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CASTOR – A PROPULSION SHAFTLINE TORSIONAL VIBRATION ASSESSMENT TOOL

Summary

Castor (Computer Assessment of Shaftline TOrsional Response) *Worksheet v2.0* is a spreadsheet tool that simply and efficiently assesses the key torsional vibration response (natural frequency, peak vibration torque, and stress) of a marine propulsion shaftline for a plant equipped with one of the offered slow speed two-stroke diesel engines. The main features of the presented tool are its low number of input data, simple user interface, and meaningful availability of results. This spreadsheet application is intended as a tool to aid machinery designers during the preliminary design phase of a propulsion shaftline. It provides sufficient information to enable designers to select the proper shaftline dimensions concerning its torsional vibration behavior. The internals behind the spreadsheet front-end include a number of simple regression metamodels built by processing the results database of already performed torsional vibration analyses.

Key words: *assessment, shaftline, torsional vibration*

CASTOR – ALAT ZA PROCJENU TORZIJSKIH VIBRACIJA PORIVNIH VODOVA VRATILA

Sažetak

Castor (Computer Assessment of Shaftline TOrsional Response) *Worksheet v2.0* je proračunska tablica koja jednostavno i učinkovito procjenjuje ključne pokazatelje odziva torzijskih vibracija (prirodnu frekvenciju, vršni moment i naprezanje) vodova vratila porivnih postrojenja gonjenih nekim od ponuđenih sporohodnih dvotaktnih dizelskih motora. Glavne značajke ovoga alata su: mali broj ulaznih podataka, jednostavno korisničko sučelje i trenutni izračun rezultata. Ova proračunska tablica je namijenjena projektantima strojarnice kao pomagalo u početnoj fazi projekta. Ona daje dovoljno informacija koje omogućuju projektantu ispravan izbor dimenzija osovinskoga voda s obzirom na njegovo torzijsko vibracijsko držanje. Proračunska tablica objedinjuje niz jednostavnih regresijskih metamodela koji su određeni obradom baze rezultata ranije izvršenih analiza torzijskih vibracija.

Ključne riječi: *procjena, torzijske vibracije, vod vratila*

1. Introduction

The appropriate design of the slow speed propulsion shaftline is one of the most challenging tasks for machinery designers. The shaftline design is mostly influenced by the torsional vibration response of the propulsion plant. However, the final torsional vibration analysis is usually unavailable in the preliminary design phase, since the majority of design data are provisional at that time.

This paper presents a simple design tool [1], developed in the form of the widely used computer spreadsheet, that simply, efficiently, and accurately assesses the key torsional vibration features of the propulsion shaftlines of a selected series of slow speed diesel engines. The presented tool uses a number of metamodels that are built by the regression analysis of already performed vibration analyses.

2. Theoretical foundations

The torsional vibration behavior of complex engineering systems is described by a well-known mathematical model [2, 3]:

$$\mathbf{J}\ddot{\boldsymbol{\theta}} + \mathbf{C}\dot{\boldsymbol{\theta}} + \mathbf{K}\boldsymbol{\theta} = \mathbf{f}_e \,, \tag{1}$$

where $\mathbf{J}, \mathbf{C}$, and $\mathbf{K}$ are the inertia, damping, and stiffness matrices, while $\boldsymbol{\theta}$ and $\mathbf{f}_e$ are the angular displacement and vibration excitation vectors, respectively.

According to the metamodel approach [4], the system response can be expressed by:

$$\mathbf{y} = \mathbf{g}(\mathbf{x}) + \boldsymbol{\varepsilon} \,, \tag{2}$$

where $\mathbf{y} = (y_1, y_2, ..., y_m)$ is the vector of system responses, $\mathbf{g} = (g_1, g_2, ..., g_m)$ is the vector of function approximations, $\mathbf{x} = (x_1, x_2, ..., x_n)$ is the design variable vector, and $\boldsymbol{\varepsilon} = (\varepsilon_1, \varepsilon_2, ..., \varepsilon_m)$ is the vector of approximation errors. In these equations m is the number of system responses and n is the number of parameters (design variables).

2.1. Parameters and metamodels

This work describes a simple propulsion plant model (Fig. 1) characterized by four parameters, namely shaftline stiffness k_t, propeller inertia J_P, turning wheel inertia J_F, and tuning wheel inertia J_T. The design variable vector is then $\mathbf{x} = \left(k_t, J_\mathrm{P}, J_\mathrm{F}, J_\mathrm{T} + b\right)$, where b is the constant that takes into account the inertia of the crankshaft flange connected to the tuning wheel [5].

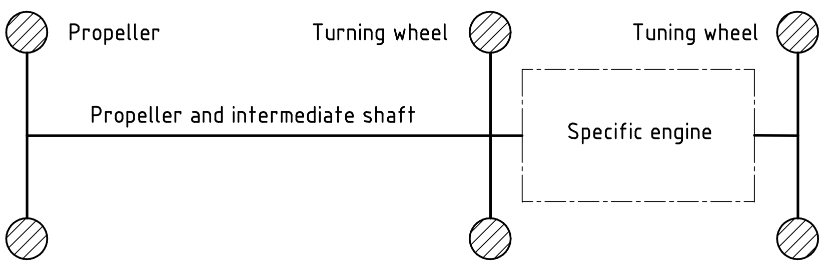

Fig. 1 Propulsion plant model

Slika 1. Model porivnoga postrojenja

The vector of system responses is also simple, i.e. $\mathbf{y} = \left(f_\mathrm{I}, T_\mathrm{C}, T_\mathrm{S} \right)$, where f_I is the system's first natural frequency, while T_C and T_S are the peak vibration torque of the crankshaft and shaftline, respectively [5].

For each of the system responses, a quadratic polynomial metamodel is utilized [5]:

$$g(\mathbf{x}) = a_0 + \sum_{i=1}^{n} a_i \cdot x_i + \sum_{i=1}^{n} \sum_{\substack{j=2, \\ j>i}}^{n} a_{ij} \cdot x_i \cdot x_j + \sum_{i=1}^{n} a_{ii} \cdot x_i^2 , \tag{3}$$

where a_0, a_i, a_{ij}, and a_{ii} are the corresponding metamodel (polynomial) coefficients. Since $n = 4$, the coefficient set totals 15 coefficients. The determination of these coefficients is the main objective of the metamodel-building process.

2.2. Metamodel-building process

When a sufficient database of system responses exists, the unknown metamodel coefficients can be determined by employing the least square technique [4]. We begin by systematically screening the design spaces of typical diesel engine propulsion plants [6]. Until now, more than two million torsional vibration analyses have been performed [1] and hundreds of metamodels have been built. Sample metamodels for typical five-cylinder slow speed diesel engine propulsion plants are provided in Table 1.

Table 1 Metamodel coefficients for propulsion plants with an MAN 5S60MC-C Mk7 engine (torsional stiffness range between 20 and 50 MNm/rad)

Tablica 1. Koeficijenti meta modela za porivna postrojenja s motorom MAN 5S60MC-C Mk7 (područje torzijske krutosti između 20 i 50 MNm/rad)

Coefficient	f_I	T_C	T_S
a_0	3.106E+02	2.649E+02	2.324E+01
a_1	6.780E–06	6.024E–05	6.072E–05
a_2	–4.789E–03	2.703E–02	3.542E–02
a_3	–5.964E–04	–5.057E–02	–2.708E–02
a_4	–6.928E–04	–2.014E–02	–2.241E–02
a_{12}	–1.997E–11	1.243E–10	1.282E–10
a_{13}	–6.320E–13	–5.907E–10	–4.489E–10
a_{14}	–1.352E–11	–9.471E–10	–1.070E–09
a_{23}	–6.286E–09	–8.725E–07	–4.550E–07
a_{24}	–3.322E–09	–3.061E–07	–4.185E–07
a_{34}	1.713E–08	2.047E–06	1.359E–06
a_{11}	–2.111E–14	3.264E–14	5.784E–14
a_{22}	3.559E–08	7.485E–08	2.033E–08
a_{33}	4.766E–09	1.169E–06	4.339E–07
a_{44}	9.664E–09	4.418E–07	7.225E–07

3. Spreadsheet description

The spreadsheet contains one worksheet, which incorporates the project title, subtitle, and input data and results sections. Navigation through the input fields is simply by pressing the Tab key. No result is shown until all required input data are provided.

3.1. Input data section

One of the main features of this spreadsheet tool is the low number of input data (Fig. 2). If a few general data (project title, subtitle, engine type, engine power, and speed) are excluded, a small set of 10 input data is all that is required to assess the torsional vibration response.

Each input data field is accompanied by the appropriate help feature, as well as a flag (in the form of a "<" sign), if the user input is outside the predefined range. The majority of input data are simple and self-explanatory (Fig. 2). The only information that needs further explanation is the equivalent diameter of the propeller shaft.

The equivalent diameter of the propeller shaft is defined as the diameter of an imaginary plain shaft that possesses torsional stiffness equal to the torsional stiffness of the stepped shaft in question. Fig. 3 depicts two typical propeller shaft designs as well as the corresponding equivalent diameters. The upper design shown in Fig. 3 is characterized by an equivalent diameter, d_e, that is nearly equal to the propeller shaft diameter, d_p. The lower design presented in Fig. 3 is somewhat different, resulting in a significantly smaller equivalent diameter, d_e.

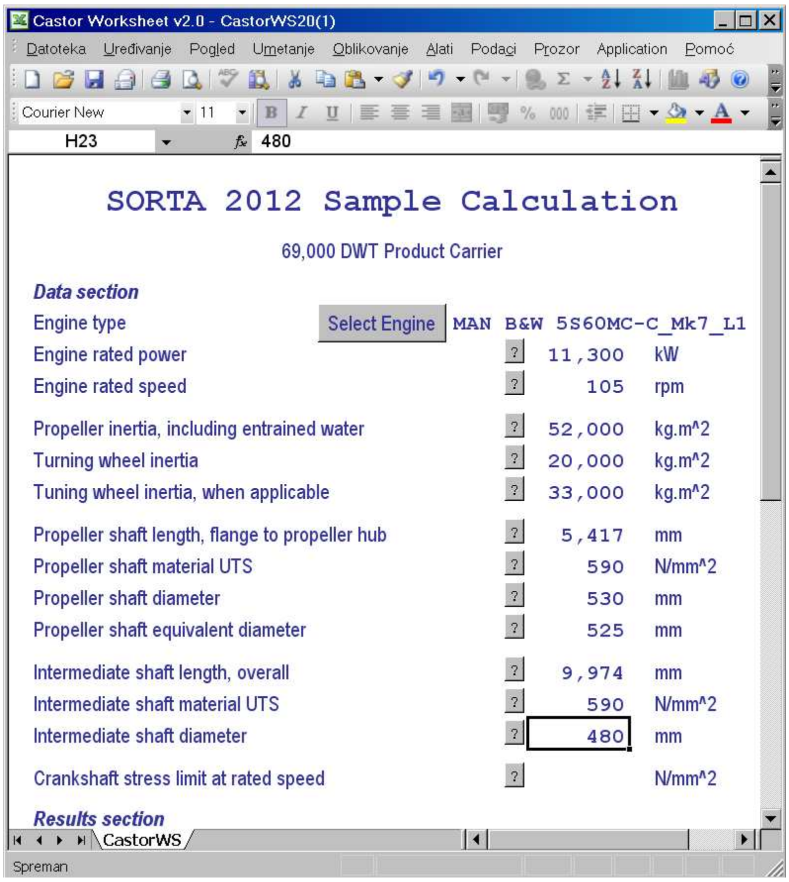

Fig. 2 Input data section of *Castor Worksheet v2.0*

Slika 2. Ulazni podaci proračunske tablice *Castor Worksheet v2.0*

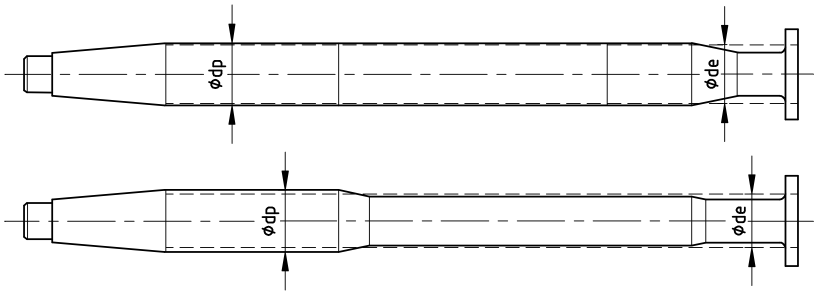

Fig. 3 The equivalent diameter of the propeller shaft

Slika 3. Odgovarajući promjer propelerskoga vratila

The crankshaft stress limit (Fig. 3) is an optional input field. If the user is unaware of the true value, this input field should be left empty and the program will thus calculate a safe estimate.

3.2. Results section

The results section of *Castor Worksheet v2.0* is shown in Fig. 4. These results are sufficient to evaluate the global torsional vibration behavior of the propulsion plant. The results are logically divided into four sub-sections, namely shafting stiffness, the critical speed and the barred speed range, the peak vibration torque and stress of the shaftline, and the stress margins.

The shafting stiffness shown in Fig. 4 is a stiffness value that follows from the program shaftline model. Although it is shown as a result, it is actually an input data that is used to

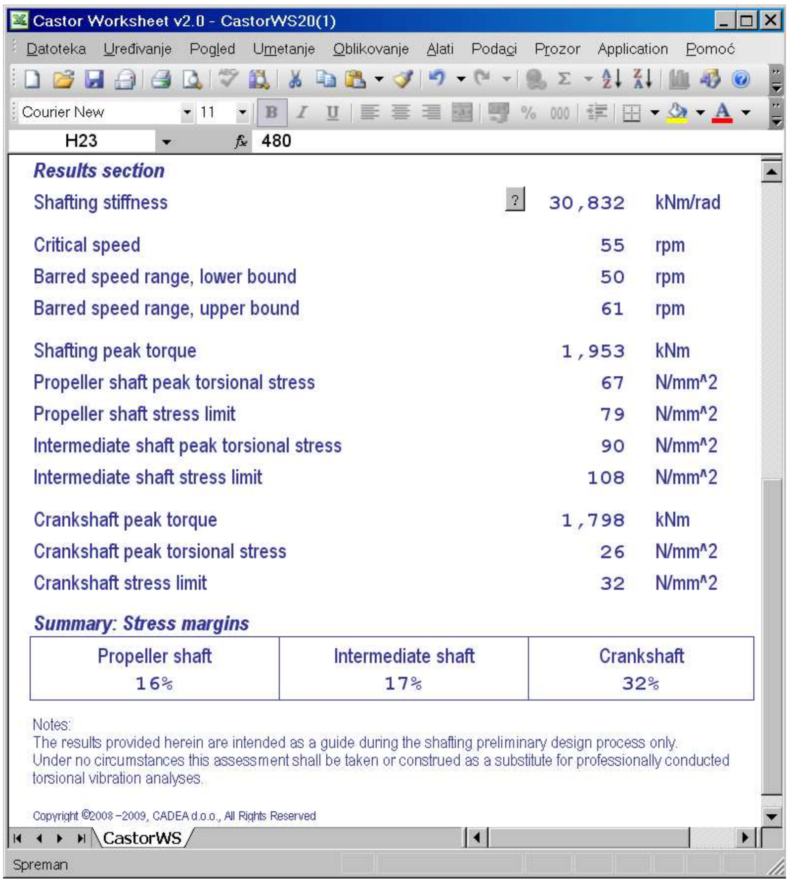

Fig. 4 Results section of *Castor Worksheet v2.0*

Slika 4. Rezultati proračunske tablice *Castor Worksheet v2.0* assess the torsional vibration response. The critical speed and barred speed range results are self-explanatory.

The vibration torque, stress, and stress limit results for the shaftline (Fig. 4) are the peak values related to the critical speed of the propulsion plant, as indicated above. Finally, the stress margins presented at the bottom of the results section are the most informative results. They summarize the overall torsional vibration behavior of the propulsion plant. The stress margin indicated in Fig. 4 is defined as:

$$SM = \left(1 - \frac{\tau_{\mathrm{PEAK}}}{\tau_{\mathrm{LIMIT}}}\right) \cdot 100\,, \tag{4}$$

where τ_{PEAK} and τ_{LIMIT} are the peak torsional vibration stress encountered and the limiting torsional vibration stress evaluated at the corresponding engine speed, respectively. SM values higher than zero denote acceptable designs, whereas negative values represent the cases when peak vibration stresses are higher than the limits imposed.

4. Approximation quality

Approximation quality is the key factor that determines the usability of the proposed metamodels. Therefore, it is closely tracked during the entire metamodel-building process. In general, the approximation quality of the natural frequency and shaftline torque metamodels is high. Natural frequency metamodels deviate from true values far below 1%. Shaftline peak torque metamodels deviate more, with mean deviations approximately 1% or less. However, crankshaft peak torque metamodels deviate to a larger degree, from very accurate to practically useless. Therefore, a specific *standard of quality* is introduced (Table 2) to allow only those metamodels that ensure technically sound approximations. All metamodels provided in *Castor Worksheet v2.0* strictly comply with the terms stated in Table 2.

On average, five-cylinder propulsion plant metamodels provide the most accurate assessments, whereas six-cylinder plant metamodels provide the least accurate ones. Other cylinder number options behave less consistently, providing mixed accuracy assessments.

Table 2 Crankshaft torque approximation quality standard imposed [1]

Tablica 2. Postavljeni standard kakvoće aproksimacije momenta u koljenastom vratilu, [1]

Error / %	Incidence / %	Comment
<10	80.0	At least four out of five assessments
10–20	15.0	At most one out of five assessments
20–22	4.5	At most one out of 20 assessments
22–50	0.5	At most one out of 200 assessments
>50	0.0	Not allowed

5. Example

To demonstrate the utility and overall accuracy of the presented spreadsheet tool, a real shaftline design problem is presented herein. The example shaftline belongs to the 69000 DWT product carrier being built in one of the famous Asian shipyards. Since the propulsion engine contained five cylinders, the shipyard's consultant proposed a shaftline design equipped with a large torsional vibration damper mounted at the crankshaft free end.

The calculation presented herein explores whether a damper-free design is possible, taking into account that the ultimate tensile strength of the shaftline material should be no higher than 590 N/mm^2. All necessary input data are provided in Fig. 2. The corresponding results are given in Fig. 4.

The assessment shows that not only he damper-free design is possible, but also a solid stress margin of 16% is available if the newly proposed design is adopted. After this assessment has finished, a complete (full-size) torsional vibration analysis is performed. Its main results are summarized in Table 3 alongside the *Castor Worksheet v2.0* assessment and corresponding error indicators.

Table 3 Comparison of the calculated and assessed results

Tablica 3. Usporedba izračunanih i procijenjenih rezultata

Propulsion plant feature	Full analysis	*Castor v2.0*	Difference, %
Critical speed (first natural frequency), rpm	54.6	55	0.73
Propeller shaft peak torque, kNm	1893.1	1953	3.16
Propeller shaft peak torsional stress, N/mm^2	64.8	67	3.40
Intermediate shaft peak torque, kNm	1905.0	1953	2.52
Intermediate shaft peak torsional stress, N/mm^2	87.7	90	2.62
Crankshaft peak torque, kNm	1621.8	1798	10.86
Crankshaft peak torsional stress, N/mm^2	23.5	26	10.64

6. Conclusions

This paper presents a simple and user-friendly spreadsheet application that enables machinery designers to quickly and accurately assess the key torsional vibration features of the propulsion plant during the project's preliminary design phase. The assessment tool is based on a number of metamodels, and it is built using the regression analysis of the results obtained from large number of previously performed torsional vibration analyses.

Designers should be aware of the tool's obvious limitations: the numerical procedure used is a statistical estimation only, and thus intrinsically approximate. In addition, the tool is not applicable to propulsion plants that incorporate any of the following devices: the torsional vibration damper, gearbox, flexible coupling, or power take-in or take-off unit.

Acknowledgements

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