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Nonlinear Resonant Jump in Rudder Positioning Electrohydraulic Systems

Original scientific paper

The rudder positioning electrohydraulic system, as many other complex systems, is a nonlinear system. In nonlinear systems, a nonlinear resonant jump can occur. The paper deals with the analysis of the rudder positioning electrohydraulic system regarding the nonlinear resonant jump caused by saturation of the electrohydraulic proportional valve. The meaning of the term "resonant jump" is explained in the introduction. Then, the basics needs for occurrence of nonlinear resonant jump phenomenon are given. The rudder positioning electrohydraulic system is also described. Two methods of analyzing system with respect to resonant jumps are described: the analytical method and the simulation method. When performing the analytical analysis based on the describing function approach, the analysis of the variations of important parameters, including saturation, is performed. Then, the confirmation of the results of analytical analysis is illustrated by the simulation method. Also, the simulation procedures, like creating an excitation signal and accelerating the simulation by using vectors in Simulink/Matlab simulation software package, are explained in detail.

Keywords: *electrohydraulics, nonlinear resonant jump, rudder positioning system*

Nelinearni rezonantni skok u elektrohidrauličkim kormilarskim sustavima

Izvorni znanstveni rad

Elektrohidraulički sustav pozicioniranja kormilarskog uređaja, kao i mnogi ostali složeni sustavi, je nelinearni sustav. U nelinearnim sustavima može se pojaviti nelinearni skok. Članak se bavi analizom elektrohidrauličkog sustava pozicioniranja kormilarskim uređajem u odnosu na rezonantni skok uzrokovan zasićenjem u elektrohidrauličkom proporcionalnom ventilu. U uvodu je objašnjeno značenje termina "rezonantni skok". Nakon toga dane su osnove fenomena nelinearnog rezonantnog skoka. Također je opisan elektrohidraulički sustav pozicioniranja kormilarskim uređajem. Opisane su dvije metode za analizu sustava u odnosu na rezonantni skok: analitička metoda i simulacijska metoda. Korištenjem analitičke metode, zasnovane na načelu opisne funkcije, izvodi se analiza varijacija značajnih parametara, uključujući zasićenje. Nakon toga, potvrda rezultata analitičke analize dana je simulacijskom metodom i posebno su objašnjeni simulacijski postupci kao kreiranje pobudnog signala i ubrzanje simulacije korištenjem vektora u simulacijskom paketu Simulink/Matlab.

Ključne riječi: *elektrohidraulika, nelinearni rezonantni skok, kormilarski sustav*

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1 Introduction

Nonlinear resonant jump is a phenomenon that occurs only in nonlinear systems. The term "resonant jump" is used in the case of a sudden jump of amplitude and/or frequency and/or phase of a periodic output signal of a nonlinear system. This is clearly not a beneficial for a system performance and the frequencies at which this phenomenon can occur should be avoided when designing the control system. Resonance jump was investigated more in the theory of oscillation of mechanical systems ([7], [11]) than in the theory of control systems ([1], [4], [6]). The resonant jump can occur in nonlinear systems and is often not desirable state in the system. The resonant jump cannot occur if excitation

is such that the response of the system is transient and cannot be defined by solving nonlinear differential equations. It is also not recommended to use experimental tests on the plant during operation in order to determine if the system can have tendency to the occurrence of this phenomenon. For that purpose the best way of analysis is to use analytical and simulation methods. However, analytical approach can be cumbersome and sometime even impossible in the case of more complex systems. The paper shows that simulation approach to resonant jump phenomenon that can occur in rudder positioning electrohydraulic systems is an efficient way of analysis.

The paper is organized as follows. In Section 2 the basics of the nonlinear jump phenomenon are explained. The short descrip-

tion of rudder position electrohydraulic system is given in Section 3. Section 4 details the analytical approach to the problem while Section 5 explains the simulation method. Finally, conclusions are given in Section 6.

2 Basics of the nonlinear resonant jump phenomenon

The resonant jump can be observed through the analysis of the frequency characteristics of a nonlinear system given in Figure 1.

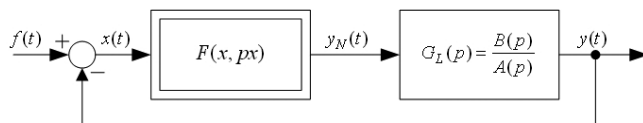


Figure 1 **Block diagram of the forced system**
Slika 1 **Blok dijagram prinudnog sustava**

The quantities from Figure 1 are:

$f(t) = F_v \sin(\omega_v t)$ - harmonic input to the system

$x(t) = X_m \sin(\omega_v t + \varphi_x)$ - input to the nonlinear part of the system

$F(x, px)$ - nonlinear part of the system

$G_L(p) = \frac{B(p)}{A(p)}$ - linear part of the system.

Input excitation signal $f(t)$ that is described in more detail in [1], [3], [5] and [9] is of the harmonic form ([1], [6]):

$$f(t) = F_v \sin(\omega_v t) \quad (1)$$

Frequency ω_v is being changed from some $\omega_{v \min}$ to $\omega_{v \max}$ and afterwards from $\omega_{v \max}$ to $\omega_{v \min}$. There are some issues of importance for the successful simulation and analysis of the nonlinear resonant jump. It is important that change of the frequency of the excitation signal may be executed only when the input signal in the nonlinear part is stabilized. In other words, the input signal in the nonlinear part must have constant values of amplitude X_m and frequency ω_v during one simulation step.

It is very important that the curve is smooth with respect to frequency of the input excitation signal.

3 Description of the system

The main parts of the analyzed rudder positioning electrohydraulic system are electro-hydraulic proportional valve and hydraulic cylinder. A position sensor is built in within the hydraulic cylinder. In the real system analyzed here the position controller was implemented using PLC (Programmable Logical Controller). Apart from the saturation inherent in hydraulic cylinder, the controller is also designed with the output saturation in order to

insure that the maximal permitted velocity of the piston of the hydraulic cylinder will not be reached, Figure 2.

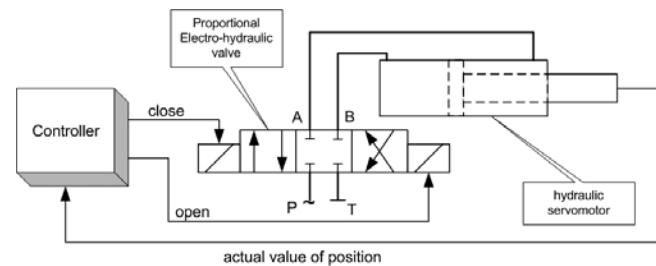


Figure 2 **Block diagram of the system**
Slika 2 **Blok dijagram sustava**

4 Analytical method

The most suitable method to determine resonant jump of a nonlinear system is the describing function method ([1], [5], [6] and [7]). The process of determining nonlinear resonant jump is based on equation (2) [1]:

$$X_m \frac{A(j\omega_v) + B(j\omega_v)[P(X_m, \omega_v) + jQ(X_m, \omega_v)]}{A(j\omega_v)} = F_v e^{-j\varphi_x} \quad (2)$$

which can be rewritten as:

$$X_m [1 + G_L(j\omega_v)G_N(X_m, \omega_v)] = F_v e^{-j\varphi_x} \quad (3)$$

where $G_L(j\omega_v) = B(j\omega_v)/A(j\omega_v)$ is the linear part of the system, $P(X_m, \omega_v)$ is the real part of the describing function of nonlinear part of the system, $Q(X_m, \omega_v)$ is imaginary part of the describing function of the nonlinear part of the system, $F_v e^{-j\varphi}$ is harmonic input to the system (excitation) and X_m represents the magnitude of the input of the nonlinear part of the system.

The area in which resonant jumps of magnitude $X_m(\omega_v)$ can occur is determined by the envelope of a family of circles drawn on the characteristics, $-1/G_N(X_m, \omega_v)$ as explained in [1].

To determine the frequency area where the occurrence of resonant jump is possible, the parametric equation (4) [1] of the envelope is determined by:

$$U(\omega_v) = - \frac{P \left(2 \frac{dP}{dX_m} + X_m \frac{d^2 P}{dX_m^2} \right) + \frac{dP}{dX_m} \left(P + X_m \frac{dP}{dX_m} \right)}{P^2 \left(2 \frac{dP}{dX_m} + X_m \frac{d^2 P}{dX_m^2} \right) + \frac{dP}{dX_m} \left(P + X_m \frac{dP}{dX_m} \right)^2} \quad (4)$$

$$V(\omega_v) = \pm \frac{-X_m \frac{dP}{dX_m} \sqrt{\frac{dP}{dX_m} \left(2 \frac{dP}{dX_m} + X_m \frac{d^2 P}{dX_m^2} \right)}}{P^2 \left(2 \frac{dP}{dX_m} + X_m \frac{d^2 P}{dX_m^2} \right) + \frac{dP}{dX_m} \left(P + X_m \frac{dP}{dX_m} \right)^2}$$

Consider our system, Figure 3:

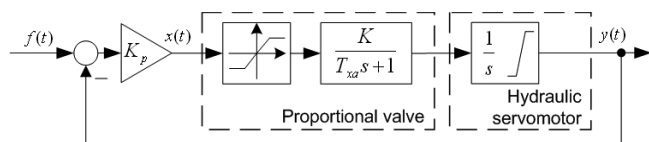


Figure 3 Block structure of the system for the analytical method
Slika 3 Blok struktura sustava za analitičku metodu

Linear part of the system is:

$$G_L(s) = \frac{K}{s(T_{xa} + 1)} \quad (5)$$

or:

$$\begin{aligned} G_L(j\omega_v) &= \frac{K}{j\omega_v(j\omega_v T_{xa} + 1)} = \\ &= -\frac{KT_{xa}}{1 + \omega_v^2 T_{xa}^2} - j \frac{K}{\omega_v(1 + \omega_v^2 T_{xa}^2)} = \\ &= U(\omega_v) + jV(\omega_v) \end{aligned} \quad (6)$$

The describing function of nonlinear part of the system is:

$$\begin{aligned} G(X_m, b) &= P(X_m, b) = \frac{2}{\pi} \left(\arcsin \frac{b}{X_m} + \frac{b}{X_m} \sqrt{1 - \frac{b^2}{X_m^2}} \right) \\ &; X_m \geq b \end{aligned} \quad (7)$$

where b is upper and lower limit saturation.

From (4) it follows:

$$\frac{dP}{dX_m} = \frac{4b}{\pi} \frac{b^2 - X_m^2}{X_m^3 \sqrt{X_m^2 - b^2}} \quad (8)$$

$$\frac{d^2 P}{dX_m^2} = \frac{4b}{\pi} \frac{2X_m^2 - 3b^2}{X_m^4 \sqrt{X_m^2 - b^2}} \quad (9)$$

From (7), (8) and (9), for $b = 0.3$ we obtain:

$$\begin{aligned} P(X_m) &= \frac{2}{\pi} \left(\arcsin \frac{0.3}{X_m} + \frac{0.3}{X_m} \sqrt{1 - \frac{0.3^2}{X_m^2}} \right); \\ &X_m \geq 0.3 \end{aligned} \quad (10)$$

$$\frac{dP}{dX_m} = \frac{1.2}{\pi} \frac{0.09 - X_m^2}{X_m^3 \sqrt{X_m^2 - 0.09}} \quad (11)$$

$$\frac{d^2 P}{dX_m^2} = \frac{1.2}{\pi} \frac{2X_m^2 - 0.27}{X_m^4 \sqrt{X_m^2 - 0.09}} \quad (12)$$

From (5) and (6) for $K = 200$ and $T_{xa} = 0.8$ we obtain:

$$G_L(s) = \frac{200}{s(0.8s + 1)} \quad (13)$$

$$\begin{aligned} U &= -\frac{160}{1 + 0.8^2 \omega_v^2}; \quad V = -\frac{200}{\omega_v(1 + 0.8^2 \omega_v^2)} \\ V^2 &= -\frac{U^3}{U + KT_{xa}}; \quad U > -160 \end{aligned} \quad (14)$$

By substituting the obtained relations into (4), the intersection points of the envelope and the linear part characteristics are determined. The area of resonant jump is defined by the frequency interval $(\omega_{v1}, \omega_{v2})$, Figure 4, Figure 5, Figure 6.

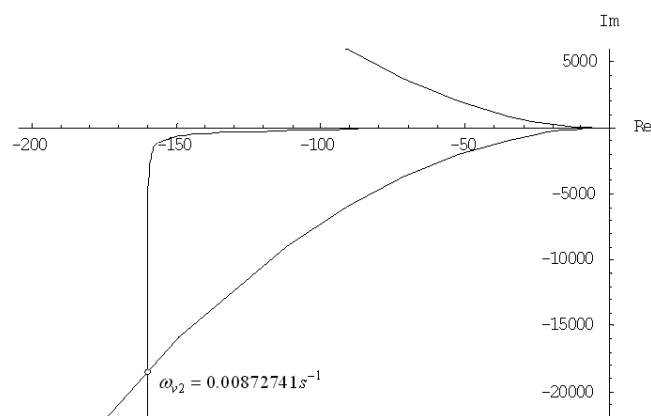
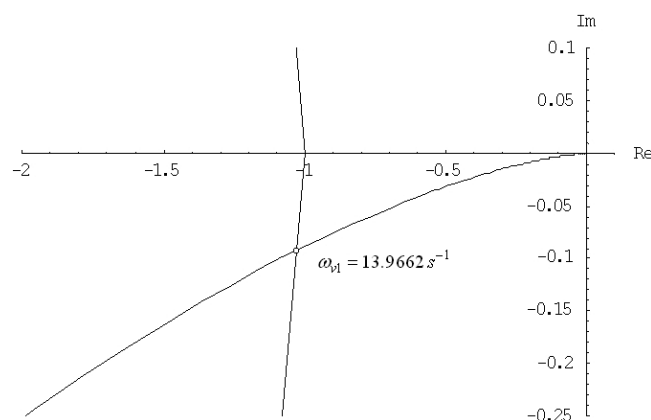


Figure 4 Frequency characteristic of the linear part of the system $G_L(j\omega_v)$ and the envelope of the nonlinear part of the system

Slika 4 Frekvencijska karakteristika linearnog dijela sustava $G_L(j\omega_v)$ i ovojnice nelinearnog dijela sustava

Figure 5 Frequency characteristic of the linear part of the system $G_L(j\omega_v)$ and the envelope of the nonlinear part of the system - Detail

Slika 5 Frekvencijska karakteristika linearnog dijela sustava $G_L(j\omega_v)$ i ovojnice nelinearnog dijela sustava - detalj



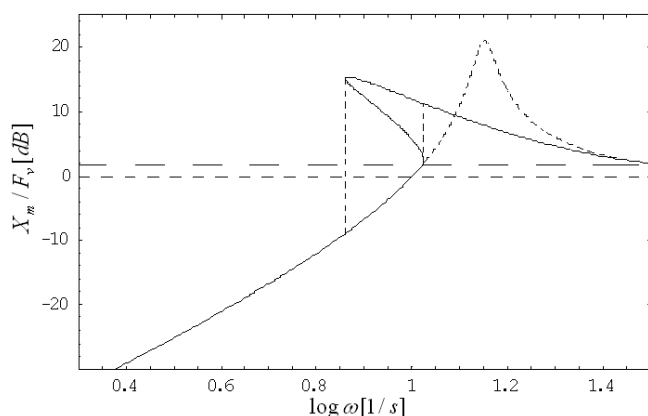


Figure 6 **Frequency characteristic $X_m(\omega_v)$ determined analytically (dashed line is linear system frequency response)**

Slika 6 **Frekvencijska karakteristika $X_m(\omega_v)$ određena analitički (isprekidana crta je frekventni odziv linearnog sustava)**

The system analyzed here is relatively simple, but the analytical approach resulted in fairly complex equations. In the case of presence of additional nonlinearities in controlled system the complexity of calculations rises to the level of unsolvability for day-to-day engineering practice. One way to address this problem is to use simulation in order to access frequency range where resonant jump could occur.

5 Simulation method

The block diagram used for the simulation analysis is given in Figure 7.

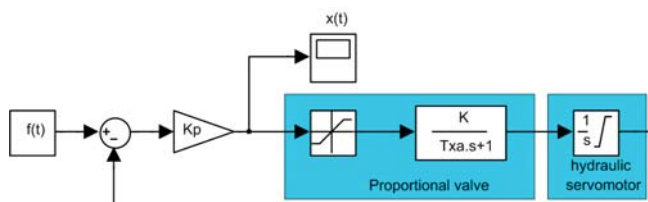


Figure 7 **Simulation block diagram of the system**
Slika 7 **Simulacijski blok dijagram sustava**

where:

$$f(t) = F_v \sin(\omega_v t) + F_{v0}; \quad F_{v0} = F_v \quad (15)$$

$$x(t) = X_m \sin(\omega_v t + \varphi_x) \quad (16)$$

In the case of simulation analysis it is important to properly set-up the simulation, otherwise the results will be insignificant and often wrong, thus leading to the wrong conclusions. The simulation analysis in this case is performed using Matlab with Simulink. The input excitation signal $f(t)$ is generated using the Matlab script file that calls the Simulink model shown in Figure 7. It is actually a modified chirp signal, the frequency of which is changed every 100 seconds with a step of 0.01 Hz. Signal $x(t)$ is input of the nonlinear part of the system. The Integrator that represents hydraulic cylinder has the upper windup limit at 0.245 m and the lower windup limit at 0 m.

5.1 Excitation signal

The excitation signal for the block diagram that is shown in Figure 7 and described in more detail in [4] has the following harmonic form:

$$f(t) = F_v \sin(\omega_v t) \quad (17)$$

and the input to the nonlinear part is:

$$x(t) = X_m \sin(\omega_v t + \varphi_x) \quad (18)$$

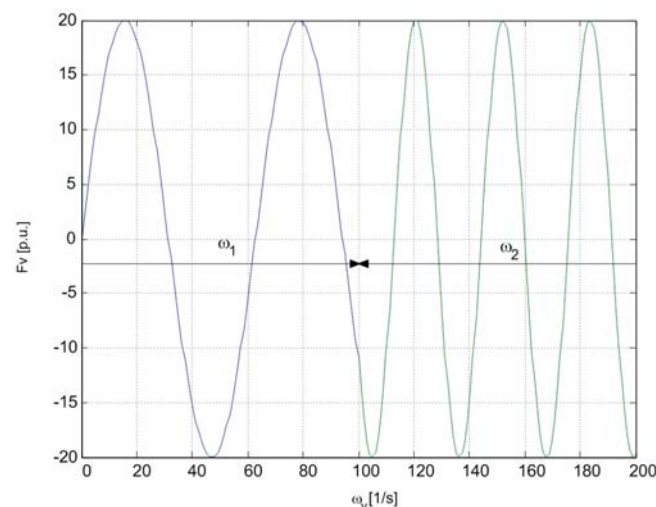


Figure 8 **Change of frequency from ω_1 to ω_2**
Slika 8 **Promjena frekvencije od ω_1 do ω_2**

The frequency ω_v is being changed from some ω_{vmin} to ω_{vmax} and afterwards from ω_{vmax} to ω_{vmin} . It is important that the change of the frequency of the excitation signal may be executed only when the input signal in the nonlinear part is stabilized, Figure 8. In other words, the input signal in the nonlinear part must have constant values of magnitude X_m and frequency ω_v during one simulation step. A conventional Bode simulation will not reveal a resonant jump, so it is of utmost importance that the change of the frequency of excitation signal is performed in the way described above. Also, because resonant jump is a nonlinear phenomenon a simulation has to be performed in two ways, by rising the frequency from ω_{vmin} to ω_{vmax} and then by lowering the frequency from ω_{vmax} to ω_{vmin} . Now, the facts described above for a proper simulation set-up have a profound effect on execution of simulation. Namely, the simulation tends to take a lot of data points and could be sometime a long process.

5.2 Acceleration of simulation using vectors

The simulation package tool MATLAB works with scripts as an interpreter, i.e. executed code is not compiled. The script is performed line by line or function by function. In this respect generation of vectors performed in a loop takes a lot of time and significantly slows simulation. Due to this Matlab feature, it is recommended to use generic functions from MATLAB for generating vectors and functions for operating with vectors and not working with particular elements of vectors. Namely, in this

way the generic functions that are compiled to the low level execution code have significantly reduced amount of the redundant unnecessary code or operations. Therefore, the amount of work to be performed by the interpreter is minimized. On Windows 2000 and Windows XP based systems this approach sped up the simulation for about 30%. In the case of old Windows 98 systems this was actually only approach available to avoid virtual memory overrun. Of course, the simulation time depends heavily on the processor speed and amount of available RAM. Average time for simulation results shown in this paper was about 4 hours with Windows 2000 OS, Intel Pentium IV machine and 500 GB of RAM when vector approach was used. That was about 35% improvement compared with the case when non-vector approach was used.

5.3 Acceleration of simulation by partition of the vectors and simulation processes

Since the nonlinear systems are usually very complex, the vectors have huge size and they are numerous. For these reasons the processor uses a swap memory for calculation. Swap memory is actually the place on the hard drive that the processor uses as RAM memory if there is not enough RAM memory for executing some operation. Working with hard drive, instead of RAM memory, is very slow in respect to working with RAM memory, so it takes much more time to execute the particular operation on the vector.

If we want that the processor uses only RAM memory when performs the simulation, it is necessary to split simulation process into more subprocesses. For these subprocesses it is necessary to generate corresponding vectors.

Special attention must be dedicated to the value of the state and input excitation vectors and the phase of input excitation signal when a subprocess is started. Every next subprocess must start with the vector values equal to the vector values with which the previous subprocess is finished.

When then frequency ω_v is being changed, it is necessary that the magnitude of the input excitation signal has the same value as the magnitude of the input excitation signal of the subprocess with the previous value of frequency ω_v .

5.4 Simulation parameters

The real parameters of the system are shown in Table 1.

Table 1 The real parameters of the system
Tablica 1 Realni parametri sustava

Parameter	value
upper and lower saturation limit	± 0.3 [p.u.]
upper windup of hydraulic cylinder	0.245 [m]
lower windup of hydraulic cylinder	0 [m]
K - gain of the electro-hydraulic valve	200 [p.u.]
K_p - gain of proportional controller	100 [p.u.]
T_{xa} - time constant of the electrohydraulic valve	0.8 [s]
F_v - amplitude of excitation	0.1225 [p.u.]

The input excitation signal $f(t)$ that is described in more detail in [1], [5] and [9] has the following harmonic form:

$$f(t) = F_v \sin(\omega_v t) \quad (19)$$

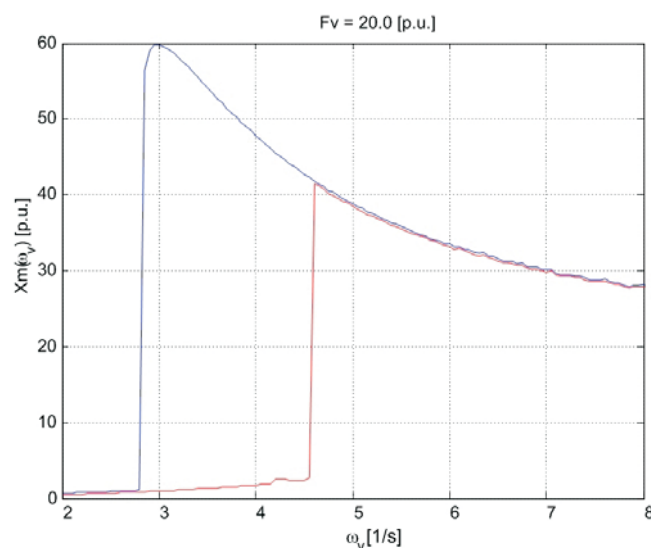
The frequency ω_v is being changed from some $\omega_{v \min}$ to $\omega_{v \max}$ and afterwards from $\omega_{v \max}$ to $\omega_{v \min}$. It is important that the change of the frequency of the excitation signal may be executed only when the input signal in the nonlinear part is stabilized. In other words, the input signal in the nonlinear part must have constant values of the amplitude X_m and frequency ω_v during one simulation step.

5.5 Simulation results

Simulation results of the system are shown in Figure 9 and Figure 10. The curve with the solid line represents the response on rising frequency, while the curve with the dashed line represents the response on falling frequency.

The influence of each particular parameter is described in more detail in [8]. The variations of the saturation, gain K of the electrohydraulic valve and the time constant T_{xa} of the electrohydraulic valve have big influence on resonant jump. Opposite to them, the variations of parameters of the dead zone have very small influence on resonant jump and can be eliminated from further analysis. Of course, the elimination of dead zone is not always allowed. It is allowed only if the dead zone has very small influence on the results of analysis. That can always be shown with the simulation. Thus, the simulation analysis is always a good starting point for the use of the analytical method.

Figure 9 Resonant jump for the real parameters
Slika 9 Rezonantni skok za realne parametre



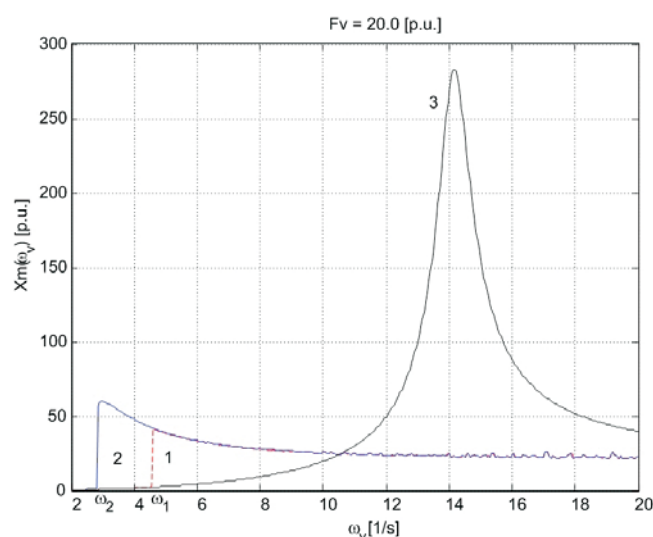


Figure 10 Frequency characteristic $X_m(\omega_v)$ for $F_v = 20$.

Legend: 1 - frequency increases,
2 - frequency decreases,
3 - frequency response of the linear system

Slika 10 Frekvencijske karakteristike $X_m(\omega_v)$ for $F_v = 20$.

Legenda: 1 - frekvencija raste,
2 - frekvencija pada,
3 - frekventni odziv linearnog sustava

6 Conclusion

Since the nonlinear resonant jump phenomenon can degrade dynamics of a nonlinear system, its analysis is recommended. In most cases the experimental analysis on the real system is not possible. In case of complex systems it is difficult or even impossible to apply analytical method. So, the only way to perform the analysis of complex nonlinear systems is often simulation approach. The methods for generating input excitation signal have strong influence on the quality of simulation results, while acceleration of simulation has big influence on the time that the simulation takes. The approaches presented in this paper can significantly improve design of nonlinear control systems. The results of the analysis can point out which operating regimes should be avoided so that the system does not operate in the area where the nonlinear resonant jump can occur. It is also possible to determine the elements to be added in control loop/circuit in order to modify the phase of the whole system in such way that the resonant jumps are avoided. For these reasons the nonlinear resonant jump may be difficult to avoid by using conventional controllers. It is useful to use nonconventional controllers like fuzzy [2], [10], neuro, robust, or similar controllers. The simulation presented here is performed using MATLAB development software from Mathworks. MATLAB is very much accepted as industrial standard in control systems community as far as system development and analysis are concerned. The competing tools are MATRIXx from National Instruments (commercial) and Scilab and Octave (free, under GNU). However, these packages operate in the same way as Matlab, thus, the simulation set-up described here can be applied to these development tools also. The paper details the simulation setup for resonance jump analysis in case

of rudder hydraulics systems which can be easily applied by engineers working in practice. On the other hand, the analytical method is complicated and in practice would usually require the control engineer with at least MSC degree to perform it, even in the case of just one nonlinearity in the system.

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Numerical Modelling of the Flow Around the Tanker Hull at Model Scale

Preliminary communication

Principles of RANSE-based (Reynolds Averaged Navier-Stokes Equations) numerical modelling of a flow around the tanker model hull are introduced with the application of the CD-adapco STAR-CCM+ (Computational Continuum Mechanics) software package in the field of ship hydrodynamics. The numerical model used in simulation is drawn up through base parameters and methods of geometrical and mathematical modelling. Results of two numerical simulations performed at design and ballast loading conditions are presented and a comparison with available experimental data is made. Some aspects of further improvements of the presented numerical model are pointed out.

Keywords: tanker ships, flow around the ship hull, numerical simulation, RANSE, model tests, experiment

Numeričko modeliranje strujanja oko trupa tankera u modelskom mjerilu

Prethodno priopćenje

Predstavljena su načela RANSE (Reynolds Averaged Navier-Stokes Equations) numeričkog modeliranja strujanja oko modela trupa tankera, primjenom programskog paketa STAR-CCM+ (Computational Continuum Mechanics) tvrtke CD-adapco u području brodske hidrodinamike. Opisani su osnovni parametri i metode geometrijskog i matematičkog modeliranja korištenog numeričkog modela. Prikazani su rezultati dvije numeričke simulacije provedene za projektno i balastno stanje opterećenja modela tankera, te je komentirana usporedba s dostupnim podacima eksperimentalnog ispitivanja. Istaknute su neke od mogućnosti daljnjeg poboljšanja prikazanog numeričkog modela.

Ključne riječi: tankeri, strujanje oko broskog trupa, numerička simulacija, RANSE, modelska ispitivanja, eksperiment

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1 Introduction

Witnessing the rapid growth of the low-cost desktop computational power and access to high performance computing platforms on one side, and development in theoretical continuum mechanics methods and their numerical implementation on the other, one must recognize its strong impact in everyday engineering practice [1]. Following this trend, numerical modelling of the real complex physical phenomena is transforming from approximate, economically unaffordable, time-consuming applications limited mainly to critical parts of product development into a reliable and common design office tool, fully integrated into the overall product development process.

In that light, driven by the need for delivering on-time, on-cost cutting edge technology products and services, Brodarski institut d.o.o. (BI) has established a new Numerical hydrodynamics department with the main objective to increase the level of its competitiveness on the global market. At the first stage of department operability, the evaluation of few commercial numerical codes for general continuum mechanics is made from

several relevant aspects of engineering usage. Recent work of the department regarding the quantitative validation of the numerical results performed in STAR-CCM+ with reference to experiment is presented in this paper.

2 Benchmark

A hull form of a tanker model extensively tested in BI's towing tank is chosen, providing a set of reference experimental data for a comparison [2]. A quantitative margin of $\pm 10\%$ to measured data is adopted as reasonable in the first iteration of computations, leaving a considerable space for further improvements of the numerical model by means of higher accuracy and reduction in computation time.

Two simulations are performed on the bare tanker model at design and ballast loading conditions (Table 1), each at a single model speed of $V=1.419$ m/s corresponding to Froude numbers based on L_{WL} $Fr=0.176/0.178$ and Reynolds numbers of $Re=8.67 \times 10^6/8.38 \times 10^6$ respectively.

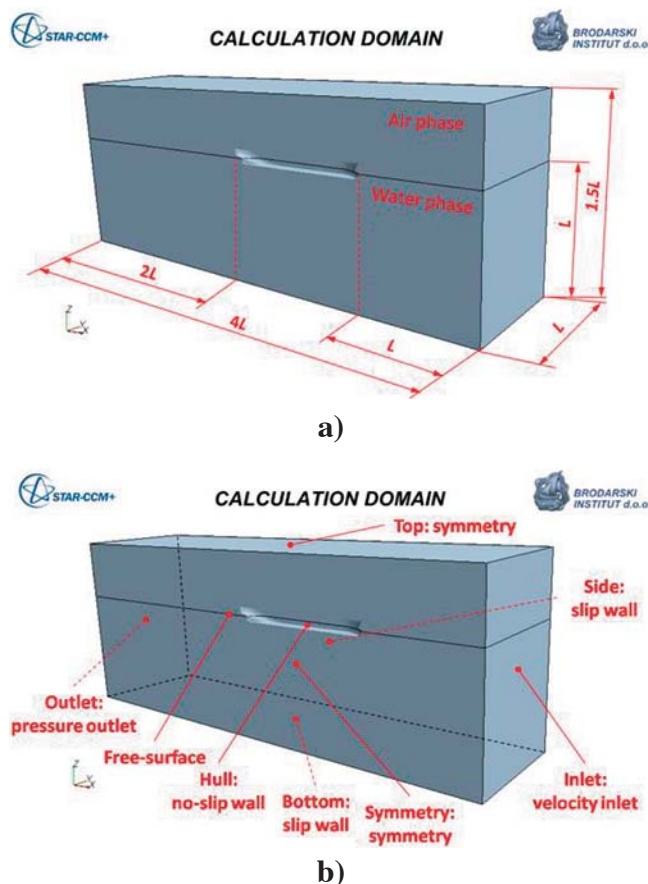
Table 1 Tanker model particulars
 Tablica 1 Karakteristike modela tankera

		Design	Ballast
Length of waterline	L_{WL}	6.6608 m	6.4538 m
Breadth, moulded	B	0.9578 m	0.9578 m
Draught at FP	T_F	0.3624 m	0.2228 m
Draught at AP	T_A	0.3624 m	0.2377 m
Displacement volume	∇	1.9478 m ³	1.1880 m ³
Wetted surface area	S_0	9.8870 m ²	7.8634 m ²

3 Geometrical model setup

STAR-CCM+ uses a finite volume method based solver [3]. The governing equations describing the physical model of the flow are discretized in the number of control volumes (CV), or cells, in which the unknown variables are solved. A 3-D rectangular computation domain representing a part of the towing tank is used in both simulations. Due to the vertical plane symmetry, only a half of the computation domain is modelled. The domain length is taken up to four model lengths, one length in front and two lengths behind the hull. Furthermore, the domain is modelled one model length wide and one and a half model length high, having a free-surface at one model length from the bottom, defining the water depth (Figure 1a).

Figure 1 Calculation domain; a – extents, b – boundary conditions
 Slika 1 Proračunska domena; a – dimenzije, b – rubni uvjeti



The process of the finite volume mesh generation starts with a definition of the core mesh surfaces and their triangulation. The core mesh is a rectangular portion of the computational domain that closely surrounds the tanker model and which is modelled with most care. At this point, the user is allowed to define the variable triangle sizes on all of the surfaces defining the core mesh. Afterwards, the trimmed cell method is applied to generate volume cells inside the core mesh according to user settings. Finally, the core mesh boundaries are extruded to the extents of the computation domain.

Finite volume meshes for both loading conditions are generated entirely with hexahedral cells. Parameters used in the generation of the meshes are identical for both loading conditions (Table 2), with the exception of the total number of generated cells due to the difference in tanker model position relative to the free-surface (Figure 2). Cell sizes in the domain are gradually refined towards the regions where high gradients of velocity and pressure are expected. A prismatic layer is generated around the hull model, defining the appropriate cell thicknesses in order to resolve the boundary layer.

Table 2 Parameters of finite volume meshes
 Tablica 2 Parametri mreže konačnih volumena

	Design	Ballast
Total number of generated cells	2447012	1904370
Max. cell size on hull (water phase)	0.0125 m	0.0125 m
Max. cell size on hull (air phase)	0.05 m	0.05 m
Max. cell size on domain boundaries	0.2 m	0.2 m
Max. cell size on free-surface	0.0125 m	0.0125 m
First cell thickness (water phase)	0.0025 m	0.0025 m
First cell thickness (air phase)	0.005 m	0.005 m

Figure 2 Finite volume mesh of the tanker model; a – design draught, b – ballast draught
 Slika 2 Mreža konačnih volumena modela tankera; a – projektni gaz, b – balastni gaz



4 Physical model setup

RANSE solver is used to solve the governing equations of continuity and momentum in a viscous flow around the hull model. The Navier-Stokes Equations (NSE) are solved with a segregated, algebraic multigrid solver [4] using the Rhie-Chow interpolation for pressure-velocity coupling [5]. The SIMPLE algorithm [6] is a guess-and-correct procedure applied to control the overall solution. Starting from the boundary conditions the velocity and pressure gradients are calculated and the discretised momentum equations are solved. That gives the intermediate velocity field which is used to calculate the uncorrected mass fluxes at the cell faces. After correcting the pressure field (p) and the boundary pressures, the mass fluxes across the cell faces can be corrected and the cell velocities (u , v , w) can be updated.

To obtain the RANSE for a turbulent flow around the ship hull, the NSE for the instantaneous velocity and pressure fields are decomposed into a mean and a fluctuating component and the averaging process may be thought of as time averaging for steady-state situations and ensemble averaging for repeatable transient situations. The effect of turbulent fluctuations on the mean flow is approximated with a set of semi-empirical expressions called turbulence model. The Menter shear-stress transport (SST) k - ω turbulence model [7, 8] is used in the simulations, in which the transport equations are solved for two variables: turbulent kinetic energy (k) and specific dissipation rate (ω).

Free-surface is modelled using the Volume of Fluid approach (VOF) with a High Resolution Interface Capturing Scheme (HRIC) based on the Compressive Interface Capturing Scheme for Arbitrary Meshes (CISAM) [9, 10]. The numerical model can be applied to any structured and unstructured grid with arbitrary shaped CV. With four conservation and two turbulence equations an additional equation is solved, introducing a variable c ($0 \leq c \leq 1$) for the volume fraction of the each fluid, where 1 stands for filled CV of one fluid in which at the same time the volume fraction of other fluid has to be 0 to achieve unity. This approach treats both fluids as a single fluid which changes its properties according to the volume fraction.

The boundary condition applied to the model hull is a no-slip wall allowing for boundary layer around the model hull to develop. All- y^+ wall treatment is used for a set of near wall modelling assumptions. Bottom and side boundaries are modelled as slip walls, while top and symmetry boundaries are modelled as symmetry. The velocity inlet and the pressure outlet are applied to inlet and outlet boundaries (Figure 1b).

5 Numerical results and comparison with experiment

The transient simulations are stopped when the difference in successive residuals of the pressure drag coefficient over a specific time period at any point on the hull model reaches the maximum value of 10^{-4} , where the specific time period refers to the time needed for a particle of water to travel one tanker model length (approximately 5 s). Mean values of the drag, the shear and the pressure component of the drag, and the lift forces

over a specific time period, are calculated for comparison with experimental data (Table 3).

Table 3 Comparison of the force coefficients
Tablica 3 Usporedba koeficijenata sile

Design	Computed	$10^3 \times C_D$	$10^3 \times C_{DS}$	$10^3 \times C_{DP}$	C_L
		3.897	2.954	0.944	1.862
	Measured	$10^3 \times C_T$	$10^3 \times C_{F0}$	$10^3 \times C_R$	C_W
		3.947	3.076	0.871	1.920
	Margin	-1.3 %	-3.1 %*	+1.8 %*	-2.3 %
Ballast	Computed	$10^3 \times C_D$	$10^3 \times C_{DS}$	$10^3 \times C_{DP}$	C_L
		4.409	3.094	1.314	1.428
	Measured	$10^3 \times C_T$	$10^3 \times C_{F0}$	$10^3 \times C_R$	C_W
		4.316	3.094	1.222	1.472
	Margin	+2.1 %	0.0 %*	+2.1 %*	-3.0 %

* Absolute margins are presented in correlation with total force coefficients.

Where

C_D ... drag coefficient

C_{DS} ... shear drag coefficient

C_{DP} ... pressure drag coefficient

C_L ... lift coefficient

C_T ... total resistance coefficient

C_{F0} ... frictional resistance coefficient of a corresponding plate (ITTC-1957 correlation line)

C_R ... residual resistance coefficient

C_W ... weight coefficient.

Results of the free-surface elevation computation around the tanker model at the design and the ballast loading condition are presented qualitatively, and compared with photographs taken during the testing of the model in the towing tank (Figures 3 and 4). Development of the bow and stern wave systems are captured realistically at both loading conditions, forming a wave patterns around the hull model similar to the ones observed in the experiment.

Streamlines plotted on the hull model indicate a possible flow separation at the stern bulb region near the propeller, at both loading conditions (Figures 5b and 5d). A further analysis of the shear stress on the hull model reveals the presence of reverse flow region at the same position (Figure 6a). This result is observed in the experiment performed at design draught as well (Figure 6b).

Wake fields computed at propeller disk for both loading conditions are compared to the experiment by overlapping the measured black-and-white iso-wake curves over computed colour-filled results (Figure 7). Qualitatively, shapes of the wake fields are very well captured at both loading conditions. On the other hand, computed axial components of velocity over propeller disk locally show the absolute margin of up to 0.15 to measurements.

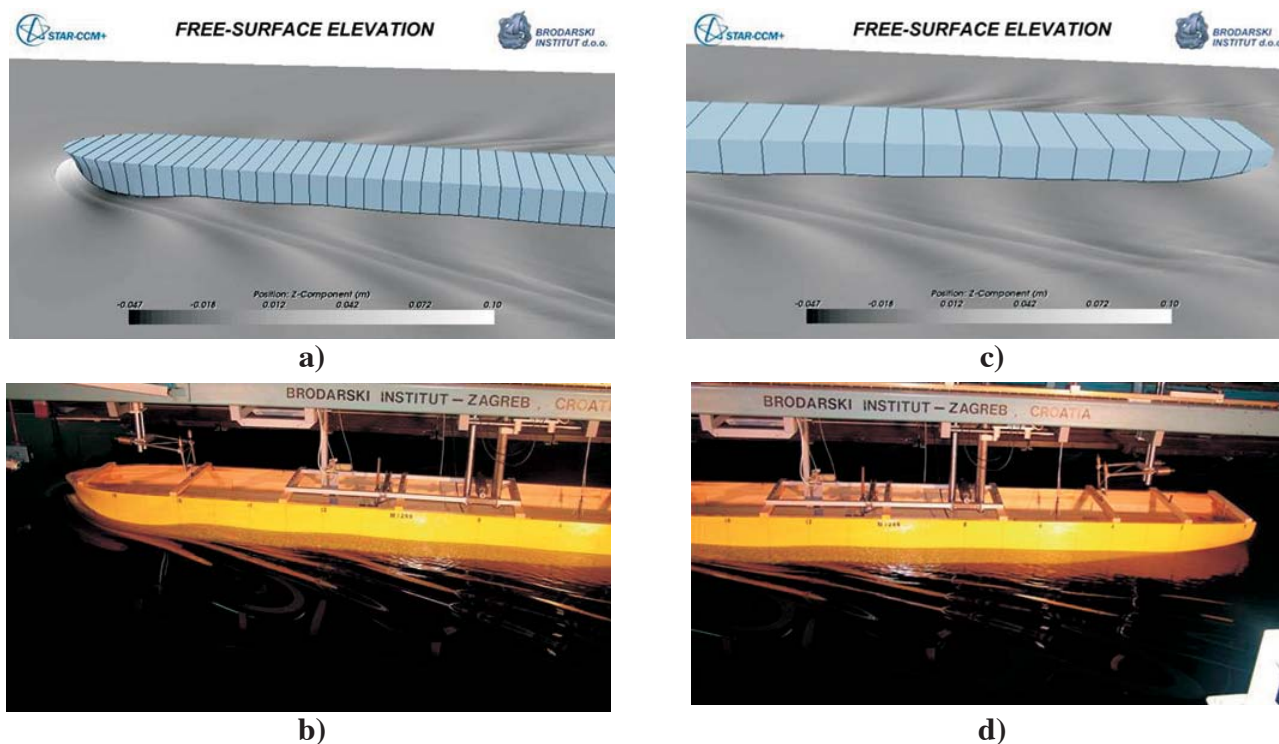
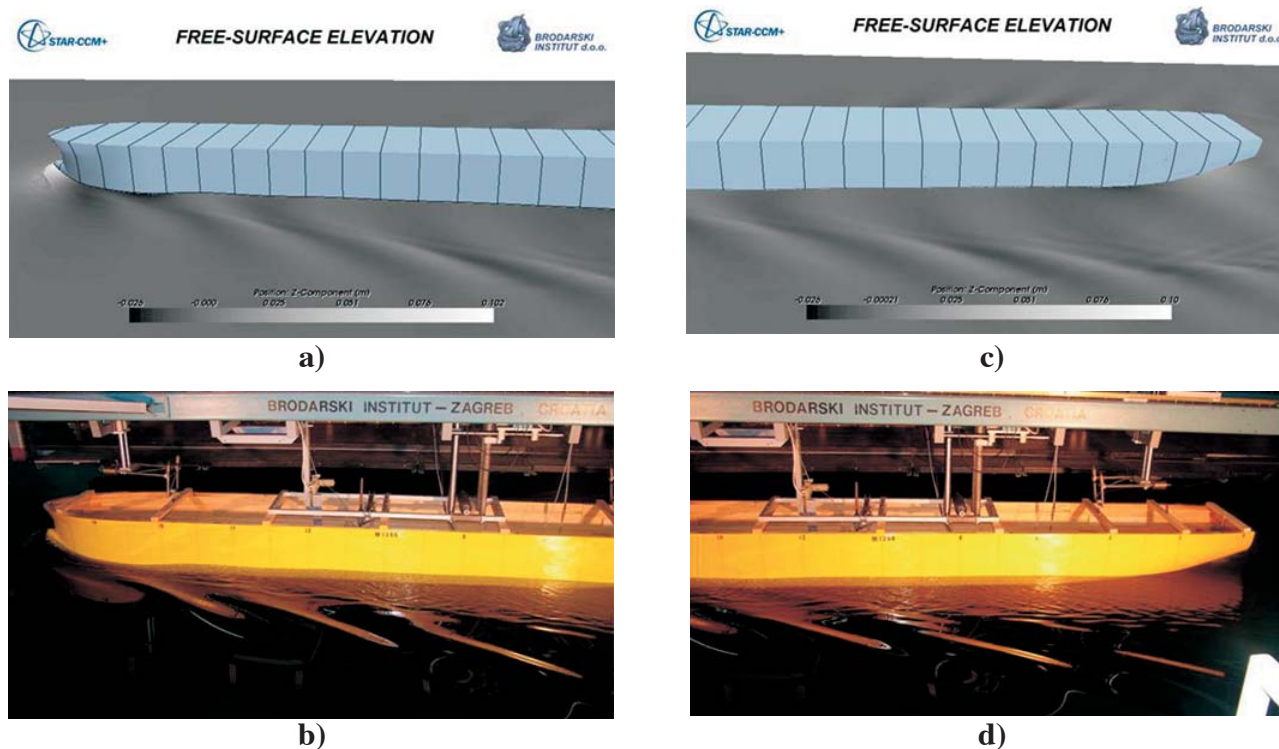


Figure 4 Comparison of the free-surface elevation around the tanker model at ballast draught
a, c – numerical computation; b, d – photograph taken during the experiment

Slika 4 Usporedba elevacije slobodne površine oko trupa modela tankera na balastnom gazu
a, c – numerički proračun; b, d – fotografija snimljena tijekom eksperimenta



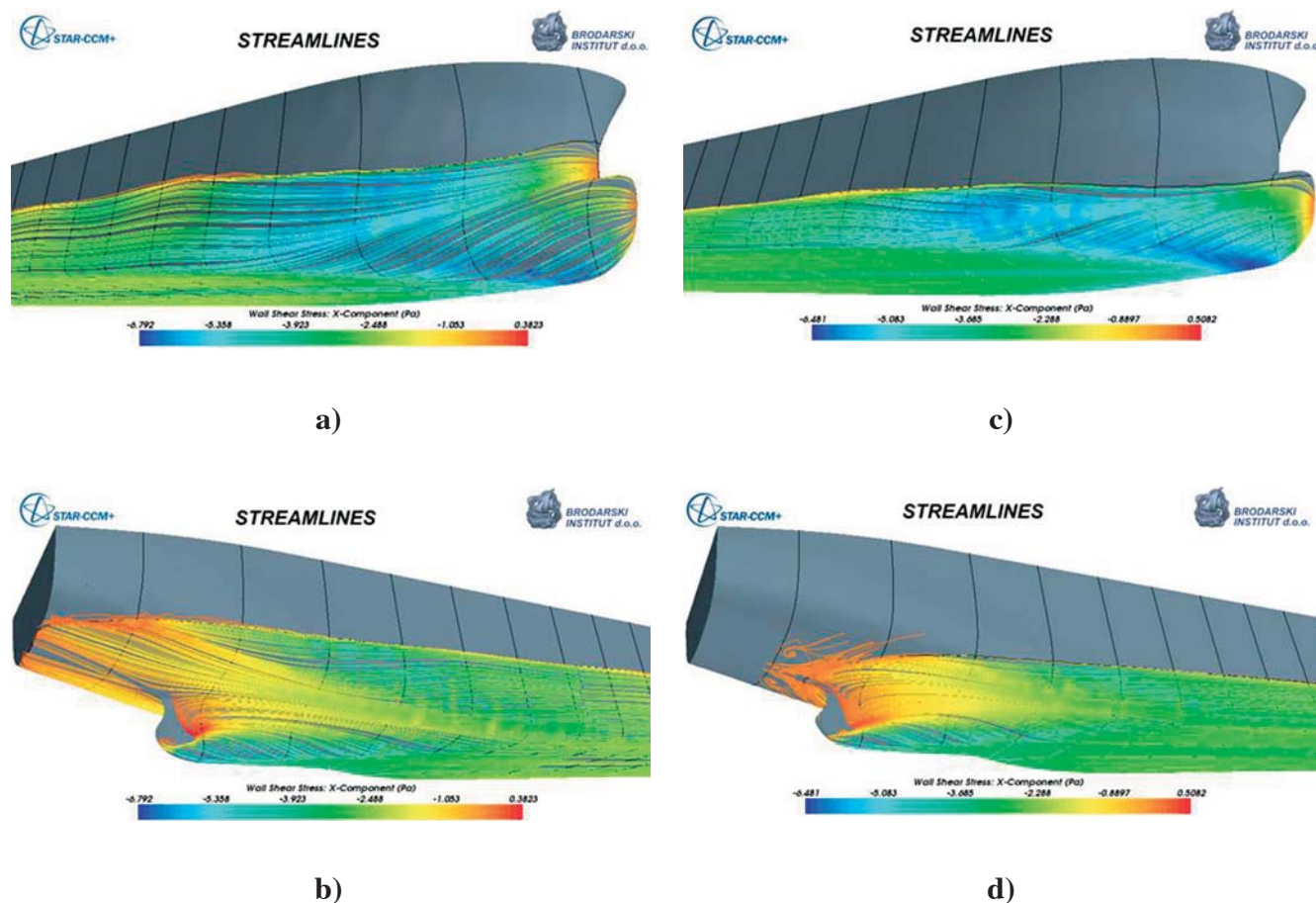
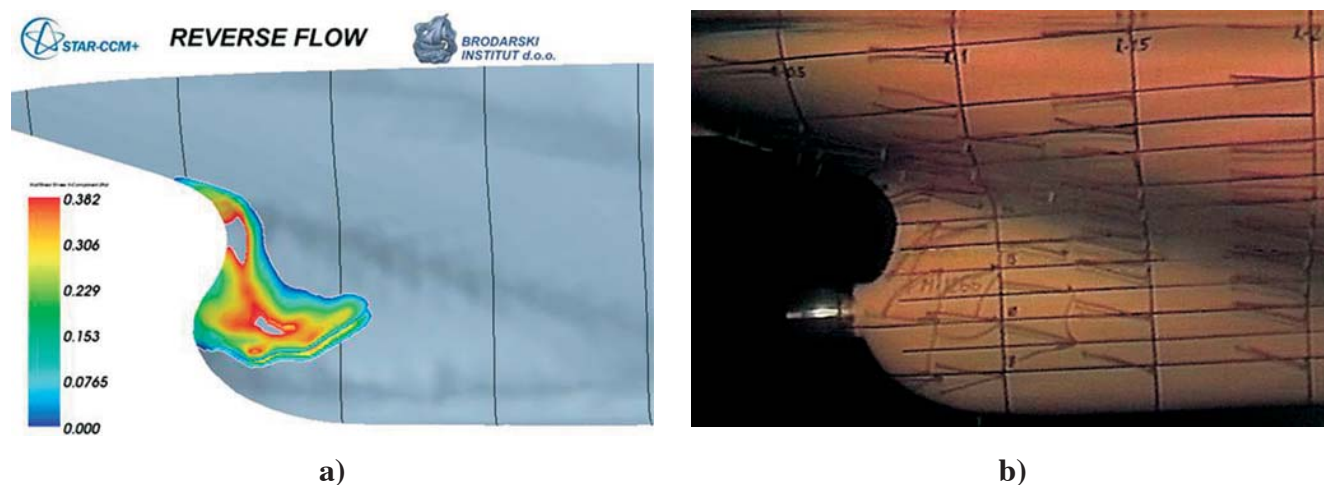


Figure 5 Streamlines on the tanker model hull; a, b – design draught; c, d – ballast draught
Slika 5 Strujnice izračunate na trupu modela tankera; a, b – projektni gaz; c, d – balastni gaz

Figure 6 Flow separation region at the stern of the tanker model;
a – numerical computation; b – photograph taken during the experiment
Slika 6 Područje odvajanje strujanja na krmi modela tankera;
a – numerički proračun; b – fotografija snimljena tijekom eksperimenta



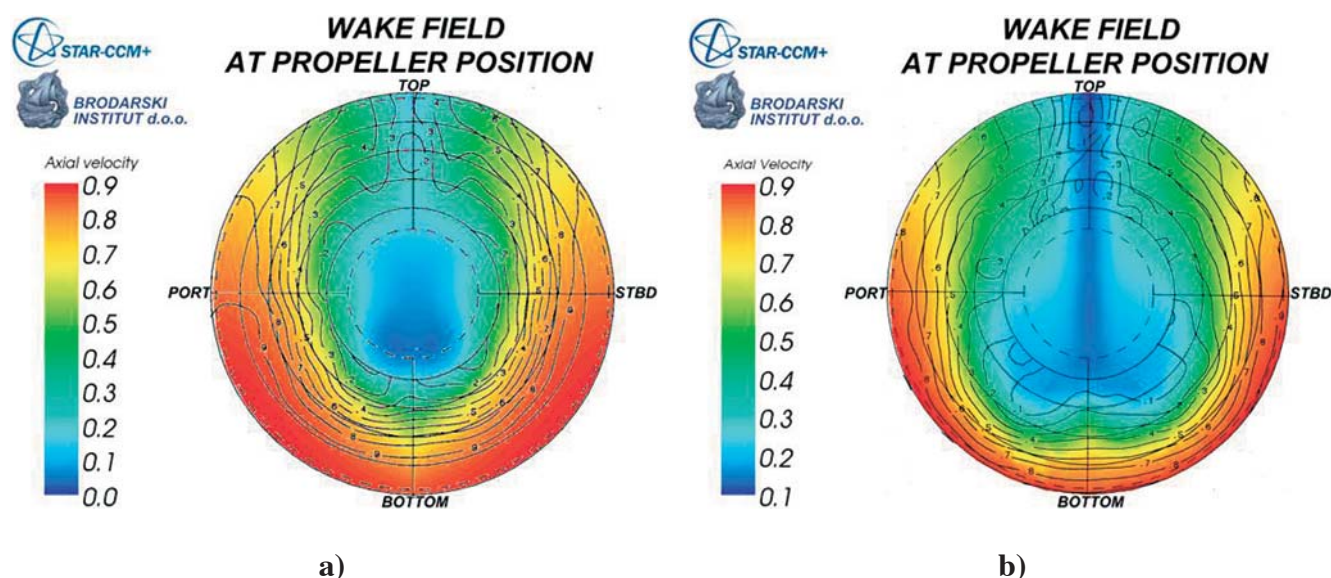


Figure 7 Comparison of the wake field at propeller position; a – design draught; b – ballast draught
Slika 7 Usporedba polja sustrujanja na poziciji vijka; a – projektni gaz; b – balastni gaz

5 Conclusions

As to the results of the numerical modelling of the flow around the tanker model and the comparison with experimental data presented in this paper, the following can be concluded:

- 1) Values of computed drag and lift coefficients are satisfactory for both loading conditions, with a margin of $\pm 3\%$ to the experiment. It must be noted, however, that the comparison of coefficients of the horizontal force components presented in the Table 3 is subjected to the method used in the decomposition of the total resistance measured in the experiment.
- 2) The elevations of the free-surface calculated around the tanker model at both loading conditions are captured realistically, according to photographs taken during the experiment.
- 3) Flow separation is detected in the stern region of the tanker model near the propeller, at the same position as observed in the experiment.
- 4) Wake fields at propeller disk are calculated for both loading conditions within absolute margin of 0.15 to the experiment. Nevertheless, due to strong time-dependent turbulent fluctuations behind the tanker model hull, the computed results are acceptable, providing a valuable insight into the flow behind the model hull.

Although the obtained computational results in the scope of the available experimental data are satisfactory from quantitative aspect, investigation on further improvements of the presented numerical model can be performed. The geometrical model can be optimized regarding the total cell number, cell sizes and cell distribution in the calculation domain. An analysis of turbulence modelling can be performed with the use of more accurate turbulence models and an analysis of different wall treatments can be carried out.

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Infrared Thermography in Marine Applications

Review Paper

Infrared (IR) thermography has become a powerful tool for basic and applied scientific research and for the application in various fields such as industry, environment, military and maritime affairs, etc. As a „predictive“ maintenance tool, IR thermography has the ability to identify problems before they occur. It is especially helpful for trouble shooting potential electrical overloads, worn or bad circuit breakers and buses. IR thermography can also be used to detect bad bearings, shafts, worn pulleys or any application where heat detection would be beneficial.

This paper has the intention to familiarize researchers, engineers and sea business staff with possibilities of applying IR thermography in the field of maritime affairs. Therefore, basic principles of IR thermography are presented and examples of the tool application are given.

Keywords: *Infrared thermography, marine application, non-destructive testing*

Primjena infracrvene termografije u pomorstvu

Pregledni rad

Infracrvena (IC) termografija postala je snažan alat za temeljna i primijenjena znanstvena istraživanja i primjenjuje se u različitim područjima poput industrije, okoliša, vojske, pomorskim poslovima itd. Kao „predskazujući“ alat održavanja IC termografija pruža mogućnost da se problemi uoče prije nego se dogode. To je posebno korisno za probleme izbacivanja zbog mogućih električnih preopterećenja, istrošenih ili loših strujnih prekidača i sabirnica. IC termografija također može biti od koristi za otkrivanje loših ležajeva, osovina, pohabanih remenica ili u bilo kojoj primjeni gdje će otkrivanje topline biti od koristi.

Nakana ovog članka jest približiti, istraživače i osoblje koje se bavi pomorstvom, mogućnosti primjene IC termografije u poslovima pomorstva. Stoga su prikazani temeljni principi IR termografije i prezentacija ilustrativnih primjera primjene.

Ključne riječi: *Infracrvena termografija, primjena u pomorstvu, nedestruktivno ispitivanje*

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1 Introduction

IR thermography is a technique for producing an image of the invisible to our eyes infrared light emitted by objects due to their thermal condition. A typical type of thermography camera produces a live video picture of heat radiation intensities. More sophisticated cameras can actually measure the temperature values of any object or surface in the image field-of-view and produce false colour images that make interpretation of thermal patterns easier. An image produced by an infrared camera is called a thermogram [1].

The properties of measuring heat transmission from objects using a thermography camera are more than an interesting novelty; this information can prove useful in a variety of applications. Defence and law enforcement applications include criminal tracking, land/airborne surveillance of vehicles which have been recently operated, all from a safe distance. With a thermography camera, industrial users can detect flaws in manufacturing or weakened thermal insulators, fire safety professionals can differentiate between full and empty flammable storage containers and use the camera to see through smoke, find lost persons, and localize the source base of the fire, etc.

Originally developed for military use during the Korean War, Thermal Infrared cameras have slowly migrated into other fields of remote sensing uses as varied as medicine and archaeology. A recent advance in IR sensor production and a reduction in prices have helped the infrared viewing technology to be adopted as a cost-effective, non-invasive measuring method. Advanced optics and sophisticated software interfaces continue to add to the variety of Thermal IR cameras. Today, the IR thermography is applied in numerous human activities, such as [2]: astronomy (telescope), fire fighting operations, military and police surveillance, target detection and acquisition, law enforcement and anti-terrorism, predictive engineering maintenance of mechanical and electrical equipment, process monitoring, condition monitoring and surveillance, energy auditing of insulation, roof inspection, masonry wall structural analysis, moisture detection in walls and roofs, medical testing for diagnosis, non-destructive testing, quality control in production environments, research and development of new products, effluent pollution detection, locating of unmarked graves, aerial archaeology, search and rescue operations, etc.

Main advantages of IR thermography are:

- Allowing corrective actions to be taken before electrical, mechanical, or process equipment fails (prevention)

- Getting a visual picture for an analysis and comparison of temperatures over a large area
- Catching moving targets in real time (video rate)
- Measurement in inaccessible areas or areas hazardous for other test methods

Some limitations and disadvantages of IR thermography are:

- Thermal Images need experience and special tools to be interpreted correctly
- Very accurate temperature measurements are hard to make because of changes in material emissivities
- Training for and developing proficiency in the IR scanning is time consuming.

2 Fundamentals of thermography

The three methods by which heat flows from one object to another are radiation, convection and conduction. While the major concern of IR viewers is with radiation effects, the effects of the other two cannot be neglected.

Conduction is the way in which heat moves in a solid by transferring thermal energy from molecule to molecule, heating up each adjacent area within the solid. Convection is a faster heat transfer effect, and moves in the way heat does in a liquid or in a gas. In convection, a medium is used to carry thermal energy and to develop a current in the medium to move it along more rapidly. This is a faster and more powerful thermal energy transfer than conduction. However, the most powerful means of thermal energy transfer is radiation, which moves at the speed of light. These three phenomena do not exclude each other, and in most situations they occur together.

IR energy is emitted by all materials above 0 °K (≈ -273 °C). Infrared radiation is part of the electromagnetic spectrum and occupies frequencies between visible light and radio waves (Figure 1). The IR part of the spectrum spans wavelengths from 0.7 μm (micrometers, microns) to 1000 μm . Within this wave band, only frequencies of 0.7 μm to 20 μm are used for practical, everyday temperature measurement [3].

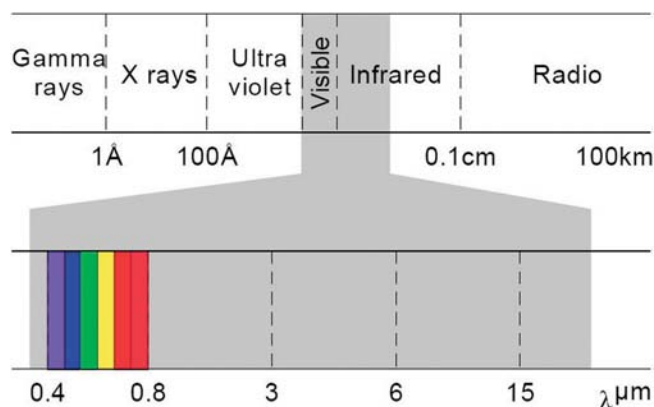


Figure 1 Electromagnetic spectrum
Slika 1 Elektromagnetski spektar

Though IR radiation is not visible to the human eye, it is helpful to imagine it as being visible when dealing with the principles of measurement and when considering applications, because in many respects it behaves in the same way as visible

light. IR energy travels in straight lines from the source and can be reflected and absorbed by material surfaces in its path. In the case of most solid objects which are opaque to the human eye, part of the IR energy striking the object surface will be absorbed and part will be reflected. A certain amount of the energy absorbed by the object will be re-emitted and a certain amount will be reflected internally. This will also apply to materials which are transparent to the eye, such as glass, gases and thin, clear plastics, but here, some of IR energy will also pass through the object. These phenomena collectively contribute to what is referred to as the emissivity (ϵ) of the object or material optical properties.

Materials which do not reflect or transmit any IR energy are known as black bodies (BB) and are not known to exist naturally. However, for the purpose of theoretical calculation, a true black body is given an emissivity value of 1.0. The closest approximation to a black body emissivity of 1.0, which can be achieved in real life, is an IR opaque, i.e. a spherical cavity with a small tubular entry. The inner surface of such a sphere will have an emissivity of 0.998. The object has an emissivity ϵ which is the ratio of radiant power from an object to that from a black body at the same temperature.

Different kinds of materials and gases have different emissivities, and will therefore emit IR energy at different intensities for a given temperature. The emissivity of a material or gas is a function of its molecular structure and surface characteristics. It is not generally a function of colour unless the source of the colour is a radically different substance from the main body of the material. Metallic paints which incorporate significant amounts of aluminium are a practical example of such a case. Most paints have the same emissivity irrespective of colour, but aluminium has a very different emissivity which will therefore modify the emissivity of metallized paints. The more highly polished some surfaces are, the more IR energy will be reflected from the surface. The surface characteristics of a material will therefore also influence its emissivity. In temperature measurement, this is most significant in the case of infrared opaque materials which have an inherently low emissivity. Thus, a highly polished piece of stainless steel will have a much lower emissivity than the same piece with a rough, machined surface. This is because the grooves created by the machining prevent a large amount of the IR energy from being reflected. In addition to molecular structure and surface condition, the third factor affecting the apparent emissivity of a material or gas is the wavelength sensitivity of the sensor, known as the sensor spectral response. As stated earlier, only IR wavelengths between 0.7 μm and 20 μm are used for practical temperature measurement. Within this overall band, individual sensors may operate only in a narrow part of the band, such as from 0.78 μm to 1.06 μm , 3.0 μm to 5.2 μm or 7 μm to 14 μm , for reasons which will be explained later (IR attenuated by the atmosphere).

The formulas upon which the infrared temperature measurement is based are old, established and well proven. It is unlikely that most IR users will need to make use of these formulas, but a good knowledge of them will provide an appreciation of the interdependency of certain variables. The important formulas are as follows [4]:

1 Planck's Law

This law describes the relationship between spectral emissivity, temperature and radiant energy from a black body.

$$E_{BB}(\lambda, T) = \frac{2 \cdot h \cdot c^2}{\lambda^5} \frac{1}{e^{\frac{h \cdot c}{\lambda \cdot k \cdot T}} - 1} \quad (\text{W} / \text{m}^2 \text{nm}), \quad (1)$$

where: E_{BB} is black-body spectral radiant emittance at wavelength λ (μm) and thermodynamic temperature T (also called absolute temperature) (K), c is velocity of light ($c = 3 \cdot 10^8 \text{ m/s}$), h is Planck's constant ($h = 6,625 \cdot 10^{-34} \text{ Joule} \cdot \text{s}$) and k is Boltzmann's constant ($k = 1,38 \cdot 10^{-23} \text{ Joule/K}$)

2 Wien's Displacement Law

This law states that the wavelength at which the maximum amount of energy is emitted becomes shorter as the temperature increases.

$$\lambda_{\text{max}} \cdot T = 2898 \text{ } (\mu\text{mK}) \quad (2)$$

For example, the sun ($\approx 6000 \text{ }^\circ\text{K}$) emits yellow light, peaking at about $0,5 \mu\text{m}$ in the middle of the visible light spectrum. At the temperature of $20 \text{ }^\circ\text{C}$ ($\approx 293 \text{ }^\circ\text{K}$) the peak of radiant emittance lies at $9,9 \mu\text{m}$, while at the temperature of $T = 473 \text{ }^\circ\text{K}$ ($\approx 200 \text{ }^\circ\text{C}$) the peak is $\lambda_{\text{max}} = 6,1 \mu\text{m}$ (Figure 2).

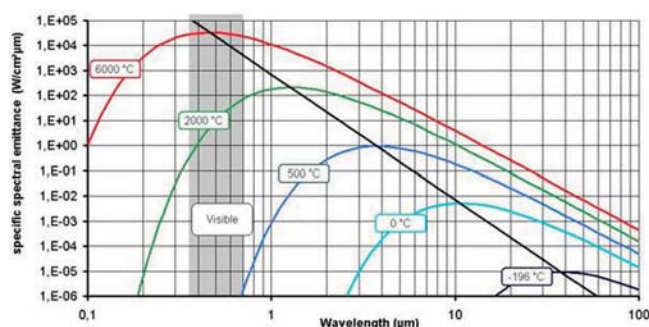


Figure 2 Distribution and the peaks of radiated energy from objects at various temperatures

Slika 2 Raspodjela energije zračenja i maksimuma s objekata različitih temperatura

3 The Stephan-Boltzmann Law

The hotter an object becomes the more infrared energy it emits.

The Stefan-Boltzmann law, also known as Stefan's law, states that the total energy radiated per unit surface area of a black body in unit time (known variously as the black-body irradiance, energy flux density, radiant flux, or the emissive power), E_{BB} , is directly proportional to the fourth power of the black body thermodynamic temperature T :

$$E_{BB} = \sigma \cdot T^4 \text{ (W/m}^2\text{)} \quad (3)$$

The constant of proportionality σ , called the Stefan-Boltzmann constant or Stefan's constant is non-fundamental in the sense that it derives from other known constants of nature. The value of the constant is $\sigma = 5,6697 \cdot 10^{-8} \text{ W/m}^2\text{K}^4$.

4 Kirchoff's Law

When an object is at thermal equilibrium, the amount of absorption will equal the amount of emission. According to Kirchoff's

law, for any material the emissivity and absorptance of a body are equal at any specified temperature and wavelength, i.e.:

$$\varepsilon = a, \quad (4)$$

where a is coefficient of absorptance (the ratio of radiant power absorbed by an object to that incident upon it).

Real objects almost never comply with these laws over an extended wavelength region although they may approach the black-body behaviour in certain spectral intervals. When the infrared energy radiated by an object reaches another body, a portion of the energy received will be absorbed (a), a portion will be reflected (r) and, if the body is not opaque, a portion (t) will be transmitted through. The sum total of the three individual parts must always add up to the initial value of radiation which left the source.

$$a + r + t = 1 \quad (5)$$

If we have a body which is totally non-reflective and completely opaque, then all the radiated energy received by this body will be absorbed. This type of a body is a perfect absorber and will also be a perfect emitter of infrared radiation. A perfect absorber and hence emitter of infrared energy is referred to as a black body. A black body would not necessarily appear to be black in colour as the words black body are a technical term to describe an object capable of absorbing all radiation falling on it and emitting maximum infrared energy for a given temperature. In practice, surfaces of materials are not perfect absorbers and tend to emit and reflect infrared energy. A non-black body would absorb less energy than a black body under similar conditions and hence would radiate less infrared energy even if it was at the same temperature.

For opaque materials $t = 0$, and the relation is simplified to $a + r = 1$. According to Kirchoff's law, $\varepsilon + r = 1$. For highly polished materials ε approaches zero, so that for a perfect reflecting material $r \approx 1$ is valid.

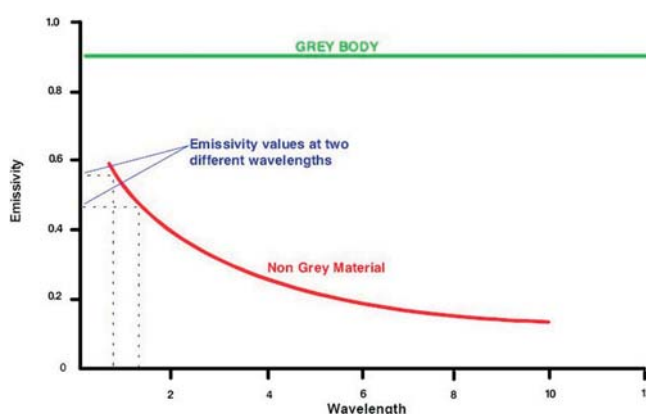
A gray body (GB) has ε less than 1 and constant value wavelength independent. Taking into account ε for gray-body radiator, the Stefan-Boltzmann formula becomes:

$$E_{GB} = \varepsilon \cdot \sigma \cdot T^4 \text{ (W/m}^2\text{)} \quad (6)$$

A real body generally has not a constant value for emissivity (Figure 3) but usually a constant value is taken for a narrow spectral band.

Figure 3 Spectral emissivity of BB, GB and Non-Grey material (the plot of BB is missing)

Slika 3 Emisivnost crnog, sivog i realnog tijela



The atmosphere is not fully transparent to IR. It attenuates the radiation passing through it and also emits radiation. The atmosphere influence on IR measurements depends mainly on the air density, temperature, visibility and relative humidity (the influence of aerosol). There are some narrow spectral bands called atmospheric windows where the attenuation is not so strong (SW – short wave, 3 – 5 μm ; LW – long wave, 8 – 14 μm ; Picture 4.) and it is the reason why Thermal IR cameras works in these bands. Modern IR cameras have a computer program for the prediction of atmospheric attenuation and use it in the analysis process.

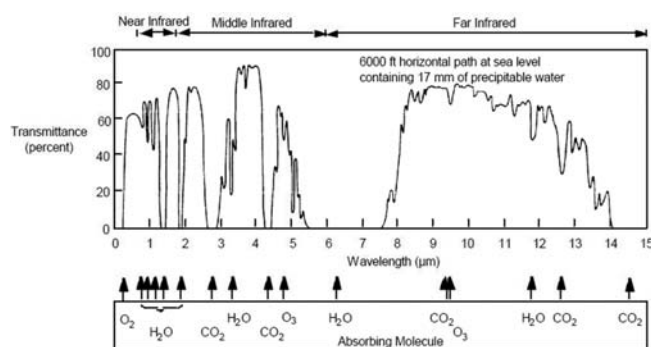


Figure 4 **Atmospheric transmissivity in different wavelength bands**

Slika 4 **Propusnost atmosfere u različitim spektralnim pojasima**

According to the approaches to measuring, thermography is classified as active thermography and passive thermography. Generally, in active thermography external stimulation is required to generate relevant thermal contrasts in thermal steady state “specimens”, while in passive thermography, the actual thermal state of the “specimen” provides enough information to characterize the sought features. Thus, the active thermography presentation elaborates on various stimulation schemes such as pulse, step, and modulated, while special attention is paid to data analysis since the active thermography is often deployed for quantitative characterization. Also, vibrothermography is an active IR thermography technique where, under the effect of mechanical vibrations induced externally to the structure at a few fixed frequencies, heat is released by friction precisely at defect locations (such as cracks and delaminations).

3 IR Thermography measuring

As already mentioned, when viewing an object, a camera receives radiation not only from the object itself. It also collects radiation from the surroundings reflected via the object surface. Both these radiation contributions become attenuated to some extent by the atmosphere in the measurement path. A third radiation contribution comes from the atmosphere between the object and the camera.

This basic description of the measurement situation, as illustrated in Figure 5, is so far a fairly true description of real conditions. What has been neglected could, for instance, be the sun light scattering in the atmosphere or stray radiation from intense radiation sources outside the field of view. Such disturbances are difficult to quantify; however, in most cases they are

fortunately small enough to be neglected. In the case when they are not negligible, the measurement configuration is likely to be such that the risk for disturbance is obvious, at least to a trained operator. It is then his responsibility to modify the measurement situation to avoid the disturbance e.g. by changing the viewing direction, by shielding intense radiation sources, etc.

Accepting the description above, we can use the figure below to derive a formula for the calculation of the object temperature from the calibrated camera output.

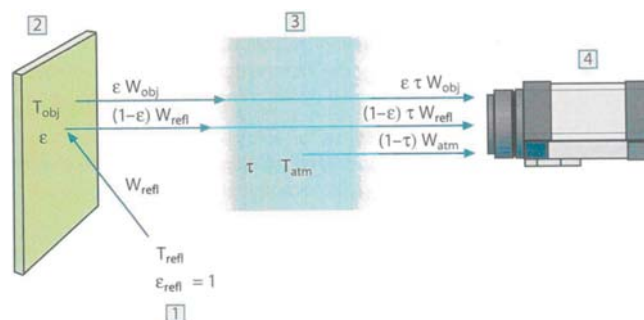


Figure 5 **A schematic representation of a general thermographic measurement situation.**

Slika 5 **Shematski prikaz situacije općeg termografskog mjerenja.**

1.: okolina; 2.: objekt; 3.: atmosfera; 4.: kamera

The three collected radiation power terms are [5]:

- 1 - Emission from the object = $\epsilon\tau W_{\text{obj}}$, where ϵ is the emittance of the object and τ is the transmittance of the atmosphere. The object temperature is T_{obj} .
- 2 - Reflected emission from ambient sources = $(1 - \epsilon)\tau W_{\text{ref}}$, where $(1 - \epsilon)$ is the reflectance of the object. The ambient sources have the temperature T_{ref} .
- 3 - Emission from the atmosphere = $(1 - \tau)W_{\text{atm}}$, where $(1 - \tau)$ is the emittance of the atmosphere. The temperature of the atmosphere is T_{atm} .

The total received radiation power can now be written as:

$$W_{\text{tot}} = \epsilon\tau W_{\text{obj}} + (1 - \epsilon)\tau W_{\text{ref}} + (1 - \tau)W_{\text{atm}}$$

According to Stefan's law, from the measured value W it is possible to get the object temperature.

Thermal IR imagers come in different configurations to suit specific needs. Some imagers are designed to give the actual temperature measurement of the scene along with a colour video representation. This type of imager is called “Thermovision” or “Imaging Radiometer” and is used mostly for industrial (predictive maintenance, process control, R&D) and medical (human and veterinary) applications. Other imagers are designed primarily for surveillance and/or target acquisition environments. These cameras can be either hand held or fixed mount remote installations. The main differences in surveillance units are the optical elements and the spatial resolution of the imager. Another use is in the aerial surveillance where the thermal imager is mounted on an air platform. These airborne TIR imagers are mounted to an aircraft in gyro stabilized all weather housings. Typically, they are remote controlled and are either alone or paired with a CCD

TV camera and a Laser range finder. Primarily, these systems are used by defence and law enforcement agencies and electronic news gathering teams.

Instead of CCD sensors, most thermal imaging cameras use CMOS Focal Plane Array (FPA) sensors. The most common types are made of materials like InSb, InGaAs, QWIP FPA. The latest sensor technologies use low cost, uncooled microbolometer FPA devices. Their spatial resolution is considerably lower than that of optical cameras, mostly 160x120 or 320x240 pixels, up to 640x512 for the most expensive models. IR Thermographic cameras are much more expensive than their visible-spectrum counterparts, and higher-end models are often export-restricted. Older bolometers or more sensitive models of sensors, such as InSB, require cryogenic cooling, usually by a miniature Stirling cycle refrigerator or liquid nitrogen.

4 IR thermography in marine applications

In 2004, Lloyd's Register, the world's most important ship classification and certification body, made the following prediction: "In the near future, mechanical machinery onboard vessels will also benefit from thermal imaging, especially as a pre-docking strategy to identify and target equipment and systems which need attention as well as to eliminate necessary work." Now IR thermography can do much more and on the market there are numerous companies offering IR thermography services for marine applications [6].

Commercial ships are rewarding objects for thermographic inspections with huge machinery, vast electrical installations, extended electronic systems that can hardly be surveyed by visual inspections. Fire prevention is an important issue and relevant prescriptions are clear. According to the International Convention for the Safety of Life at Sea (SOLAS), the maximum surface temperature of machinery, parts and components in a vessel's engine room should not rise above 220 °C. In order to avoid the ignition and fire development, all surfaces above 220 °C are to be insulated or otherwise protected.

Statistics show that the majority of engine room fires are caused by ruptured fuel or oil pipes which eventually spray fuel/oil on adjacent hot surfaces. This does not happen often, but an engine room fire will have severe and costly consequences for the ship and its cargo, its crew and the shipping company. Smaller deficiencies are numerous, and the piping or cable insulation, as required by the SOLAS rules, often appears to be missing. As engines become more complex and get steered by a growing number of electrical or electronic components, the need for regular inspection and maintenance rises. IR thermography has the advantage of being a non-contact inspection and measurement tool able to display and store exact temperature values as well as visual evidence. Moreover, time-saving becomes an important asset in the shipping business as required inspections have to be done at a fast pace. When something happens to the engines or to other vital installations, the losses by far exceed the investment in such a convincing, time-saving and hence affordable inspection tool as an infrared camera.

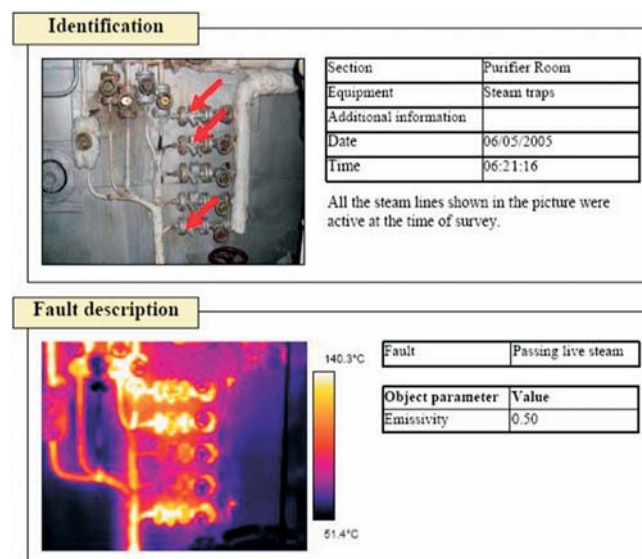
Moreover, thermographic inspections with an infrared camera (Figure 6) will instantly show the thermal condition of electrical circuits, electronic systems and other installations and parts onboard. In more general terms, infrared cameras allow fast and secure inspections in line with the tight scheduling in the maritime trade. Sooner or later, all electrical installations will, by nature, develop faults. On board ships, these faults can be attributed to

vibrations and to poor quality maintenance by crew and/or shipyard repairs, but may also be attributed to incorrect installation. By utilising the thermographic scanning process, these potential failure areas can be discovered before they become a hazard. Thermography can be used in all types of electrical installations, i.e. fuses, contacts, circuit boards, cable runs and other electrical components. Typical areas for scanning are: switch boards in engine control rooms, emergency generators, galleys, laundries, accommodation fans/air conditioners, lifts, bridge consoles, thrusters, light and power distributors, etc. Thermographic scans of electrical installations are possible while systems are operative, without causing costly downtime. In nearly all cases, this form of troubleshooting is extremely cost effective and in some critical situations, the only method available. For commercial and technical managers, this will avoid additional costs associated with potential fires and/or shutdowns of a large electrical system.



Figure 6 Using a hand held thermovision camera on board ship
Slika 6 Uporaba ručne termovizijske kamere na razvodnoj ploči broda

Figure 7 Example page of thermography report (SeaTec)
Slika 7 Primjer stranice termografskog izvješća (SeaTec)



Thermography offers the advantage of not interfering with the vessel's operation. Engines must work at their normal loads and temperatures for good inspection conditions. A three to four hour trip at full speed and in full load condition is ideal to get a clear picture of the ship's electrical and propulsion systems. An example of thermography report is presented in Figure 7.

Severity criteria clearly define the ship engine room maximum temperature at 220 °C. Based on this threshold, thermographers utilize a set of severity criteria [7]:

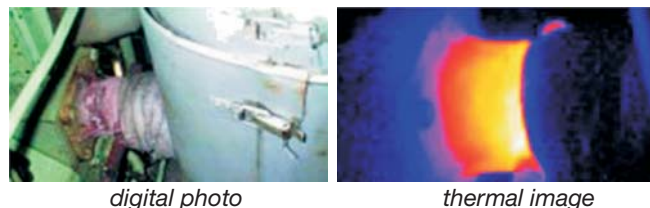
Severity 0: OK (measured temp. < 210.0 °C)

Severity 1: to be monitored (210.0 °C < [measured temp.] < 220.0 °C)

Severity 2: unacceptable deviation (measured temp. > 220.0 °C)

However, severity criteria are void without careful observation and knowledge of the ship's engines. If there is some oil-piping right next to a spot detected as a class 1 spot, the thermographer gives it immediate repair status and upgrades it to Severity 2.

Some results of a thermography inspection done on a passenger ship are presented to illustrate this. The thermography inspection was carried out during the vessel's sea trials by a certified operator from Thermo-protection Ltd, Fredrikstad, Norway (Figures 8 and 9).



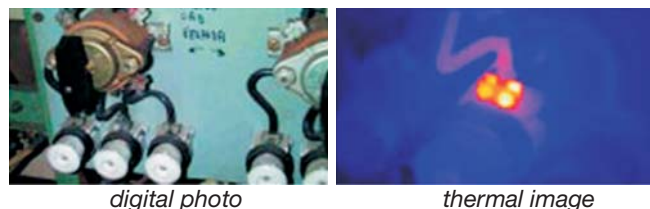
digital photo

thermal image

Location: Engine room
Equipment: Main engines nos. 1-4
Status: Engine parts > 220 °C
Date: 13.06.2002
Time: 10:24:42

Maximum temperature: 329 °C
Normal temperature: 204 °C
Temperature difference: 125 °C

Figure 8 Main engine exhaust
Slika 8 Ispuh glavnog motora



digital photo

thermal image

Location: Emergency switchboard
Equipment: E-Heizung KL W5
Date: 13.06.2002
Time: 14:54:56

Maximum temperature: 156 °C
Normal temperature: 49 °C
Temperature difference: 107 °C
Category of fault A

Figure 9 Electrical switchboard
Slika 9 Električna razvodna ploča

Global Switchgear Services Limited uses the versatility of thermal imaging to carry out electrical and mechanical inspections of marine and industrial equipment (Figures 10 to 12). The company has a wide variety of customers including: commercial and royal navy shipping; nuclear, coal, oil, gas and hydro energy

industries; pumped storage; rail and heavy industry such as steel mills. Global can quickly identify areas of potential concern that if left undetected could cause damage, fires or be potentially life threatening.

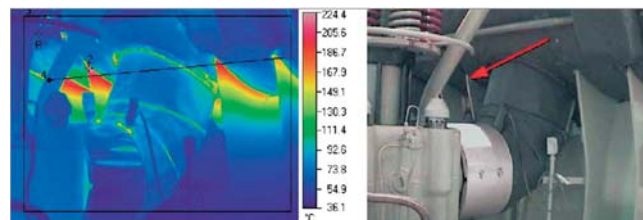


Figure 10 Thermal and digital image of the ship engine exhaust
Slika 10 Toplinska i digitalna slika ispuha brodskog motora

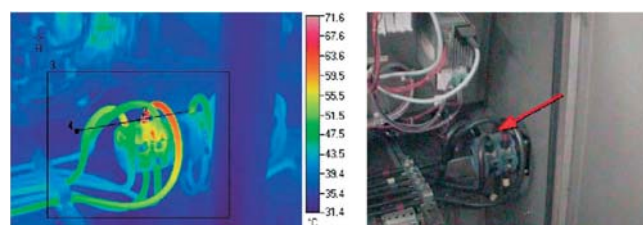


Figure 11 Thermal image showing that there is poor connection on the main switch insulator

Slika 11 Toplinska slika pokazuje da je slaba veza na izolatoru glavnog prekidača

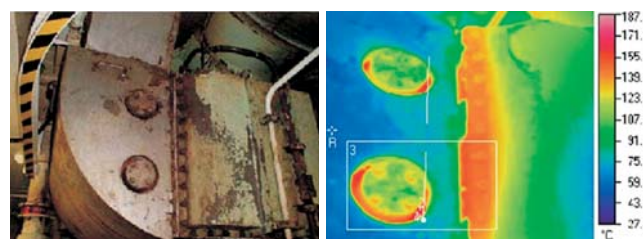


Figure 12 Thermal image of the main engine charge air cooler showing hot spots on seals

Slika 12 Toplinska slika hladnjaka glavnog motora pokazuje vruća mjesta na brtvama

A specialty of Thermowind, a Germany company, is yacht inspection, particularly the search for delamination on the yacht's fibreglass reinforced plastic (FRP) or composite wood-FRP hulls. Delaminations can lead to harmful moisture accumulation within the vessel, which destroys the material and the wooden core of the hull.

The non-destructive nature of thermal imaging was found to be a good tool for yacht service and repair facilities. One of such surveys revealed cracks in both the port and starboard torque boxes in the engine room of a 13.1 m (43-foot) yacht ('PERSISTENCE') [8]. The detection of cracks and their depths was of vital importance in assessing the seaworthiness of the vessel. The information allows the repair facility to give a more comprehensive and accurate estimate as to the cost of repairs, and it also provides the boat owner with visual documentation as to the extent of the damage. In the paper [b], the authors explained the procedures used for determining the presence of cracks, their

location with respect to critical areas, and the depth of these fractures in relation to the extent of the damage.

Thermography finds its largest marine application on cargo ships. Typical applications of thermography on cargo ships are not entirely different from those on land-based facilities. The most common application is the electrical system survey. A typical electrical survey on a ship would cover such items as switchboards, motor controllers, circuit breaker panels and major junction box connections on motors and generators. There are also typical mechanical surveys performed aboard ships for bearings, shaft alignment, steam lines and steam traps. Many of these mechanical surveys would again not be very different from a common land-based survey.

When it comes to cargo surveys, if there are differences in surface temperatures, a trained operator can interpret thermal patterns. This is helpful in dealing with moisture problems in bulk cargoes. As moisture migrates to the cargo surface, creating temperature differences or only slight evaporation of water, a trained operator will spot the thermal pattern. Deterioration of hold insulation can cause great problems when reefer vessels trade in warm areas; the condition of the insulation of reefer holds or freon and brine piping can be verified by using thermography. When claims arise due to cargo temperature problems during discharge, a thermographer can be of great help. From a thermal pattern of cargo pallets inside the holds or inside the reefer containers, a thermographer can locate the source of the problems [9].

Figure 13 **Early detection of engine / equipment failures on cargo ship using thermography**

Slika 13 **Rano otkrivanje kvarova motora/opreme na teretnom brodu uporabom termografije**



Brodarski institute, Marine Research & Special Technologies, have used modern thermography equipment (FLIR P65) and the appropriate software for the measuring and analysis of electrical and mechanical systems in marine applications [10]. IR thermography relating to other NDT methods can solve various problems.

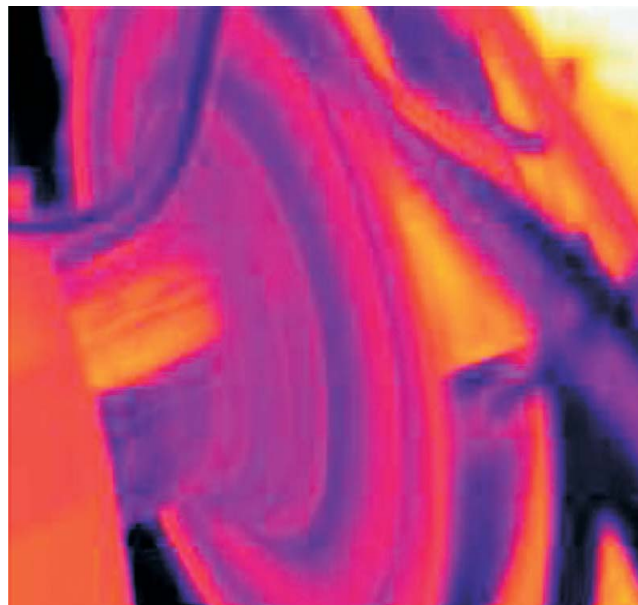
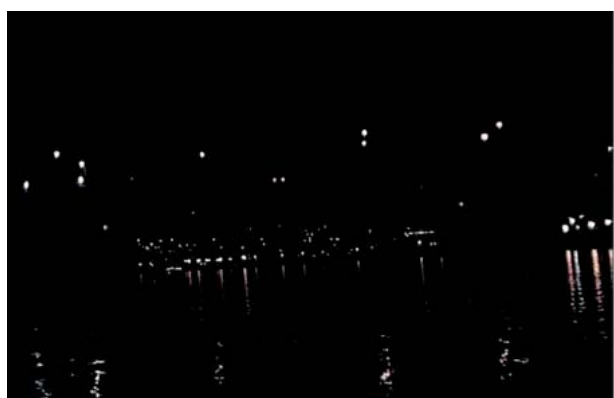


Figure 14 **Example of dynamic investigation of a ship's engine (Brodarski institute)**

Slika 14 **Primjer dinamičkog ispitivanja brodskog motora (Brodarski institut)**

Thermovisions are used for maritime navigation, search and rescue, and security applications. With thermovision navigators have the ability to see in total darkness, through light fog, and smoke.



Visible image



Thermal image

Figure 15 Example of thermovision using for navigation, [11]
Slika 15 Primjer uporabe termovizije u navigaciji, [11]

One of the main tasks in the ecological monitoring of the seas is an operational satellite and aerial detection of oil spillages, determination of their characteristics, establishment of the pollution sources and forecast of probable trajectories of the oil spill transport. There are several airborne remote sensors for application to oil spill detection and assessment. A common sensor is an IR radiometer or an IR/ultraviolet (UV) system. This sensor class can detect oil under a variety of conditions, discriminate oil from some backgrounds and has the lowest cost of any sensor. UV/IR-scanner together with standard remote sensing equipment like Side Looking Airborne Radar (SLAR), photocameras, Imaging Airborne Laser Fluorosensor (IALFS) and Microwave Radiometer (MWR) are available and has been used during routine plain flight [12].

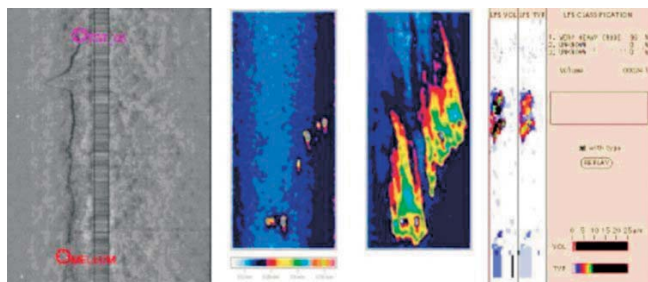


Figure 16 From left to right: SLAR with oil-slick, MWR, IR and LFS information. [12]
Slika 16 Od lijeva na desno: SLAR, MWR, IR i LFS podaci s naftnom mrljom. [12]

5 Conclusion

IR thermography is a mature and widely accepted maintenance technology. Thermography is increasingly used in marine applications for engineering inspection of electrical and mechanical systems of ships and stationary and mobile marine systems. In addition, IR thermography can be used to monitor the quality of the sea water surfaces and to detect any pollution or hazardous materials.

In addition to saving money and increasing uptime, IR thermography can play a major role in maintaining the safety and reliability of marine facilities where a system failure could lead to the loss of a vessel or its crew.

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Modular Wavemaker Design for Harbours and Ships Physical Model Testing

Professional paper

The paper presents design and implementation of a portable modular wavemaker system for producing regular and irregular waves in laboratory basins and flumes. The system was built for the purpose of testing the impact of the sea waves on ships and coastal facilities. It is suitable for generation of all types regular and irregular surface waves. Modular system structure maintains high degree of flexibility and reusability. Finally, the testing process on the physical model of Split harbour is described, and the currently obtained results are shown.

Keywords: wave maker, harbor

Modularni generator valova - konstrukcija i primjena u ispitivanju fizičkih modela brodova i luka

Stručni rad

U tekstu je opisana konstrukcija i primjena prijenosnog modularnog generatora pravilnih i nepravilnih valova u laboratorijskim uvjetima. Generator valova izrađen je za potrebe ispitivanja utjecaja morskih valova na brodove i priobalne građevine. Prikladan je za stvaranje svih vrsta pravilnih i nepravilnih površinskih valova. Modularna izvedba sustava osigurava visoku fleksibilnost i upotrebljivost. Funkcionalnost sustava dana je opisom ispitivanja na modelu luke Split.

Ključne riječi: generator valova, luka

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1 Introduction

Design of new ships and coastal sea facilities requires many tests to be done prior to actual construction. Validity of construction plans is often verified by simulations on numerical models and on scaled-size physical models.

The article discusses design of portable modular wavemaker. The system was designed and built by *Brodarski Institute – Marine Research & Special Technologies, Zagreb Croatia*, in cooperation with *Faculty of Civil Engineering, Zagreb, Croatia*. It is installed in laboratory basin of *Civil Engineering Institute of Croatia*.

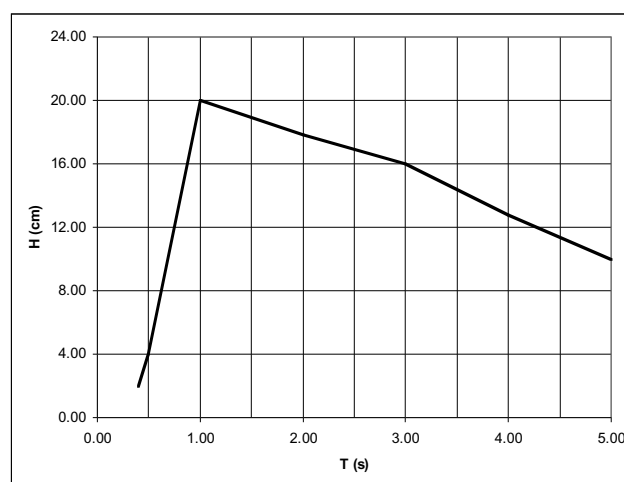
The goal of the project was to build a modular system which can be easily customised according to the end user requirements. Since the wavemaker is to be used mostly for shallow water wave generation, a piston-type paddle was chosen for water displacement. To achieve configurability, wavemaker paddle is broken to sections, each of which can be operated independently.

2 Wavemaker design

Wave producing system is designed as a two-dimensional piston-type wavemaker. Translational movement of the submerged paddles generates waves which propagate perpendicularly to

the paddle surface. It is composed of 6 sections, each 3 m wide. Stroke of the piston equals 0.4 meters. Wave heights of up to 20 cm and wave periods of 0.4 - 5 s are supported. Performance graph of the system is shown in Figure 1.

Figure 1 **Wavemaker performance**
 Slika 1 **Radna svojstva generatora valova**



a - Actuators and mechanical construction

Wavemaker section is composed of the frame, supporting the paddle submerged in the water. The frames are placed at the edge of the basin. Waves generated behind the frame are dampened using porous plates fixed to the frame. The frame and paddles are made of aluminium to minimize weight of the structure, while retaining construction strength and solidity.

Individual sections of the wavemaker can be grouped in various combinations. For example, all six paddles can be merged in a row to form one wide paddle, or they can be placed individually to generate waves from six different directions.

The paddle is actuated by electrical drive installed on the supporting frame, with a rigid link between the drive and the paddle, Figure 2. Optical encoder built in the drive is used to obtain paddle position. The wavemaker group, consisting of 3 sections, is shown in Figure 3.

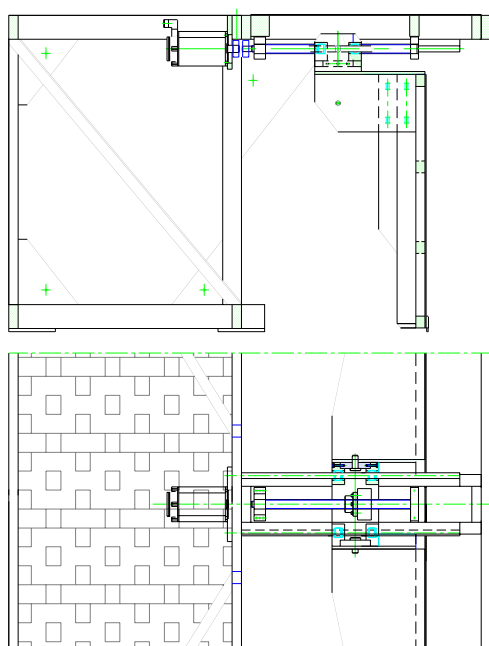


Figure 2 **Wavemaker section design**
Slika 2 **Nacrt sekcije generatora valova**

Figure 3 **Wavemaker - group of 3 sections**
Slika 3 **Generator valova - grupa od 3 sekcije**



Water surface elevation is measured by 20 electrical water level sensors, placed in front of the wavemaker and on the model. Sensors are used to verify the characteristics of the produced waves, and to analyze the behaviour of the water surface in the basin. Measurement is based on electrical resistance of the medium. Sensors used are BM500, manufactured by *Krohne*.

b - Control section

The wavemaker is controlled by personal computer (PC) via a programmable automation controller (PAC).

Paddle control, for all of the six paddles, and other real-time operations are performed by the programmable automation controller, NI CompactRIO 9012. The PC is used to set the experiment parameters, and to run and monitor the experiment.

Data transfer between the PC and the PAC is realized via LAN, over TCP-IP protocol. Interfaces to actuators and level gauges are achieved through a *floating point gate array* (FPGA) card within the PAC.

Block diagram of the wavemaker system is shown in Figure 4. η_a and X_a represent the surface elevation waveform and paddle movement control signals respectively, whereas η_l are the surface elevation signals measured on and in front of the wavemaker paddle. ω_{REF} is the velocity control signal for paddle motor axis, and ρ is the feedback signal of the motor axis angle.

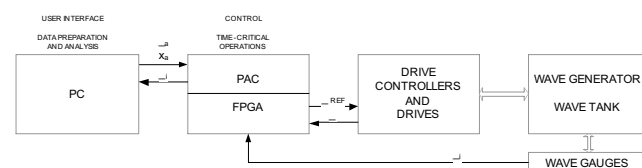


Figure 4 **Functional block diagram of the wavemaker system**
Slika 4 **Funkcionalni blok dijagram generatora valova**

Angle of the rotor is provided by incremental encoders embedded in the motors. Motor drives are equipped with an absolute encoder emulation module that outputs angle in the SSI (*Simple Sensor Interface*) communication protocol. The SSI signal is read in the PAC through a decoder implemented on the FPGA card. Motor control and wave gauges are read as analog voltage and current signals. *Indradrive* series by *Bosch-Rexroth* was used for motors and drives.

c - User interface

The wavemaker system is operated via user application installed on the PC. The following features are supported:

- simultaneous independent control of six paddles
- system configuration and setup of the experiment parameters
- starting/stopping the experiment
- online experiment monitoring
- data logging for offline analysis.

User application consists of two parts, experiment setup and online monitoring. In Figure 5, the user interface for experiment setup is shown. It is used to select paddle groups, set the experiment type and start the wavemaker. The graphs containing paddle movement and surface elevation signals and spectrum are interactively updated to represent the type of experiment set.

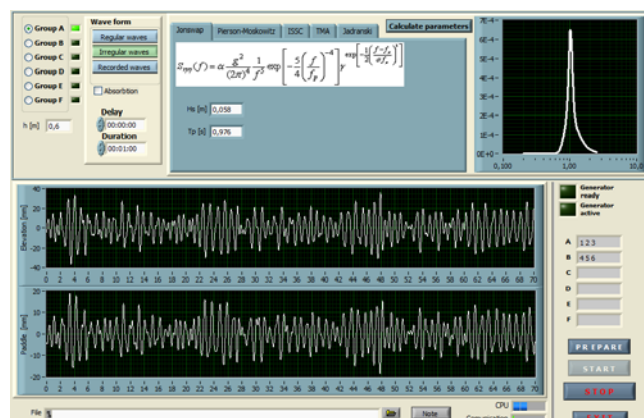


Figure 5 User interface – experiment setup
Slika 5 Korisničko sučelje – postavke eksperimenta

The user interface for online monitoring is displayed upon the start of the experiment (Figure 6). Signals from all level sensors can be displayed, with corresponding energy spectra of the signal.

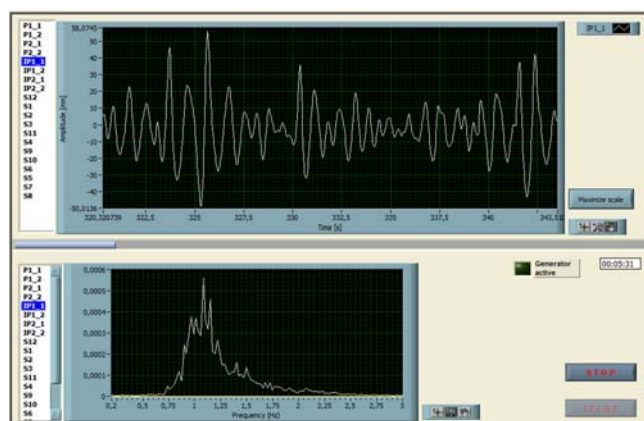


Figure 6 User interface – online monitoring
Slika 6 Korisničko sučelje – nadzor eksperimenta

3 Waveform calculation

Wind blowing across the sea surface transfers energy into the water. Initially, light winds generate small ripples on the water surface. The added roughness causes an increase in energy transfer and waves begin to form. By observing the energy spectra of sea surface elevations, waves with identical characteristics can be reproduced in wave flume or basin. Generation of such waves is performed here by translational motion of a vertical paddle submerged in the basin.

Different waveform calculation algorithm is used for each of the three kinds of wave forms: regular waves, irregular waves, and prerecorded waves.

Generation of all waveforms relies on Biesel equations to transform surface elevation data to paddle movement:

$$S_{\eta}(f) = 0 + ie_0 S_x(f), \quad (1)$$

where S_x represents paddle movement and S_{η} surface elevation data.

For piston-type paddles transfer function e_0 is

$$e_0 = \frac{4 \sinh^2(k_0 h)}{2k_0 h + \sinh(2k_0 h)}, \quad (2)$$

where k_0 is the wave number, and h is the water depth.

a - Regular waves

System design allows for all kinds of regular waves to be generated. The following wave types are presently supported:

- Stokes first-order,
- cnoidal, and
- solitary waves.

Waveform generation for Stokes first-order (sinusoidal) waves is based on the Biesel equations for piston-type wavemaker, (1) and (2).

b - Irregular waves

Irregular waves are used to simulate sea water behaviour in nature more accurately. The waveform is calculated from energy density spectra functions, specifically:

- Jonswap
- Pierson - Moskowitz
- ISSC
- TMA
- Adriatic Sea waves spectrum

Waveform is calculated from the discrete spectrum using the random phase method. Random phase is assigned to each component in the frequency domain [2]. Subsequent use of the Inverse Fast Fourier Transform (IFFT) algorithm provides the time domain representation of the wave train.

Energy density spectrum with added phase data is also used to calculate paddle movement. Prior to IFFT, the Biesel equation is used for each component in the frequency domain (1).

$$x(k) = \sum_{f=f_1}^{f_M} \sqrt{2S_x(f) \Delta f} \sin(2\pi f \Delta t k), \quad (3)$$

where S_x is the wave spectrum, f is the frequency, Δf is the frequency interval, Δt is the time period, f_1 is the starting frequency, and f_M is the maximum frequency.

c - Prerecorded waves

The wavemaker system is able to reproduce waveform made in software or acquired from measurement of natural waves. Paddle position data are computed in the following steps:

- 1 - calculation of wave spectral density,
- 2 - calculating paddle position data – inverse Biesel function in the spectral domain,
- 3 - frequency to time domain transformation.

It is also possible to rescale and resample loaded waveform to match the scaled model values.

4 Testing on the physical model

a - Model description

The model of the Split harbour was built in the *Water Engineering Department* laboratory of the *Civil Engineering Institute of Croatia (IGH)*.

The city harbour of Split is scheduled for large reconstruction in a few years. Different variants of piers and docks are tested with an objective to get the best solution in wind wave suppression in the harbour. Testing is done with both regular and irregular waves. Wind waveforms are simulated using theories for developed sea waves.

Model scale is 1:50, with dimensions of 30 m x 25.0 m. The layout of the model is shown in Figure 7.

The current setup includes two wavemakers placed on the southwest and southeast of the harbour entrance. Each wavemaker is 9 meters wide. Routers are placed at the sides of the wavemakers to minimize wave dissipation between the paddles and the harbour entrance. The model is shown in Figures 8 and 9.

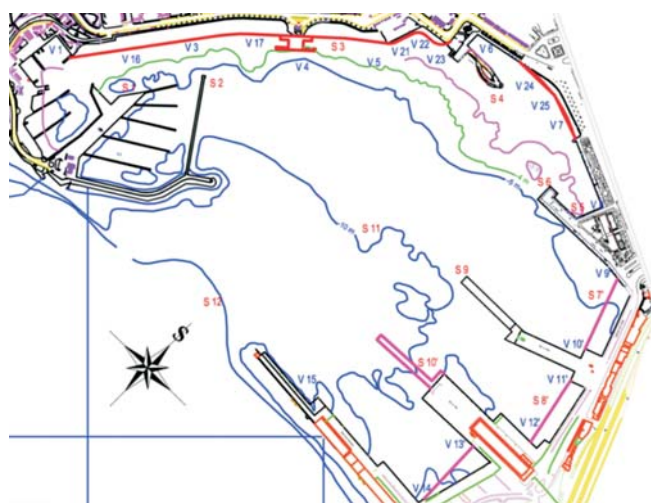


Figure 7 **Model of Split city harbour - layout**
Slika 7 **Model splitske luke – tlocrt**

Figure 8 **Split harbour model - south**
Slika 8 **Model splitske luke - jug**

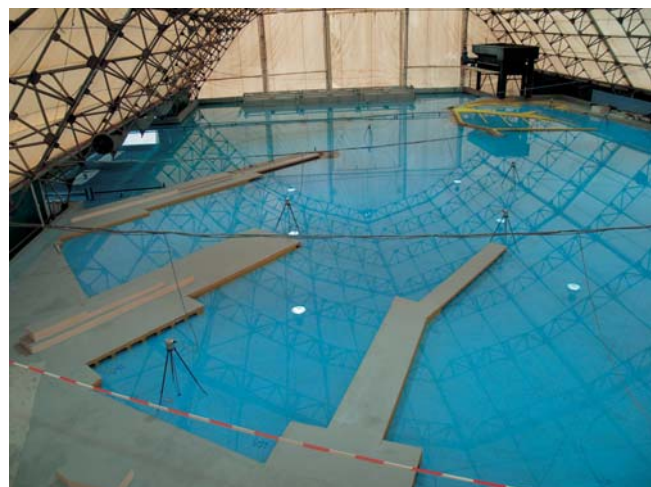
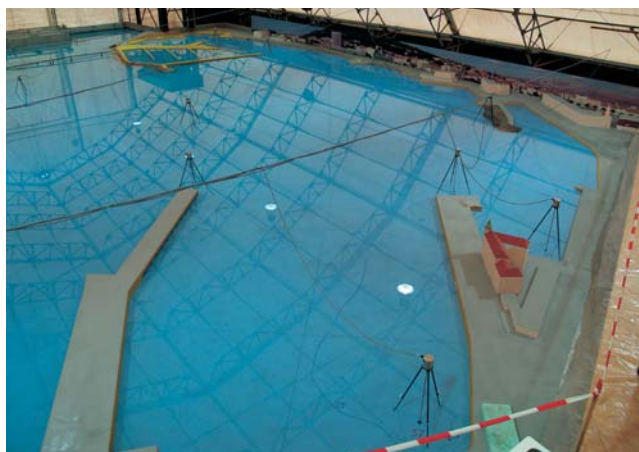


Figure 9 **Split harbour model - north**
Slika 9 **Model splitske luke - sjever**

b - Results

The main goal of model testing of the Split harbour is to analyze the impact of the reconstruction of harbour facilities on the propagation and reflection of sea waves. Yearly measurements of the wind speeds around the Split harbour have provided statistical data regarding the occurrences and directions of sea waves in front of the harbour. Based on the data provided, a set of experiments was prepared (Table 1). The experiment set was conducted on the harbour model, with and without planned harbour modifications. Reconstruction of the harbour is organized in phases. Thus, the impact of each modification can be inspected individually.

Table 1 **Experiment set**
Tablica 1 **Lista valova za eksperimente**

Wave type	Source direction	Wave height $H_n[m]$	Wave period $T_n[s]$	Model wave height $H_m[m]$	Model Wave period $T_m[s]$
Stoke's 1'	SE	2.0	4.38	0.04	0.62
Stoke's 1'	SE	2.9	5.28	0.058	0.75
Stoke's 1'	SE	4	6.2	0.08	0.88
Stoke's 1'	SW	2.1	4.49	0.042	0.635
Jonswap	SE	2.9	6.9	0.058	0.976
Jonswap	SE	3.6	7.7	0.072	1.089
Jonswap	SW	1.2	4.5	0.024	0.636
Jonswap	SW	2.0	5.6	0.04	0.806

Irregular waves were tested using Jonswap spectrum:

$$S_{\eta}^{JONSWAP}(f) = \frac{\alpha g^2}{(2\pi)^4 f^5} \exp\left(-\frac{5}{4}\left(\frac{f_p}{f}\right)^4\right) \cdot \exp\left(\ln(\gamma) \exp\left(\frac{-(f-f_p)^2}{2\sigma^2 f_p^2}\right)\right) \quad (4)$$

$$\gamma = 3.3$$

$$\sigma = 0.07 \quad \text{for } f \leq f_p$$

$$\sigma = 0.09 \quad \text{for } f > f_p$$

where α is the scaling parameter, γ is the peak enhancement factor, f_p is the peak frequency and σ is the spectral shape parameter.

An example of generated wave spectrum is shown in Figure 10. Jonswap spectrum is used with significant wave height of $H_s = 2.9$ m and a peak period of $T_s = 6.9$ s. Density spectrum shown in the figure is measured at the wavemaker, 2 meters in front of the paddles.

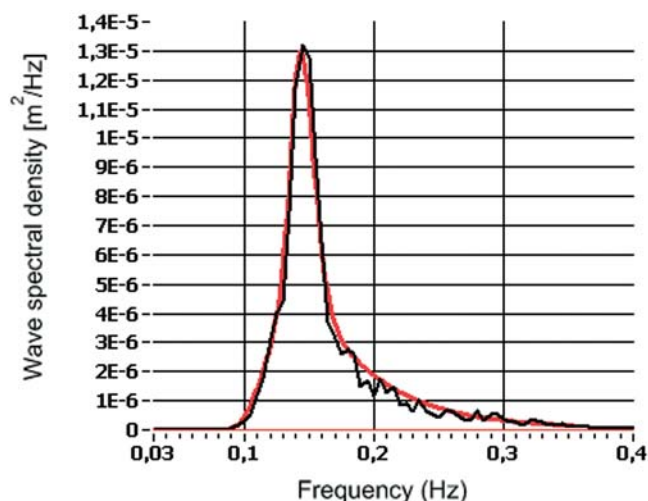


Figure 10 Spectral density of control signal (red) and measured wave elevation (black)

Slika 10 Energetski spektar zadanog (crveno) i izmjerene valnog oblika (crno)

Once the necessary data are collected, they are sorted by measurement site and reconstruction phase for comparison and

Figure 11 Sample of measurement result

Slika 11 Primjer usporednih rezultata



analysis. Figure 11 shows an example diagram of the data collected in one point, for four phases.

Irregular waves from the experiment set are also tested on the numerical model, for additional validation of the obtained results.

5 Conclusion

Modular wavemaker was built for the purpose of testing sea wave's interactions with ships and coastal facilities. The system was designed and constructed by *Brodarski Institute* in cooperation with *Faculty of Civil Engineering, Zagreb*. Modular implementation allows the system to be used in various combinations of paddle widths and wave propagation directions. It can also be reinstalled without difficulties in another basin or flume.

Measured spectral density deviation of obtained waveform to the control signal is within 5%, which proves the system suitable for intended purposes. Further work will focus on expansion of waveform calculation algorithms and improvements of wave making accuracy.

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