Increase of the Effective Production of Crankshafts for Ship Engines

Poboljšanje u proizvodnji koljenastih osovina za brodske motore

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Summary

The paper elaborates on the problem on theoretical and practical level. Results of research were used as a background during realization of this technology in company Vítkovice HEAVY MACHINERY A.S. Analysis of current manufacturing technology of the final product is described, its specification, reaching of economic benefits and realization methods. Geometrical and mathematical model of the crankshaft and adjusting algorithm of computer simulation were made to design the wireless measurement systems or crankshaft breathing, design of the steady's control system and marine drives. This method eliminates eventual failures in time of realization, respectively minimizes costs in connection with repairs and modifications of the equipment during commissioning and testing. In conclusion, testing, verification of prototype functions of the steadies control system and comparative laboratory measurement with reality are described.

KEY WORDS

crank shaft
mathematical model
geometrical model
economical benefits

Sažetak

U radu se tema proučava s teorijskog i praktičnog gledišta. Prikupljeni su rezultati istraživanja tijekom tehnološkog procesa u poduzeću Vitkovice Heavy Machinery a. s. Dana je analiza današnje tehnologije proizvodnje konačnog proizvoda, specifikacija radova, ekonomske prednosti i metode realizacije. Postavljeni su geometrijski i matematički model koljenaste osovine i algoritam računalne simulacije za dizajn bežičnog sustava mjerenja ili ventilacije prostora koljenaste osovine, dizajn pouzdanog kontrolnog sustava i brodskog pogona. Ova metoda eliminira mogućnost pogreške tijekom rada te smanjuje troškove popravaka i modifikacija opreme tijekom puštanja u rad i testiranja. U zaključku je opisano testiranje, verifikacija funkcija prototipa pouzdanog kontrolnog sustava i komparativna laboratorijska mjerenja u stvarnim situacijama.

KLJUČNE RIJEČI

koljenasta osovina
matematički model
geometrijski model
ekonomske prednosti

1. INTRODUCTION / *Uvod*

Vítkovice Machinery Group embraces science to resolve issues in order to create new techniques and innovations. For research and development purposes, company experts cooperate with universities, research institutes and professionals from other fields. It is due to this cooperation that an effective solution for the machining and alignment of crankshafts for ship engines was found. [1]

The production of crankshafts for ship engines is a demanding task in terms of the accuracy of the machining (0.01 mm), their complex shape, huge proportions and heavy weight. The most powerful engine in the world, which was built for a freight ship, has 108,920 horsepower. Its crankshaft weighs 300 tonnes.

The key issue when machining crankshafts is that of the change in the proportions between the arm shafts. The arm shafts are characterized by breathing (see Figure 1), which corresponds to the opening of the adjacent arms which connect two adjacent journals with the appropriate connecting rod journal. This operating procedure functions on the basis of the flexibility of the cranks, their weight, and the rotation axis not corresponding to the axis of the shaft axis. The procedure is carried out by rotary movement during the machining process.

The breathing figures attributed to the particular connecting rods are changeable in relation to the shaft angle. Provided the shaft is properly balanced, the rotation does not cause involuntary breathing between the adjacent arms of the shaft (the distance between the arms is constant). At present, this intended status can only be achieved through the optimal set-up of a lunette. A model of a mechanically controlled lunette is depicted in Figure 2.

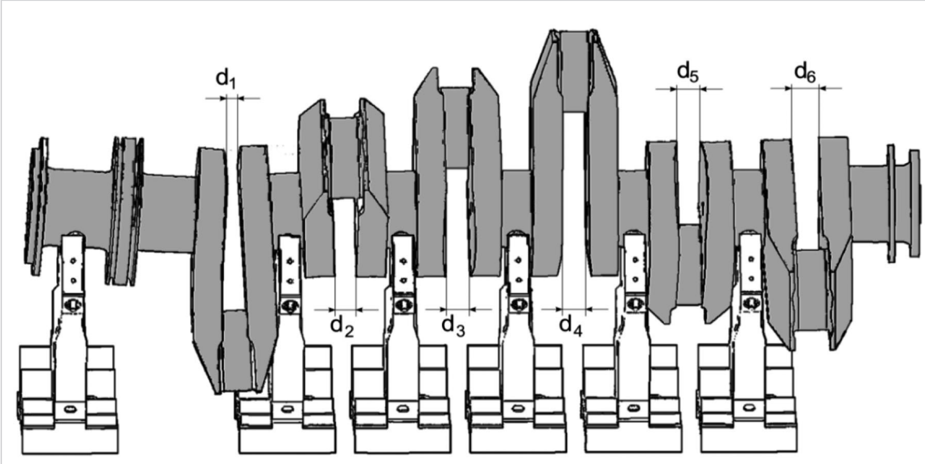

Figure 1 Crankshaft centred on a lathe with "breathing" proportions "d_i"
Slika 1. Centrirana koljenasta osovina na uporištu s proporcijama ventilacije „d_i"

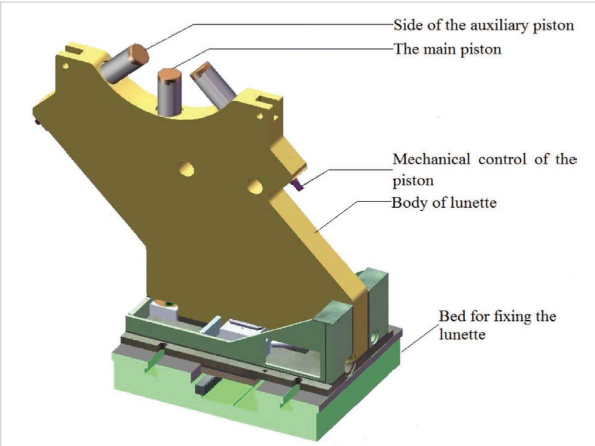

Figure 2 Model of a mechanically controlled lunette
Slika 2. Model mehanički kontrolirane linete

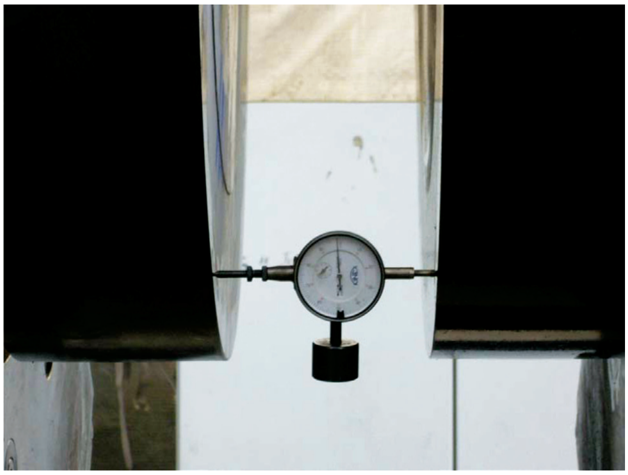

Figure 3 Placement of a micrometre for the mechanical measuring of "breathing"
Slika 3. Mehaničko mjerenje ventilacijskog prostora s pomoću mikrometra

The essential aim of the whole process is to produce a shaft that complies with strict criteria in terms of accuracy - to hundredths mm. The process of balancing therefore needs to be repeated by the manual setting of the support force of the oscillation lunettes.

The process of balancing without the electrical output on the existing manner of breathing, as measured by mechanical micrometres (fig. 3), is enormously complex. The actual time needed for such a process is proportional to the experience and skills of the service staff of the machining centre. The machining of each crankshaft journal is subject to proper balancing even during the operation.[2]

2. ANALYSIS OF THE EXAMINED PART OF THE PROCESS CHAIN / *Analiza ispitivanog dijela lančanog procesa*

An in-depth analysis of the machining process shows that there are contact places for two different links (see Figure 4). The first of the links is characterized by its space-time transformation (logistic). The second is subjected to machining so that it changes shape (technological transformation).

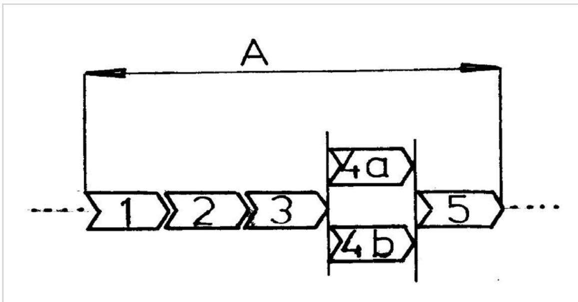

Figure 4 Model of the process chain for crankshaft machining [4]
Slika 4. Model lančanog procesa za izradu koljenaste osovine [4]

Legend: A – examined time period of production; 1 – shaft setting in the machining centre; 2 – static adjustment of the lunettes; 3, 5 – check; 4a – machining: technological operation; 4b – process of lunette control during the course of breathing.

It is possible to come across such cases in technical practice. An example of this is wrought ingots suspended from the hook of a crane, whereby the requirement for the course of forging (a technological process for changing shape) the ingot is processed (by revolving and pushing) by a crane. This involves a logistic process.

Table 1 depicts the basic elements of large-scale production: substance, energy and information. The substance

Table 1 Characteristics of the transformation processes [3, 4]

Tablica 1. Karakteristike procesa transformacije [3, 4]

Changes to processed matter	Processed matter		
	Substance (matter)	Energy	Information
Changes to structure	Chemical reaction	Energy transformation	Measured figures transformation
Change in shape	Shaping	Voltage transformation	Measured figures intensification
Change in place coordinates	Control transit	Electric energy transit	Measured figures transit
Change in time coordinates	Storing	Electric energy accumulation	Measured figures accumulation

is subject to changes in the structure, form, position within the transformation process. This course of action runs through the process of machining crankshafts. The course of action is realized in the parallel processes (see Figures 4a and 4b) of the value-creating chain.

The researchers' aim was to develop an automatic control system to enhance the effectiveness of the production of bent crankshafts for ship engines. The automatic process of balancing represents a multidisciplinary project which strives to achieve the following attainable goals:

- concept layout for a proposed solution;
- layout of a prototype alignment control system;
- development of a prototype alignment control system;
- testing and implementation of possible changes.

The effective use of automated shaft balancing during the course of machining should enable the company to employ less experienced workers i.e. by ruling out the influence of the human factor on the accuracy of production and minimizing the risks associated with inexperienced workers.

3. CONCEPT LAYOUT FOR PROPOSED SOLUTION / *Koncept predloženog rješenja*

A geometrical model of a crankshaft, as well as a mathematical model of a shaft, were developed on the basis of drawn documentation in order to verify the theory behind the active control of the oscillation lunette. The Finite Element Method (FEM) was used for stress-strain analysis purposes. Since models made on the basis of FEM carry a huge number of degrees of freedom, it was necessary to make a substantial reduction in the degrees of freedom so that the static and dynamic qualities were preserved. The central aim was therefore to generate a reduced model with $n < 100$ degrees of freedom.

In order to verify the accuracy of the model layout, it was necessary to carry out comparative gauging on a real crankshaft.

3.1. Mathematical Description of a Crankshaft / *Matematički opis koljenaste osovine*

The employed method for mathematically describing a crankshaft is based on an entirely different principle than the analytical method of flexibility. While analytical methods are based on differential and integral calculus, FEM is based on the lesser known calculus of variation i.e. seeks a minimum functional [5].

3.2. Geometric Model / *Geometrijski model*

The geometric model of a crankshaft which was developed on the basis of drawn documentation was done by using Catia V5 software. Minor details, such as small roundness, were neglected. The model was subsequently transferred into the ANSYS software package (see Figure 5), whereby the geometric model was used to generate the mathematical model. [6]

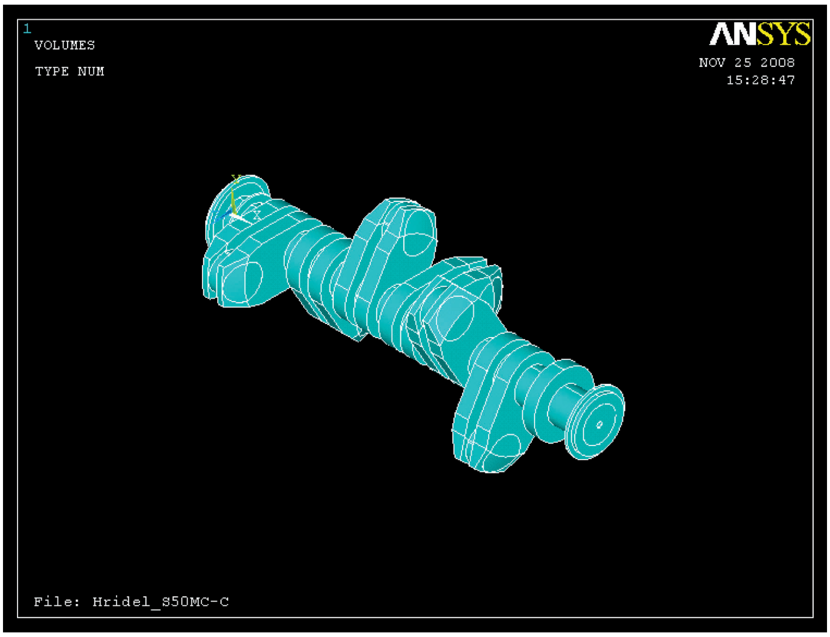

Figure 5 Geometric model of a crankshaft [6]

Slika 5. Geometrijski model koljenaste osovine [6]

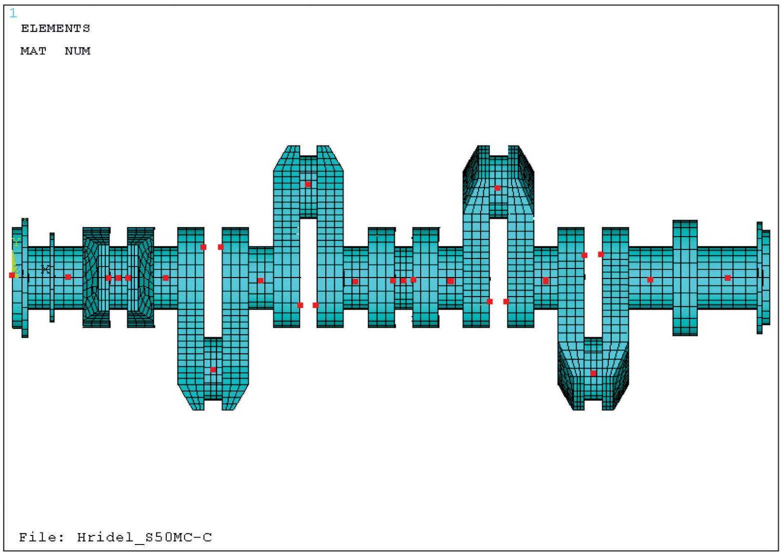

Figure 6 Reduction of the number of points
Slika 6. Redukcija broja točaka

3.3. FEM Model / *FEM model*

The mathematical model of a crankshaft was developed by means of reliable brick elements with quadratic descriptions. Quadratic elements were used to produce a more accurate result. The reason for using brick elements was the huge number of calculations that would be required according to the same model. It is therefore apt for the model to depict the original work as plausibly as possible, whilst maintaining the smallest number of degrees of freedom. As a result, the SOLID95 element from the ANSYS 11 software package database was therefore employed (see Figure 6) [7].

3.4. Fused Model of a Crankshaft / *Fuzirani model koljenaste osovine*

The proposed method for the management of the machining process, as well as the machining process itself, can be simulated and verified virtually. This requires an appropriate mathematical model. As previously mentioned, in terms of managing vibrations, the models created by means of the finite element method (FEM) have too many degrees of freedom**.** It is therefore necessary to create a model with a reduced number of degrees of freedom ($n < 100$). Given that actively managed forces will be in the support reactions too, it is therefore necessary, for the creation of a mathematical model, to consider the places that are free of active support. The only place where there is zero movement of the crankshaft is in the lathe clamping chuck (see Figure 8). In the same figure, the reduction is marked in the number of points whose generalised movements in three directions correspond to the preserved degrees of freedom. These must at least match the shooting locations of the stated variables (displacement, velocity and acceleration) and places of the generalised actively managed support forces.

In order to determine specific numbers **(**the squares of the own frequencies – we assume symmetric coefficient matrix and commutative damping matrix) and own modes (eigenvectors), a model was created in ANSYS software (see Figure. 1) which operates on the basis of FEM.

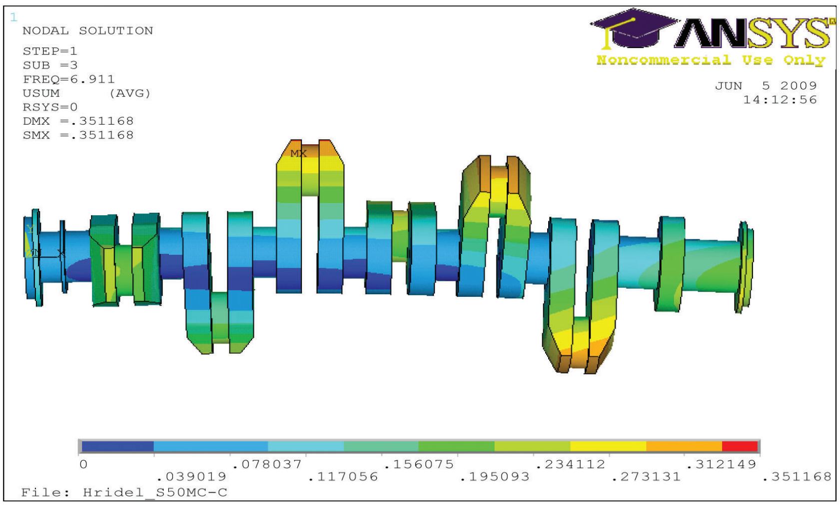

Figure 7 Color representation of the appropriate shape of the oscillation 4 [6]
Slika 7. Prikaz u boji odgovarajućeg obrisa oscilacije 4 [6]

3.5. Quasi-static Solution / *Kvazistatičko rješenje*

A quasi-static solution involves resolving the static problem of loads in different positions on a crankshaft, that is, with angular displacement. It was assumed that an equilibrium exists in the coordinate system connected to the shaft (with a zero steering angle – at the beginning of the process, both systems are identical). A methodology was therefore developed for the generation of static and dynamic models of a crankshaft with a small number of degrees of freedom which have spectral/modal characteristics identical to the original models created by means of FEM in a given frequency band and selected locations. This methodology was also used for designing algorithms and appropriate software and verified using a model of the S50 MC-C crankshaft. The verification involved comparing the data contained in a condensed stiffness matrix obtained from structural formulas and data contained in a similar stiffness matrix obtained from the inversion of a compliance matrix which resulted from repeated static calculations carried out on the original model.

3.6. Creating Algorithms for Crankshaft Alignment / *Kreiranje algoritama za centriranje koljenaste osovine*

Under the proposed method for the automatic alignment of a crankshaft during the machining process, the elastic deformation should be characterized by the broadening and narrowing of adjacent arms connecting two adjacent journals with the relevant connecting rod pin. More specifically, the distance between the opposite points of the two neighbouring arms of the connecting rod (so-called breathing) is required to remain constant during the rotation of the shaft. Breathing is generally defined as a periodic function of the shaft steering angle which is dependent on the adjustment of the lunettes which support the shaft. Breathing depends primarily on the position of the pistons of the supporting side lunettes because they determine the centre of shaft rotation in the plane of the axes of the pistons of the given side lunette. Breathing can be minimized by the suitable movement of side rollers. An alignment algorithm for calculating the optimal position of the pistons of the side lunettes was created, based on the method of least squares [9, 10].

One of the most difficult phases in the production and assembly of a crankshaft is the machining of journals. Figure 1 shows a crankshaft clamped in a lathe and supported by controlled lunettes. The basic requirement which is imposed on the machining process is compliance with manufacturing tolerances. A key indicator of the accuracy of a crankshaft is so-called breathing. Breathing is caused by deviations from the ideal required shape and the elastic deformation of the shaft during the course of one complete revolution, which corresponds to gravity and supporting forces acting on the shaft. Figure 1 shows the respective breathing processes marked by symbols $d_i, i = 1, \ldots, p$. The number of breathing processes p depends on the number of connecting rods on a specific crankshaft. There is just one breathing process per connecting rod. The breathing capacity d_i is generally dependent on the crankshaft steering angle $\varphi \in [0, 2\pi)$, whereby $d_i(\varphi)$ is a periodic function of the steering angle φ. If the crankshaft is aligned properly and perfectly produced, function $d_i(\varphi)$ is constant for all $i \in \{1, \ldots, p\}$ in the $\varphi \in [0, 2\pi)$ interval (distance remains constant). Any inaccuracies in journal cylindrical shape or the wrong alignment of the side supporting lunette rollers will result in at least one unsteady breathing process. In such cases, it is not possible to machine all the journals by fixing the settings of the lunettes. The machining of the respective journals must therefore be done alternately whilst adjusting the position of the side lunette rollers according to serial numbers. Qualified lathe operators in this process still use their "proven" iterative strategy whose ultimate objective is to make all breathing processes constant or at least almost constant [11, 12, 14].

The verification and testing of the generated algorithm for optimal crankshaft alignment was performed according to the "model in the loop" and "software in the loop" methods. A condensed bar shaft, as previously described, was used as the model for clamping a crankshaft to a lathe with support from a set of controlled lunettes. The model´s application in MATLAB software enabled the functions of breathing to be tested for any position or force acting on a shaft. The generated alignment algorithm was applied in MATLAB with the appropriate user interface. The results of the simulations prove the utility and accuracy of the proposed solution [13].

4. CONTROL SYSTEM FOR STRAIGHTENING ELASTIC DEFORMATION OF A BENT CRANKSHAFT DURING MACHINING / *Kontrolni sustav za izravnavanje elastične deformacije iskrivljene koljenaste osovine tijekom izrade*

Based on the data obtained from the mathematical model, hardware and software products were developed for the automatic balancing of a crankshaft during clamping and the machining process. This includes: a technology centre which consists of a special machine with eight actively controlled oscillating lunettes (see Figure 9); a REX CONTROL control system for the technology centre; a purpose built control system for the partial control of the oscillating lunettes; and a Sinumerik 840D control system - specifically developed for the phase of the machining process which steers the electronic performance of the lunette actuators. [15]

5. CONCLUSION / *Zaključak*

Until recently, the experience of operating personnel in machining centres was priceless. In the past, operators, when machining a crankshaft, worked instinctively because each crank shaft acted differently during the machining process. The active application of automatic crankshaft balancing technology during the machining process allows less qualified workers to be employed because the use of technology excludes the risks associated with the human factor and the lack of knowledge or experience.[16, 17]

The resulting parameters of the crankshaft´s main journals after completion of the automated machining process increased machining accuracy to 0.005 mm.

Automated crankshaft balancing during the manufacturing process represents the optimal solution for achieving qualitatively higher levels of machining process control, whilst increasing quality and productivity.[18] The impact of these achievements are listed below:

- reduced machining costs;
- shortened production times;
- improvements in geometric parameters;
- increased production capacity;
- reduced dependence on the expertise of operating personnel;
- reduced risks of poor production quality as a result of the

Figure 8 Technology centre with a system of control lunettes for straightening elastic deformation of a bent crankshaft during machining [8]
Slika 8. Tehnološki centar sa sustavom kontrolnih lineta za izravnavanje elastične deformacije iskrivljene koljenaste osovine tijekom izrade [8]

human factor;
- increased levels of safety for operating personnel.

The objective of the cooperation of VÍTKOVICE MACHINERY GROUP with universities is to achieve synergies which will lead to the streamlining of research, development and the innovation process.

The benefits for users:
- the risk associated with the human factor elimination – automation of the crankshafts balancing during production is the optimal solution how to achieve a qualitatively higher level of control the machining process while increasing quality and productivity.
- the cost saving – on the tested ZH-6S 50MCC during the second test was achieved saving of 81 hours. The saving is 162.000,- CZK.
- the economic benefits of the solution – the solution brings effects for owners of existing know-how not only the savings from the Works hours and from the elimination of risks associated with human factors, but also from the yields of the sale of know-how.

Research provides to use the gaps on the market in their chosen market segment, hen there is an increasing demand both, finished shafts and the segments of shafts for final assembly at the manufacturers mainly marine engines, particularly in the Asian region. The number of demands for crankshafts varies with the technical condition and of service life the ships. Due to the design of high-capacity ships the motors are currently building with higher performance. Due to the very good mechanical engineering technological know-how is it a stable branch.

The total capacity of market in Europe and Asia is currently estimated about 750 miles CZK.

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