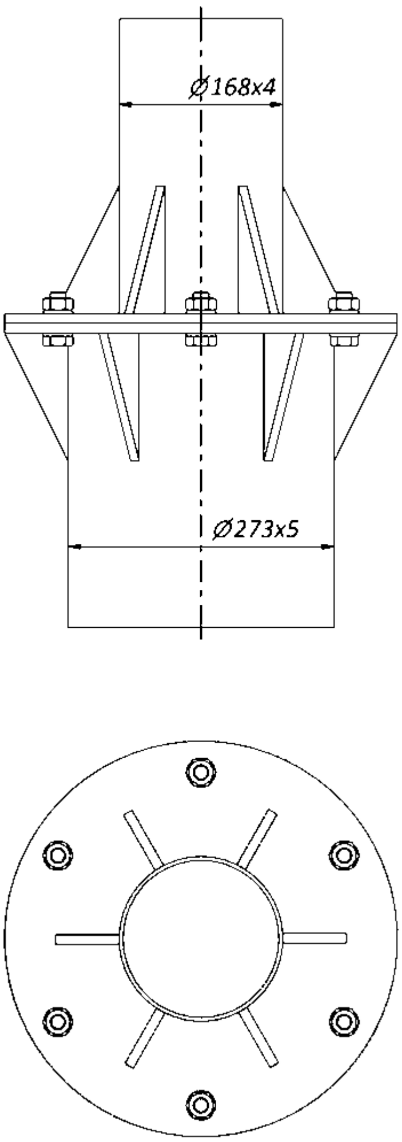

Fig. 2. The joint between the first and second segment

3. ANALYSIS OF THE LOADS

The loads on the mast are from the mounted antennae at different heights. For this mast a project was prepared for the real condition where structural analysis at various cases of loads was given [1]. In the structural analysis is shown that the dominant loads occur by the forces of wind over the antennas and the mast. In the analyzed combinations of loads at different sections stresses occur that are exceeding the permitted.

Fig. 3. Photo of the fallen mast segments

Figure 3 shows the state of the mast after the fall of the second, third and the fourth segment. The calculated bending moment at the cross-section where the break occurred in the worst case of load is $M = 6.5$ kNm [1].

Also, the wind loads have to be taken into consideration, that are with variable magnitude and dynamic knock effect. These conditions can easily lead to local tension overloads in the critical sections of the mast [3] and [4].

4. ANALYSIS OF THE CRITICAL SECTION

The critical section of the mast where the breaking happened, the welded joint was long time exposed to corrosion (Figure 4). The mast is in use since 1987, which is a time frame of 30 years.

The processes of corrosion in this case are the dominant causes of weakening of the cross section of the welded joint. On Figure 4 torn welded connections can be seen. That could not withstand the loads acting on the mast in the moment of the disaster. Likewise, at the breaking section evident are insufficient weld connections.

Fig. 4. The critical section at the welded joint

The transition of the mast between the segment number 1 to segment number 2 is made with big difference between the sections of the steel tubes (Figure 2). Namely, the first segment has diameter of Ø273 mm and wall thickness of 5.0 mm, while the second segment is a tube with diameter of Ø168.3 mm and wall thickness of 4.0 mm.

Usualy, the maintenance of these objects is irregular and often is avoided because of the difficult access to the location of the antenna mast. Anticorrosive protection is done relatively rare. Often practice is that the anticorrosive protection is only done with a simple application of the protecttion paint without thorough cleaning. Thus, the checks of the weld connections and bolt joints are missed.

To support these comments in the following text are given few examples of corrosion at other antenna masts (Figures 5 to 7).

On Figure 5 evident is mature phase of corrosion due to many years of not maintaining the anticorrosive protection. Corrosion in this case is especially dangerous at the welded joints.

Fig. 5. Corrosion of the connecting flange

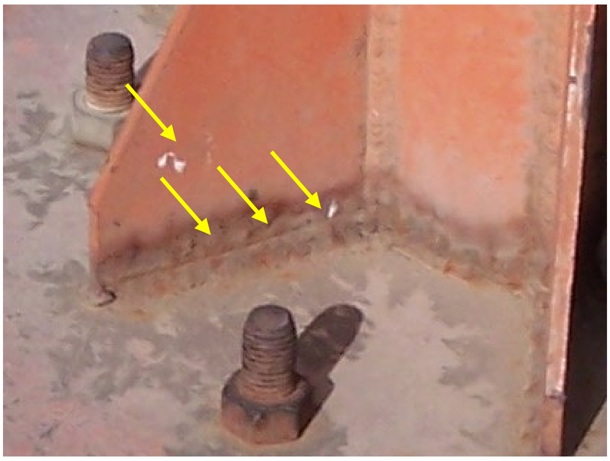

Fig. 6. Tensile stress crack caused by corrosion

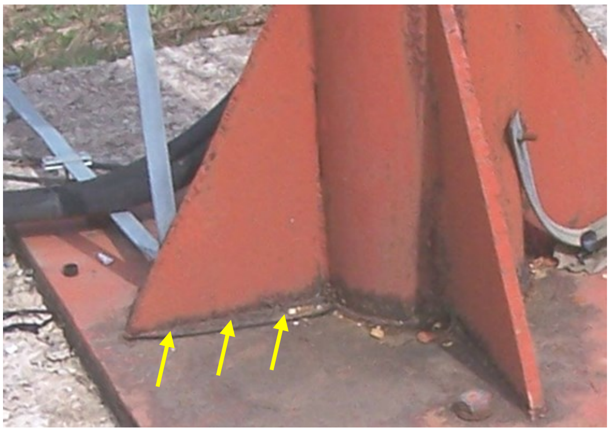

Fig. 7. Tensile crack caused by corrosion

This condition in combination with the tension state shown on Figure 8 clearly points that development of the cracks in the welded joints started at the locations with the highest concentration of tensions stresses.

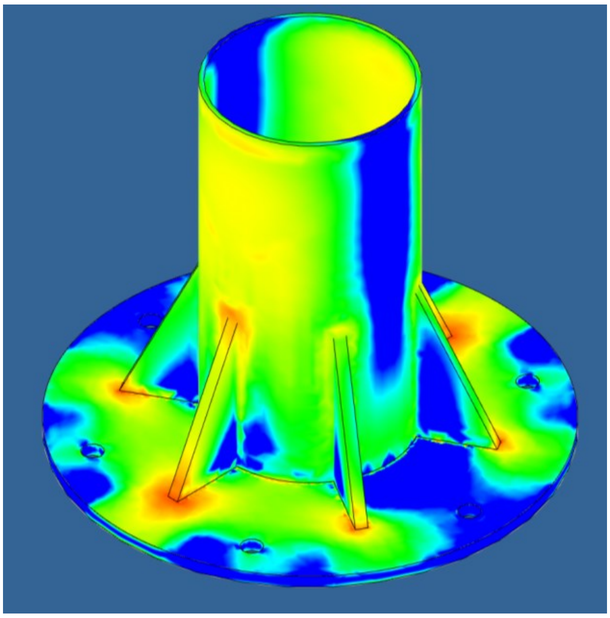

Fig. 8. Computer simulation of the tension stress state at the critical section of the mast

With these types of welded joints, it is clear to expect the development of welded fatigue cracks to occur in the zones of higher local concentration of tensions stresses [2] to [6].

5. CONCLUSIONS

Over the many years of usage of the steel structures for antenna masts, occasionally happen disasters of minor or severe type. In this case the analysis of the causes of the disaster of one antenna mast shows a mutual effect of more factors that in a given time period superposed and lead to the breaking of the mast in the critical section. One of the basic causes in this case is the corrosion effect in the welded connections of the joint between the steel tube, reinforcing ribs and the connection flange. The effect of corrosive weakening at the sections with the greatest concentration of tensions stresses lead to the critical decreasing of the loadable area of the section between the first and second segment of the mast.

As a basic conclusion from the above mentioned analysis the following can be summed up:

– The antenna masts are specific objects that often act in complex environments.

– Renewal and maintenance of the anticorrosive protection is often neglected or procrastinate to longer time intervals.

– The negative effects of the corrosion at the welded joints can cause disasters of the masts.

– In mountainous and rural environments the damage is often manifested in the material damage of the antenna systems and the antenna mast as a whole.

– In the urban environments these disasters, besides property damage can cause human losses.

To avoid these events, regular checks and maintenance of the antenna masts are mandatory by qualified teams.

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DYNAMIC ANALYSIS OF CANTILEVER BEAM WITH BONDED PIEZOELECTRIC TRANSDUCERS BY FINITE ELEMENTS METHOD

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A b s t r a c t: Finite element modeling of a cantilever beam is presented and numerical analysis is conducted for effect of adding collocated piezoelectric transducers to dynamic characteristic natural frequency. The beam is modeled using the Euler-Bernoulli beam formulation. Two nodes beam element with two degrees of freedom at each node is considered to solve the governing equation. Hybrid beam element is used to model the section where the pair of piezoelectric transducers are bonded, one as sensor and other as actuator, and the rest of the structure is modeled by the regular beam elements.

Key words: finite elements method; Euler-Bernoulli beam model; piezoelectric transducers

ДИНАМИЧКА АНАЛИЗА НА КОНЗОЛЕН НОСАЧ СО ДОДАДЕНИ ПИЕЗОЕЛЕКТРИЧНИ ПРЕТВОРУВАЧИ СО ПОМОШ НА МЕТОДОТ НА КОНЕЧНИ ЕЛЕМЕНТИ

А п с т р а к т: Претставено е моделирање на конзолен носач со помош на методот на конечни елементи и е спроведена нумеричка анализа за утврдување на влијанието на додадени пиезоелектрични претворувачи на динамичката карактеристика на основната фреквенција. Гредата е моделирана со помош на теоријата на Ојлер-Бернули. За решавање на равенката на движење е земен предвид греден елемент со два јазла со два степена на слобода. Хибридниот греден елемент се користи за моделирање на делот каде се залепени пиезоелектрични претворувачи, едниот како сензор, другиот како актуатор, додека преостанатиот дел од структурата е моделиран од основниот греден елемент.

Клучни зборови: метод на конечни елементи; Ојлер-Бернулиев модел на греда; пиезоелектрични претворувачи

1. INTRODUCTION

The process of transfer of energy between the mechanical and electric domain and vice versa as the phenomenon of piezoelectricity is useful to be involved in a complex “smart structure” for control dynamic responses or for structural health monitoring. Piezoelectric material can be used both for sensor and actuator, as it is a generalized transformer between mechanical and electrical state. When the forces are applied on the structures it produces voltage and this voltage goes to active devices and controls the vibration. Also, advances in sensor and IT technologies enable structural health monitoring to assess damage using near real-time dynamic responses measured from structures. Electromechanical interaction between a piezoelectric transducer and a host structure is motivation for many conducted researches in purposes for damage detection as crack and delimination in metallic and composite structural elements.

A comprehensive survey and discussion about advances and trends in the formulations and applications of the finite elements modeling of adaptive structural elements can be found in [1]. A piezoelectric effect in thin ceramic layers using finite elements method and a model of piezoelectric bimorph beam are presented in [2]. The beam is composed of two actuators loaded by opposite electric potentials which cause the beam to bend. Further, the influence of approximation of electric potential through the thickness has been tested on a simple piezoelectric cantilever beam loaded by external tip force. The Euler-Bernoulli beam theory and linear piezoelectricity are used to model the electro-mechanical behavior of the piezoelectric wafer in [3] and presented spectral elements method is one of alternatives to finite elements method used for computing the coupled dynamic responses since the inertia effect of the structure can be represented properly without dense mesh refinement. In [4] two nodes beam element with two degrees of freedom per node is considered for solving the governing equation. The effects of material damping (proportional damping) on output voltage are presented and the results are compared with that of prismatic beam. The numerical analysis observed that nonprismatic beam produces more voltage for a given length of piezoelectric patch compared to prismatic beam due to uniform distribution of strain.

This paper attempts to present finite element modeling of a cantilever beam and numerical analysis is conducted for the effect of adding collocated piezoelectric transducers to dynamic characteristic natural frequency. The beam is modeled using the Euler-Bernoulli beam formulation. Two nodes beam element with two degrees of freedom at each node is considered to solve the governing equations, also hybrid beam element is introduced to model the section where the pair of piezoelectric transducers are bonded on cantilever beam.

2. EQUATION OF MOTION

The Euler-Bernoulli equation for beam bending is:

$$\frac{\partial^4 v(x,t)}{\partial x^4} + \rho A \frac{\partial^2 v(x,t)}{\partial t^2} = f(x,t), \qquad (1)$$

where $v(x,t)$ is transversal displacement at location x at time t, ρ is mass density per volume, A is area cross section, $f(x,t)$ is externally applied loading.

Boundary conditions are:

$$\frac{\partial^2 v}{dx^2} \partial \left(\frac{\partial v}{\partial x} \right) \Big|_0^1 = 0 \qquad (2)$$

$$\frac{\partial^3 v}{dx^3} \partial \left(\frac{\partial v}{1} \right) \Big|_0^1 = 0 . \qquad (3)$$

Because there are four nodal variables for the two beams element, is assumed a cubic polynomial function for $v(x)$ to be:

$$v = c_0 + c_1 x + c_2 x^2 + c_3 x^3 . \qquad (4)$$

For boundary conditions $x = 0$ and $x = l$, follows:

$$\begin{aligned} & v(0) = c_0 = v_1 \\ & \theta(0) = \frac{\partial v}{\partial x} = c_1 = \theta_1 \\ & v(l) = c_0 + c_1 l + c_2 l^2 + c_3 l^3 = v_2 \\ & \theta(l) = \frac{\partial v}{\partial x} = c_1 + 2c_2 l + 3c_3 l^2 = \theta_2 \end{aligned} \qquad (5)$$

The displacement function along the beam element is:

$$\begin{aligned} v(x) = & H_1(x) v_1 + H_2(x) \frac{\partial v_1}{\partial x} + \\ & + H_3(x) v_2 + H_4(x) \frac{\partial v_2}{\partial x}, \end{aligned} \qquad (6)$$

where Hermitian shape functions $H_i(x)$ are:

$$\begin{aligned} & H_1(x) = 1 - \frac{3x^2}{l^2} + \frac{2x^3}{l^3} \\ & H_2(x) = x - \frac{2x^2}{l} + \frac{x^3}{l^2} \\ & H_3(x) = \frac{3x^2}{l^2} - \frac{2x^3}{l^3} \\ & H_4(x) = -\frac{x^2}{l} + \frac{x^3}{l^2} \end{aligned} \qquad (7)$$

The equation (6) gives the displacement function that satisfies the fourth order partial differential equation (1), and has constants c_i satisfying the boundary conditions of the equation (5).

2.1. *Finite beam element*

A beam element with a constant cross section has potential energy [5]:

$$E_p = \frac{1}{2} E_e I_e \int_{l_e} \left(\frac{\partial^2 v}{\partial x^2} \right)^2 dx = \frac{1}{2} E_e I_e \int_{l_e} \left[v''(x,t) \right]^T \left[v''(x,t) \right] dx \tag{8}$$

and kinetic energy:

$$E_k = \frac{1}{2} \rho_e A_e \int_{l_e} \left(\frac{\partial^2 v}{\partial t^2} \right)^2 dt = \frac{1}{2} \rho_e A_e \int_{l_e} \left[\dot{v}(x,t) \right]^T \left[\dot{v}(x,t) \right] dt, \tag{9}$$

where E_e is modulus of elasticity, I_e ismoment of inertia, ρ_e is material density, A_e is cross sectional area and l_e is length for the finite beam element (Figure 1).

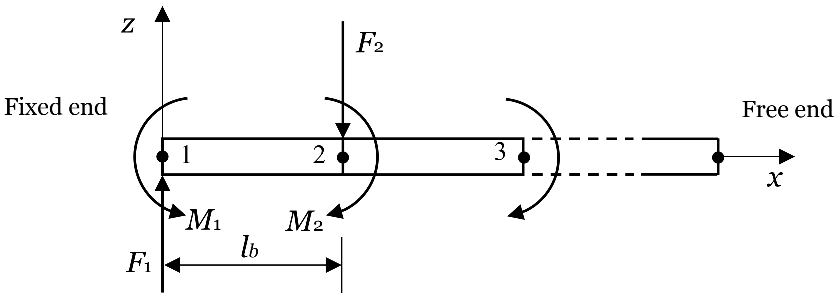

Fig. 1. Finite beam element of cantilever beam

The equation of motion for this two nodes element is obtained by using the equations (8) and (9) in Lagrange's equation:

$$\frac{d}{dt} \left(\frac{\partial E_k}{\partial \dot{q}_i} \right) + \left(\frac{\partial E_p}{\partial q_i} \right) = Z_i, \tag{10}$$

and the equation of motion represented in terms of finite elements is:

$$M^e \ddot{q}_i + K^e q_i = f(t), \tag{11}$$

where $q = [v_i \ \theta_i \ v_j \ \theta_j]^T$ is displacement and rotation vector of the endpoint nodes which represents the degree of freedom of the nodes i, j of the element, Z_i is the vector of forces and moments, $M^e_{(4\times4)}$ is element mass matrix, $K^e_{(4\times4)}$ is element stiffness matrix and $f_{(4\times1)}$ is the force vector.

Element mass matrix is determined by:

$$M^e_{i,j} = \rho_e A_e \int_{l_e} H_i(x) H_j(x) dx, \quad i,j = 1,\ldots 4 \tag{12}$$

and element stiffness matrix is:

$$K^e_{i,j} = E_e I_e \int_{l_e} \frac{\partial^2 H_i(x)}{\partial x^2} \cdot \frac{\partial^2 H_j(x)}{\partial x^2} dx, \quad i,j = 1,\ldots 4 \tag{13}$$

Then, for forces F_1, F_2 and bending moments M_1, M_2 which all acting at nodes 1 and 2 of the beam element for equation (11) follows:

$$\frac{\rho_e A_e l_e}{420} \begin{bmatrix} 156 & 22l_e & 54 & -13l_e \\ 22l_e & 4l_r^2 & 13l_e & -3l_e^2 \\ 54 & 13l_e & 156 & -22l_e \\ -13l_e & -3l_e^2 & -22l_e & 4l_e^2 \end{bmatrix} \cdot \begin{bmatrix} \ddot{v}_1 \\ \ddot{\theta}_1 \\ \ddot{v}_2 \\ \ddot{\theta}_2 \end{bmatrix} +$$

$$+ \frac{E_e I_e}{l_e^3} \begin{bmatrix} 12 & 6l_e & -12 & 6l_e \\ 6l_e & 4l_e^2 & -6l_e & 2l_e^2 \\ -12 & -6l_e & 12 & -6l_e \\ 6l_w & 2l_e^2 & -6l_e & 4l_e^2 \end{bmatrix} \cdot \begin{bmatrix} v_1 \\ \theta_1 \\ v_2 \\ \theta_2 \end{bmatrix} = \begin{bmatrix} F_1 \\ M_1 \\ F_2 \\ M_2 \end{bmatrix} \tag{14}$$

2.2. *Hybrid beam element*

A hybrid beam element is consist of two piezoelectric beam elements and a beam element, what mean one beam element is located between two collocated piezoelectric transducers, one as a sensor against other as an actuator (Figure 2).

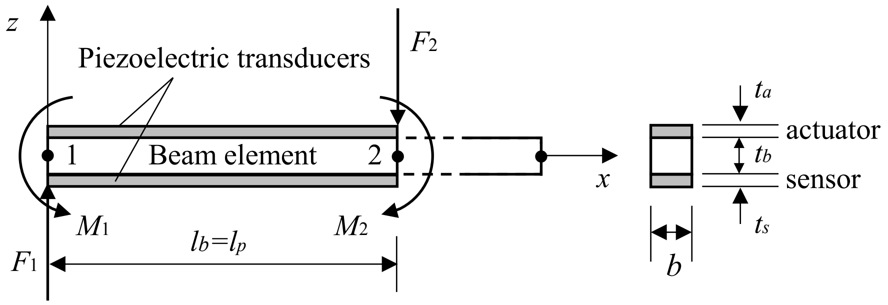

Fig. 2. Hybrid beam element

The piezoelectric beam element can be used as an actuator and as a sensor on cantilever beam, and has two degrees of freedom in terms of transversal displacement and angle of rotation, i.e. slope. The equation of motion for piezoelectric beam element can be obtained as:

$$M^p \ddot{q}_1 + K^p \dot{q}_i = f^p(t)\,. \tag{15}$$

where $M^p_{(4\times4)}$ is mass matrix, $K^p_{(4\times4)}$ is stiffness matrix of the piezoelectric element and $f^p_{(4\times1)}$ is force vector.

The mass matrix of the piezoelectric element is determined by:

$$M^p_{i,j} = \rho_p A_p \int_{l_p} H_i(x) H_j(x) dx, \quad i,j = 1,\cdots 4 \tag{16}$$

and stiffness matrix can be obtained as:

$$K^p_{i,j} = E_p I_p \int_{l_p} \frac{\partial^2 H_i(x)}{\partial x^2} \cdot \frac{\partial^2 H_j(x)}{\partial x^2} dx, \quad i,j = 1,\cdots 4 \tag{17}$$

Mass and stiffness matrices of the piezoelectric element are obtained in case when piezoelectric actuator has same dimensions as piezoelectric sensor, and they are collocated to each other as a pair on both sides of the cantilever beam. Hence, for mass and stiffness matrix of the piezolectric element follows:

$$M^p_{i,j} = \frac{\rho_p A_p l_p}{420} \begin{bmatrix} 156 & 22l_p & 54 & -13l_p \\ 22l_p & 4l_p^2 & 13l_p & -3l_p^2 \\ 54 & 13l_p & 156 & -22l_p \\ -13l_p & -3l_p^2 & -22l_p & 4l_p^2 \end{bmatrix}$$

$$K^p_{i,j} = \frac{E_p I_p}{l_p^3} \begin{bmatrix} 12 & 6l_p & -12 & 6l_p \\ 6l_p & 4l_p^2 & -6l_p & 2l_p^2 \\ -12 & -6l_p & 12 & -6l_p \\ 6l_p & 2l_p^2 & -6l_p & 4l_p^2 \end{bmatrix} \tag{18}$$

Once beam finite element and piezoelectric element have been defined, then for hybrid beam element which is consist of two collocated piezoelectric elements and between them one beam element, mass matrix M^h and stiffness matrix K^h are [5]:

$$M^h = (b\rho_e t_e + 2b\rho_p t_p) \int_{l_e=l_p} H^T(x) H(x) dx \tag{19}$$

$$K^h = E_e I_e + 2E_p I_p \int_{l_e=l_p} \frac{\partial^2 H^T(x)}{\partial x^2} \cdot \frac{\partial^2 H(x)}{\partial x^2} dx \tag{20}$$

3. FINITE ELEMENT MODEL OF CANTILEVER BEAM

Mass matrix M^e and stiffness matrix K^e for finite beam element that were previously defined and related to Euler-Bernoulli beam theory, are assembled in global matrices in order to determine the behavior and dynamic characteristics of the whole structure previously discretized to N finite elements (Figure 3).

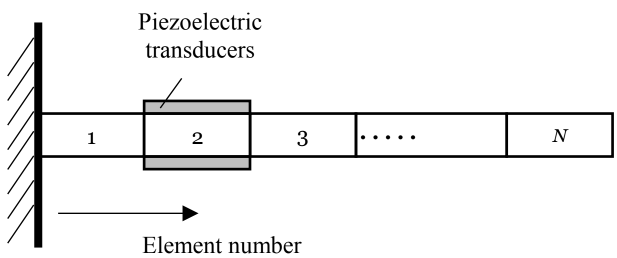

Fig. 3. Model of cantilever beam by finite element

The assembly process on global matrix for mass M^g and stiffness K^g refers to the total energy of the system, thus for cantilever beam which is divided into N elements, total kinetic energy E_k^g and total strain energy U^g are:

$$E_k^g = \sum_{i=1}^{N} E_k^{e(i)}, \quad i = 1 \cdots N \tag{21}$$

$$U^g = \sum_{i=1}^{N} E_p^{e(i)}, \quad i = 1 \cdots N \tag{22}$$

where $E_k^{e(i)}$ is kinetic and $E_p^{e(i)}$ is potential energy for i-th element, and by connectivity of elements in the structure, the total kinetic energy of the structure, i.e. cantilever beam can be expressed as

$$E_k^g = \frac{1}{2}\dot{q}_g^T M^g \dot{q}_g, \tag{23}$$

where q_g is global vector related to all the degrees of freedom of the structure. Similarly, the total strain energy is given by

$$U^g = \frac{1}{2}\dot{q}_g^T K^g \dot{q}_g. \tag{24}$$

The assembly process is based on compatibility with respect to the displacement between two adjacent elements e_1 and e_2 for common node point. Thus, for adjacent elements e_1 and e_2:

$$v_2^{(e_1)} = v_1^{(e_2)} \quad \text{and} \quad \frac{\partial v_2^{(e_1)}}{\partial x} = \frac{\partial v_1^{(e_2)}}{\partial x}.$$

This relation of compatibility also applies to force and moment, hence for whole structure global vector q_g can be obtained for all degrees of freedom. For cantilever beam discretized on N finite elements, the dimension of mass and stiffness matrices is $2(N+1) \times 2(N+1)$, while the dimension for the load vector is $2(N+1) \times 1)$ [6].

Substituting (23) и (24) in Lagrange's equation:

$$\frac{d}{dt}\left(\frac{\partial E_k^g}{\partial \dot{q}_g}\right) + \left(\frac{\partial U^g}{\partial q_g}\right) = Z_g \tag{25}$$

and the equation of motion for whole structure represented in terms of finite elements is obtained as:

$$M^g \ddot{q}_g + K^g q_g = Z_g(t). \tag{26}$$

Presented process of discretization for the cantilever beam as continuous thin structure leads to the infinite number of degrees of freedom to be actually reduced and a model with a finite number of elements with two degrees of freedom nodes to be obtained. Thus, this procedure represents deliberately imposition of non-natural constraints for the structure and indicates the fact that the discretized model of the structure is stiffer than the exact one, which consequently means a higher natural frequency, lower deflections and transversal vibrations. By increasing the number of beam elements the constraints are reduced and the solution obtained by the finite elements method begins to converge to the exact solution.

4. NUMERICAL RESULTS

The finite elements beam model is based of laboratory set-up experiment for cantilever aluminium beam with following dimensional properties: thickness $t_b = 0.002$ m, height $b = 0.035$ m, length from fixed end $l_b = 0.88$ m, and material properties: Young's modulus $E = 69 \times 10^9$ N/m^2, density $\rho = 2700$ kg/m^3, Poisson ratio $\mu = 0.35$. Piezoelectric transducers are with following dimensional properties: thickness $t_a = t_s = 0.0005$ m, height $b = 0.035$ m, length $l_p = 0.061$ m, and material properties: Young's modulus $E_p = 23.3 \times 10^9$ N/m^2, density $\rho_p = 7800$ kg/m^3.

In Table 1, the first four natural frequencies of the discretized cantilever beam of 5, 15 and 50 beam elements are given according to the Euler-Bernoulli theory.

In Table 2, the first four natural frequencies of the discretized cantilever beam with one pair of piezoelectric transducers in position 1 are given (Figure 3) thus the model is composed of one hybrid element (h) and 4, 14, 49 beam elements (b) according to the Euler-Bernoulli beam theory.

In Table 3 are given percent errors for the first four natural frequencies related to the number of finite elements for case when cantilever beam is without piezoelectric transducers and when collocated piezoelectric transducers are added to position 1 (Figure 3), one as a sensor against other as an actuator.

Table 1

Natural frequencies (Hz) of cantilever beam finite elements model discretized of 5, 15 and 50 beam elements

Number of beam elements	ω_1	ω_2	ω_3	ω_4
5	2.12431	13.31929	37.40969	73.90225
15	2.12428	13.31273	37.27770	73.05991
50	2.12428	13.31264	37.27580	73.04578

Table 2

Natural frequencies (Hz) of cantilever beam finite elements model discretized of 1 hybrid element (h) in position 1 and 4, 14, 49 beam elements (b)

Number of elements	ω_1	ω_2	ω_3	ω_4
1(h) + 4(b)	2.25280	14.01376	39.16455	77.00148
1(h) +14(b)	2.25274	14.00017	38.91027	75.66573
1(h) +49(b)	2.25274	14.00007	38.90813	75.65025

Table 3

Percent errors for the first four natural frequencies without and with pair of piezoelectric transducers at position 1

Number of finite elements	ω_1	ω_2	ω_3	ω_4
5	6.04	5.21	4.69	4.19
15	6.04	5.16	4.38	3.57
50	6.04	5.16	4.38	3.56

5. CONCLUSION

The present article focused on effect of adding collocated piezoelectric transducers to dynamic characteristic natural frequency of cantilever beam through finite element modeling. The beam is modeled using the Euler-Bernoulli beam formulation. Two nodes beam elements with two degrees of freedom at each node is considered to solve the governing equation.

By increasing the number of finite elements of cantilever beam model without and with pair of piezoelectric transducers, for each of the first four natural frequencies percent error decreases, due to value of convergence of the natural frequencies to exact solution by increasing the number of finite elements.

For the first natural frequency, the number of finite elements does not affect the percent error apart from other higher natural frequencies. The number of finite elements is more significant and influences percent error for the fourth natural frequency in case when cantilever beam is without piezoelectric transducers compared to case when they are added at position 1.

The effect of adding a pair of piezoelectric transducers on cantilever beam to dynamic characteristic natural frequency is the least indicator for the first natural frequency, which follows constant value tendency of the percent error. By increasing the natural frequencies, the influence of addition pair of piezoelectric transducers to dynamic characteristic natural frequency of the cantilever beam is specified, so the percent error is not constant and decline in relation to case without piezoelectric transducers by increasing the number of finite elements.

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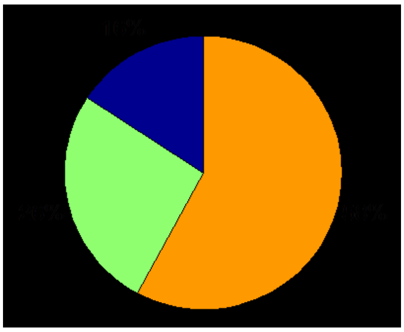

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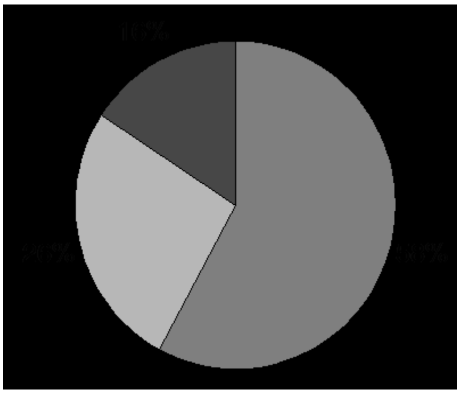

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