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Vertical Motion Assessment in the Concept Design Stage of a Small Cruise Ship

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Abstract. The traditional approach to cruise ship concept design has always focused on satisfying constraints related to propulsive and strength issues, shifting the estimation of other attributes to more advanced design stages. This is the specific case for the motion induced comfort onboard a vessel, a quantity related to the vertical accelerations onboard. The literature does not provide examples of simple formulations that can be used in concept design to estimate vertical motions. To this end, the present work provides a set of simple formulations for estimating vertical motions onboard cruise ships in the concept design stage. Starting from an initial database of 58 hulls, dedicated seakeeping calculations have been carried out for several sailing conditions. As a result, regression formulae have been generated for the TRFs of the vertical motions, providing useful instrument for the concept design predictions of a vessel. This work presents the database and the calculations performed to determine the TRFs, together with the process employed to obtain the simple regressions. An example performed on a vessel not included in the initial database underlines the good approximations provided by the obtained regressions.

Keywords. concept design, cruise ship, regression analysis, comfort onboard

Introduction

Ship design is one of the most complex engineering topics to address [1]. In some cases, it is closely linked to design traditions. However, with the development of increasingly powerful computational techniques, it is now conceivable to abandon these empirical techniques and develop mathematical models specific to different types of ships [2,3,4].

By leveraging these models, a designer could generate multiple designs with and, using multi-attribute decision-making (MADM) methods, select feasible options by com-

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paring them based on attributes and design constraints set by the shipowner. Attributes expressed as function of main ship geometrical parameters [5], refer to technical criteria that define design quality across various fields, such as stability [6], costs, and weight. Currently, no mathematical models exist for luxury cruise ships. In particular, during the conceptual design phase, the characteristics of seakeeping are often overlooked, even though comfort onboard should be one of the primary concerns of these vessels [7]. It is therefore crucial, during this design stage, to identify the main operational areas for cruise ships and develop metamodels for estimating motion transfer functions [8]. Since comfort onboard is closely related to the ship's vertical motions, this paper aims to estimate the transfer functions of vertical heave and pitch motions in head seas [9]. In the early design stages, the estimation of lateral motions could be challenging, due to a difficult estimate of the roll damping and effective metacentric height. Therefore, only bow sea conditions were considered to decouple lateral motions from longitudinal ones. Two families of hulls were modelled, using a design of experiments (DoE) approach [10], developing a design space of 58 hull forms. The transfer functions were computed using a housebuild code based on theories by Salvesen, Tuck, and Faltinsen [11]. It is important to note that the transfer functions of a ship are highly dependent on the shape of the hull. Therefore, this paper aims to develop a methodology capable of reproducing the transfer functions (TRFs) of vertical motions using the main geometric parameters available during the concept design stage. The first section presents the database and the calculation of the transfer functions. The second section introduces the methodology developed for fitting the transfer functions using a composition of sine and cosine terms, where the harmonic coefficients are regressed against the main design parameters. Finally, an application to a ship not included in the database demonstartes the generality of the obtained models.

1. Ship database

The database includes 58 cruise ship hulls. The database consists of two smaller databases created with two different DoEs starting from mother hulls presented in 1.

Table 1. Mother hulls of the space design

ID	L_{WL}	B	T	LCB	C_P	C_X	C_{VP}	L/B	B/T	$L/\nabla^{1/3}$
M0000	170.78	24.750	6.000	88.205	0.725	0.945	0.764	6.900	28.463	6.592
V0000	167.50	24.500	6.000	76.569	0.715	0.941	0.769	6.837	27.917	6.515

The first database originates from a previous stability study [12] in which seven hulls were created using AVEVA© modelling software. Three families of hulls were identified, each with a different midship section coefficient (C_X) of 0.900, 0.945, and 0.990. An initial hull was selected for each family to undergo a Lackenby transformation by varying the prismatic hull coefficient (C_P). By adopting a central composite design with L/B, B/T, C_X, C_P as variables, the first 43 ships were generated. The second database originates from a fourth hull with a C_X of 0.945. A Central Composite Circumscribed (CCC) DoE with three design variables, L/B, B/T, and C_P was applied to this hull.Table 2 summarises the design variables used for the DoE, along with their respective variability ranges.

Table 2. CCF and CCC design space

CCF				CCC			
ID	Min	Mean	Max	ID	Min	Mean	Max
$\frac{L}{B}$	6.600	6.900	7.200	$\frac{L}{B}$	6.540	6.840	7.140
$\frac{B}{T}$	3.900	4.125	4.350	$\frac{B}{T}$	3.897	4.083	4.270
C_P	0.700	0.725	0.750	C_P	0.690	0.712	0.734
C_X	0.900	0.945	0.990	-	-	-	-

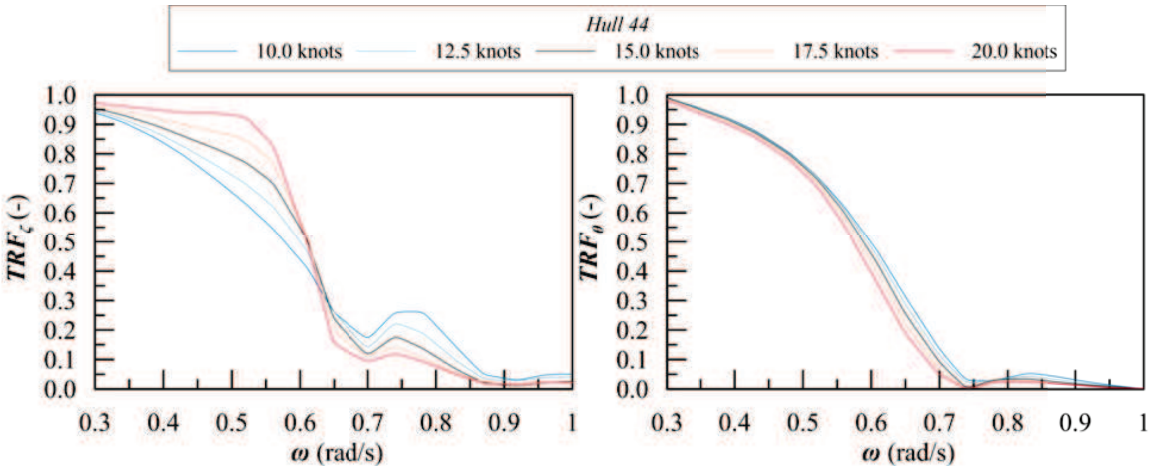

Figure 1. Heave and pitch head seas transfer functions for one of 58 ships in the database at different speeds.

For both databases, the draught T was kept constant at 6 metres.

1.1. Transfer functions

Once the database was defined, the transfer functions for heave and pitch in head sea conditions for regular waves were calculated for each ship. A homemade code, based on the theory by Salvesen, Tuck, and Faltinsen [10], was utilised.
Five typical speeds, ranging from 10 to 20 knots in steps of 2.5 knots, were analysed to cover the most likely operating profile for a cruise ship.
A condition is defined in the program as a particular heading and ship speed for which the ship's transfer functions will be computed as a function of wave frequency (ω) from 0.3 to 1.0 rad/s.
For the sake of brevity, due to the large amount of data, only the example of the heave and pitch amplitude transfer functions for one of 58 ships in the database is presented in Figure 1.

2. Fitting methodology

The following section presents the methodology developed to fit the heave and pitch transfer functions. As shown in Figure 1, the transfer functions follow a somewhat oscillating pattern. Therefore, it is proposed to approximate the transfer functions through a combination of sine and cosine functions:

$$TRF_u = \sum_{i=1}^{N} a_i \cdot cos(i \cdot \omega) + b_i \cdot sin(i \cdot \omega) \tag{1}$$

where u identify heave (ζ) or pitch (θ) motion. N represents the number of terms in the equation. N is determined iteratively through an optimisation process, minimising the sum of squared errors (SSE). The following formula determines SSE:

$$SSE = \sum_{i=1}^{n} (y_i - y_i')^2 \tag{2}$$

where n is the number of ships, y_i is the i-th transfer function value, and y_i' are the fitted transfer function points. Quality of fit has been assured according to the statistical index R^2:

$$R^2 = 1 - \frac{SSE}{SST} \tag{3}$$

where $SST = \sum_{i=1}^{n} (y_i - \overline{y_i})^2$ is the sum of the quadratic deviations of the mean $\overline{y_i}$. The optimisation function is based on Nelder-Mead simplex algorithm [13], where, starting from initial coefficient values, the corresponding coefficients have been computed to minimise the SSE. A preliminary adjustment of the transfer functions is necessary: it has been decided to redefine the reference of the angular functions within the interval [0, π].The sea wave frequency has been normalised to a range between 0 and π by scaling it using its minimum and maximum values. This preserves the relative distribution while ensuring the data are comparable and more suitable for further analysis. To normalise the sea wave frequency, the following expression is introduced:

$$\omega^* = \frac{\omega - \min(\omega)}{\max(\omega) - \min(\omega)} \pi \tag{4}$$

where ω denotes the sea wave frequency, and ω^* is the normalised and scaled version of this frequency. This transformation maps the values of ω to a range between 0 and π, using the minimum and maximum values of the dataset. Specifically, $\min(\omega)$ corresponds to the lowest observed frequency, while $\max(\omega)$ represents the highest. Additionally, the transfer function values were centred around zero using the following transformation:

$$TRF_u^* = 2 \cdot TRF_u - 1 \tag{5}$$

where TRF_u represents the generic motion transfer function of a ship. This linear transformation shifts and scales the original values so that TRF_u^* spans the range [-1,1], with zero as the central reference point. This centring facilitates symmetrical interpretation of the response around a neutral baseline and enhances comparability across different conditions.

Subsequently, each normalised transfer function TRF_u^*, corresponding to a specific ship motion variable ζ and θ, was approximated using 1. This representation expresses the frequency-dependent behaviour of the response as a linear combination of sine and cosine terms at increasing harmonics of the normalised frequency. The coefficients a_{u_i} and b_{u_i} serve as the parameters of the surrogate model, providing a compact and flexible

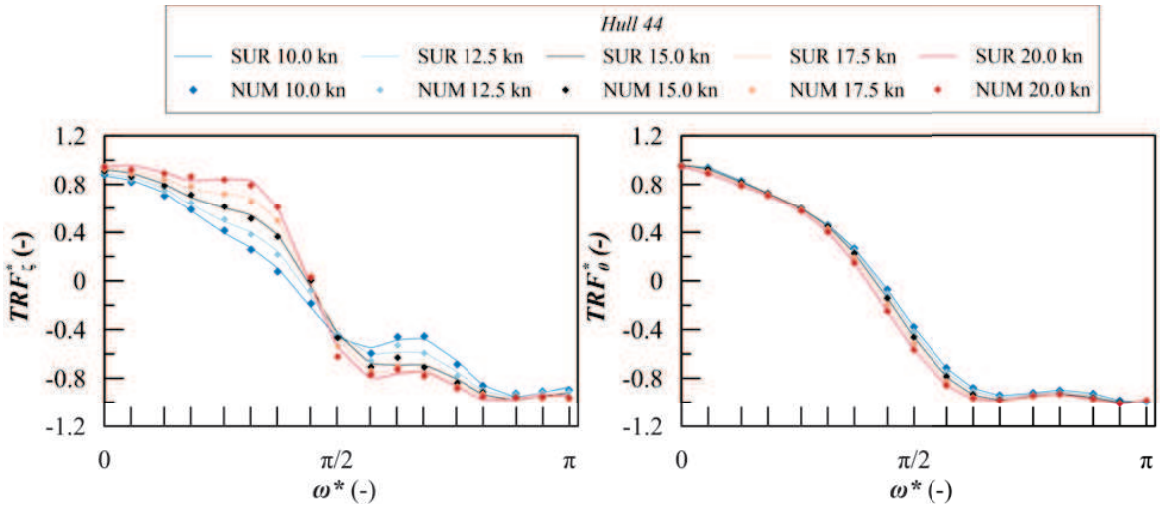

Figure 2. Comparison between numerical (NUM) and surrogate (SUR) TRFs for a ship of the database.

characterisation of the original transfer function. Through a suitable trial-and-error procedure, involving the adjustment of amplitudes, it was observed that only the odd terms contribute to reconstructing the heave transfer function, whereas both even and odd terms are involved in the pitch transfer function. The number of harmonics was determined to formulate an expression to minimise the *SSE* value for the different operating speeds considered. Equations (6) and (7) show the fitting results for the heave and pitch transfer functions. The regression terms for both pitch and heave are 8. Each harmonics have a coefficient a_{u_i} for the cosine terms and b_{u_i} for the sine terms of the generic motion u. They consist of 290 elements (58 ships at 5 different speeds).

$$
\begin{aligned}
TRF^*_\zeta = {} & a_{\zeta_1} \cdot cos(\omega^*) + a_{\zeta_2} \cdot cos(3\omega^*) + a_{\zeta_3} \cdot cos(5\omega^*) + a_{\zeta_4} \cdot cos(7\omega^*) + \ldots \\
& + b_{\zeta_1} \cdot sin(\omega^*) + b_{\zeta_2} \cdot sin(3\omega^*) + b_{\zeta_3} \cdot sin(5\omega^*) + b_{\zeta_4} \cdot sin(7\omega^*)
\end{aligned}
\tag{6}
$$

$$
\begin{aligned}
TRF^*_\theta = {} & a_{\theta_1} \cdot cos(\omega^*) + a_{\theta_2} \cdot cos(2\omega^*) + a_{\theta_3} \cdot cos(3\omega^*) + a_{\theta_4} \cdot cos(4\omega^*) + \ldots \\
& + b_{\theta_1} \cdot sin(\omega^*) + b_{\theta_2} \cdot sin(2\omega^*) + b_{\theta_3} \cdot sin(3\omega^*) + b_{\theta_4} \cdot sin(4\omega^*)
\end{aligned}
\tag{7}
$$

Figure 2 shows a comparison between numerical (NUM) and surrogate (SUR) TRFs for one of 58 ships in the database.

Once the sine and cosine term coefficients were determined, the next step is to establish a relationship between the a_{u_i} and b_{u_i} coefficients and the hull form parameters within the ship database. Multiple Linear Regression (MLR) is adopted as a suitable approach for identifying these relationships [14]. MLR is a widely used statistical method for analysing how a dependent variable is influenced by several independent variables. A full second-order polynomial expansion of the independent variables x_i has been adopted being compliant with the design space creation technique employed. In order to limit the number of regressors, an automated selection procedure is applied. This process systematically eliminates terms that do not significantly contribute to the regression, based on their associated p-values and their effect on the coefficient of determination, R^2 The general form of the MLR model is given as follows:

$$\eta = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i=1}^{k} \sum_{j=1, i \neq j}^{k} \beta_{ij} x_i x_j \tag{8}$$

where η is the generic dependent variabile, x_i or x_j the k independent variables and β_0 the intercept of the model, β_i the linear coefficient, β_{ii} second-order linear coefficients and β_{ij} the mixed coefficients. In this case seven predictors were used: the four project variables identified by the DoE ($L/B, B/T, C_X, C_P, C_{VP}$) to take into account the vertical distribution of volumes and Froudes numbers ($L/\nabla^{\frac{1}{3}}$ (with ∇ hull volume) and Fn) to take into account the different operational profiles.
The key terms in the regression are the vertical prismatic coefficient, which is crucial for seakeeping performance as it defines the vertical distribution of volumes, and the Froude number, which helps establish a single correlation valid for different speeds. Stepwise regression model [15] were applied to estimate the surrogate model terms. The terms of the regression equation were added or removed depending on their respective p-values. Once again, the criterion adopted was to minimise the sum of squared errors (SSE).
Various statistical coefficients were used to assess the quality of the fit. Table 3 summarises the mean absolute percentage error ($MAPE$), R^2, Number of terms n_p, R^2_{adj}, Root Mean Square Error ($RMSE$), the Relative Root Mean Square Error ($RRMSE$) for the different regressed coefficients by heave and pitch. The quality of fit indicated are defined by the following equations:

$$MAPE = \frac{1}{n} \cdot \sum_{i=1}^{n_c} (c_i - c_i') \tag{9}$$

$$R^2_{adj} = 1 - (1 - R^2) \frac{n_c - 1}{n_c - n_p - 1} \tag{10}$$

$$RMSE = \sqrt{\frac{SSE}{n_c}} \tag{11}$$

$$RRMSE = \sqrt{\frac{SSE}{n_c \sum_{i=1}^{n_c} c_i'^2}} \tag{12}$$

where n_c is the number of coefficients to be regressed for different ships and different operating profiles, c_i is the i-th coefficient, and c_i' is the fitted coefficient.

3. Application

The methodology was applied to a test ship that is not part of the database. The main caracteristics and body plan are shown in 3. Transfer functions were calculated using both the numerical and surrogate methods for the same five operating speeds: 10.0, 12.5, 15.0, 17.5, and 20.0 knots. The derived regressions were used to calculate the coefficients

Table 3. Quality of fit

-	a_{ζ_1}	a_{ζ_2}	a_{ζ_3}	a_{ζ_4}	b_{ζ_1}	b_{ζ_2}	b_{ζ_3}	b_{ζ_4}
SSE	0.1064	0.1317	0.0358	0.0137	0.2995	0.0105	0.0107	0.0057
$MAPE$	0.0143	0.0163	0.0084	0.0053	0.0244	0.0044	0.0046	0.0034
R^2	0.9596	0.9558	0.8822	0.8567	0.6876	0.9771	0.9563	0.9522
n_p	17	20	18	22	14	24	26	27
R^2_{adj}	0.9572	0.9526	0.8749	0.8455	0.6728	0.9752	0.9522	0.9475
$RMSE$	0.0004	0.0005	0.0001	0.0001	0.0011	0.0000	0.0000	0.0000
$RRMSE$	0.0012	0.0107	0.0151	0.0132	0.0064	0.0036	0.0034	0.0041
-	a_{θ_1}	a_{θ_2}	a_{θ_3}	a_{θ_4}	b_{θ_1}	b_{θ_2}	b_{θ_3}	b_{θ_4}
SSE	0.3321	0.1049	0.2968	0.0697	0.0635	0.6464	0.0967	0.0647
$MAPE$	0.0217	0.0110	0.0205	0.0084	0.0103	0.0316	0.0101	0.0100
R^2	0.9062	0.8857	0.9137	0.9049	0.8826	0.9072	0.8634	0.9106
n_p	29	24	34	24	33	34	30	34
R^2_{adj}	0.8962	0.8758	0.9026	0.8967	0.8679	0.8953	0.8482	0.8991
$RMSE$	0.0013	0.0004	0.0012	0.0003	0.0002	0.0025	0.0004	0.0003
$RRMSE$	0.0029	0.0154	0.0059	0.0121	0.0024	0.0052	0.0177	0.0040

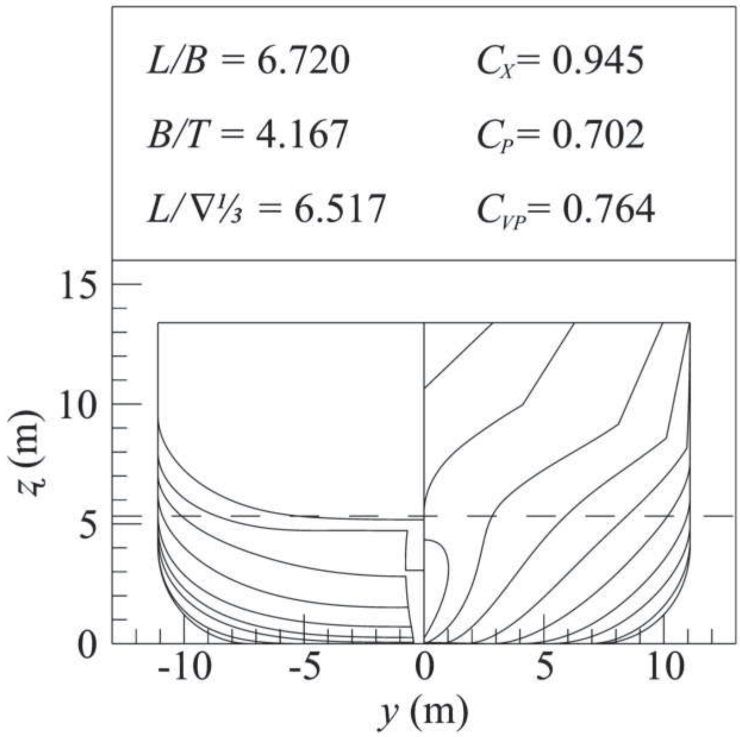

Figure 3. Test ship body plan

a_i and b_i for Eqs. (6) and (7). Table 4 presents the results for the five speeds for both heave and pitch. Equations (6) and (7) were then applied to calculate the heave and pitch transfer functions for the test vessel. A comparison between the surrogate method and the numerical method is shown in Figure 4.

Table 4. Surrogate fit coefficients for each speed

V (kn)	a_{ζ_1}	a_{ζ_2}	a_{ζ_3}	a_{ζ_4}	b_{ζ_1}	b_{ζ_2}	b_{ζ_3}	b_{ζ_4}
10.0	0.841	0.070	0.002	-0.037	-0.287	0.069	-0.089	0.041
12.5	0.909	-0.008	0.030	-0.040	-0.267	0.060	-0.080	0.043
15.0	0.973	-0.077	0.050	-0.040	-0.246	0.065	-0.082	0.049
17.5	1.033	-0.136	0.062	-0.035	-0.226	0.086	-0.095	0.060
20.0	1.088	-0.186	0.065	-0.027	-0.205	0.122	-0.120	0.075
V (kn)	a_{θ_1}	a_{θ_2}	a_{θ_3}	a_{θ_4}	b_{θ_1}	b_{θ_2}	b_{θ_3}	b_{θ_4}
10.0	0.604	-0.036	0.376	0.023	-0.301	0.619	0.124	-0.250
12.5	0.597	-0.004	0.385	-0.008	-0.308	0.640	0.091	-0.255
15.0	0.611	0.027	0.371	-0.038	-0.320	0.626	0.059	-0.249
17.5	0.644	0.059	0.336	-0.068	-0.337	0.578	0.027	-0.233
20.0	0.698	0.091	0.278	-0.099	-0.357	0.496	-0.005	-0.206

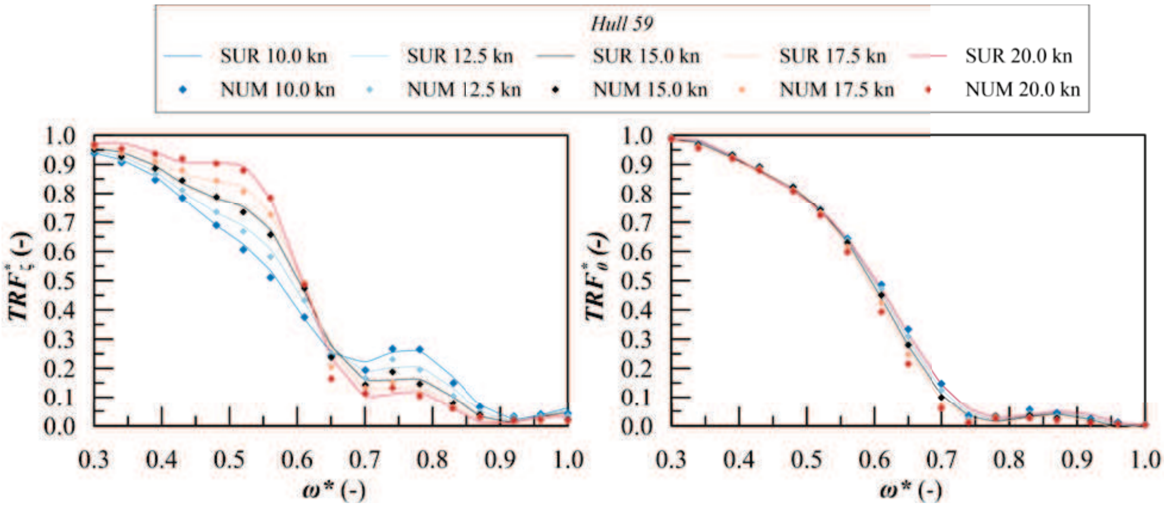

Figure 4. Comparison between numerical (NUM) and surrogate (SUR) TRFs for Hull 59 (test ship).

4. Discussion

Tables 4 and 5 present a comparison between the transfer function values obtained from numerical simulations (TRF_u) and those predicted by the surrogate models (TRF_u^*) for the heave and pitch responses, respectively, across a range of wave frequencies and five different operative profile.

Regarding the heave response (Table 4), the surrogate models provide a satisfactory approximation of the numerical results, with generally moderate deviations across most of the frequency domain. However, larger discrepancies are observed compared to the pitch case, particularly at intermediate and higher frequencies where the response changes rapidly or reaches very low magnitudes. The coefficient of determination R^2 ranges from 0.916 to 0.942, confirming a reasonable predictive accuracy and the practical suitability of the surrogate model for tasks such as optimisation and sensitivity analysis.

In contrast, for the pitch response (Table 5), the surrogate models show even closer agreement with the numerical values, with very small differences observed throughout the entire frequency range. Slight discrepancies appear at low-amplitude regions, but they remain negligible overall. The R^2 values are consistently above 0.989, reaching up to

Table 5. Comparison between the numerical model TRF and the surrogate TRF^* of the heave and pitch at different speeds

	V_1		V_2		V_3		V_4		V_5	
ω	TRF_ζ	TRF_ζ^*	TRF_ζ	TRF_ζ^*	TRF_ζ	TRF_ζ^*	TRF_ζ	TRF_ζ^*	TRF_ζ	TRF_ζ^*
0.30	0.9388	0.9382	0.9443	0.9457	0.9510	0.9535	0.9592	0.9617	0.9683	0.9702
0.34	0.9060	0.9154	0.9145	0.9279	0.9268	0.9417	0.9389	0.9568	0.9540	0.9733
0.39	0.8467	0.8580	0.8649	0.8755	0.8861	0.8951	0.9102	0.9168	0.9364	0.9407
0.43	0.7850	0.7829	0.8120	0.8068	0.8447	0.8355	0.8810	0.8690	0.9199	0.9072
0.48	0.6900	0.6903	0.7355	0.7332	0.7883	0.7836	0.8438	0.8413	0.9033	0.9064
0.52	0.6057	0.6239	0.6678	0.6870	0.7351	0.7531	0.8070	0.8220	0.8785	0.8937
0.56	0.5108	0.5332	0.5819	0.6070	0.6566	0.6728	0.7255	0.7306	0.7844	0.7803
0.61	0.3754	0.3704	0.4321	0.4260	0.4740	0.4629	0.4935	0.4812	0.4852	0.4807
0.65	0.2441	0.2572	0.2516	0.2755	0.2376	0.2785	0.2055	0.2663	0.1649	0.2389
0.70	0.1939	0.2228	0.1664	0.1918	0.1433	0.1617	0.1324	0.1326	0.1135	0.1045
0.74	0.2671	0.2554	0.2311	0.2022	0.1873	0.1605	0.1518	0.1302	0.1325	0.1115
0.78	0.2649	0.2590	0.1952	0.2039	0.1470	0.1621	0.1151	0.1335	0.1040	0.1182
0.83	0.1492	0.1686	0.1049	0.1301	0.0792	0.0994	0.0625	0.0764	0.0589	0.0612
0.87	0.0650	0.0740	0.0487	0.0523	0.0373	0.0350	0.0312	0.0219	0.0286	0.0132
0.92	0.0327	0.0235	0.0295	0.0164	0.0198	0.0122	0.0178	0.0108	0.0175	0.0123
0.96	0.0401	0.0378	0.0334	0.0336	0.0206	0.0309	0.0166	0.0297	0.0213	0.0299
1.00	0.0418	0.0618	0.0338	0.0543	0.0207	0.0465	0.0169	0.0383	0.0183	0.0298
R^2	0.916		0.924		0.931		0.937		0.942	
ω	TRF_θ	TRF_θ^*	TRF_θ	TRF_θ^*	TRF_θ	TRF_θ^*	TRF_θ	TRF_θ^*	TRF_θ	TRF_θ^*
0.30	0.9912	0.9838	0.9936	0.9852	0.9936	0.9857	0.9907	0.9854	0.9854	0.9842
0.34	0.9686	0.9822	0.9689	0.9788	0.9673	0.9731	0.9625	0.9649	0.9556	0.9544
0.39	0.9332	0.9289	0.9336	0.9272	0.9314	0.9230	0.9262	0.9164	0.9188	0.9073
0.43	0.8932	0.8761	0.8928	0.8788	0.8907	0.8789	0.8862	0.8764	0.8789	0.8713
0.48	0.8228	0.8091	0.8229	0.8149	0.8213	0.8170	0.8148	0.8154	0.8070	0.8100
0.52	0.7456	0.7411	0.7465	0.7442	0.7419	0.7426	0.7344	0.7361	0.7235	0.7249
0.56	0.6445	0.6431	0.6393	0.6394	0.6302	0.6304	0.6154	0.6162	0.5973	0.5968
0.61	0.4868	0.4729	0.4724	0.4590	0.4505	0.4410	0.4240	0.4189	0.3929	0.3928
0.65	0.3337	0.3172	0.3095	0.2985	0.2800	0.2776	0.2475	0.2545	0.2149	0.2292
0.70	0.1480	0.1464	0.1249	0.1287	0.1004	0.1113	0.0705	0.0941	0.0595	0.0771
0.74	0.0346	0.0607	0.0238	0.0482	0.0120	0.0370	0.0140	0.0270	0.0115	0.0183
0.78	0.0321	0.0283	0.0337	0.0216	0.0330	0.0161	0.0302	0.0118	0.0247	0.0086
0.83	0.0552	0.0376	0.0433	0.0341	0.0354	0.0310	0.0289	0.0284	0.0249	0.0263
0.87	0.0441	0.0498	0.0331	0.0447	0.0259	0.0398	0.0204	0.0351	0.0189	0.0307
0.92	0.0241	0.0374	0.0182	0.0288	0.0140	0.0211	0.0113	0.0143	0.0103	0.0085
0.96	0.0125	0.0110	0.0096	0.0033	0.0082	-0.0028	0.0072	-0.0073	0.0053	-0.0102
1.00	0.0040	0.0030	0.0036	0.0029	0.0040	0.0037	0.0040	0.0054	0.0029	0.0080
R^2	0.989		0.990		0.990		0.991		0.992	

0.992, indicating a high level of reliability of the surrogate model, even for computationally demanding applications.

5. Conclusion

The proposed method demonstrates a god performance in the most critical frequency ranges of a ship's transfer function, those that most significantly influence onboard motion and passenger perception. This makes it a robust foundation for the development of a metamodel aimed at estimating statistical indices related to onboard comfort, such as the Motion Sickness Index (MSI). The MSI, in turn, can be used as a key attribute within a broader multi-criteria decision-making framework, supporting the evaluation and comparison of cruise designs or operational scenarios with respect to passenger wellbeing.
Despite its advantages, the method exhibits certain limitations at higher frequency ranges, where the approximation errors tend to increase. This is likely due to the decreasing influence of high-frequency components on the overall response, combined with the finite number of harmonics used in the surrogate model representation.
Nevertheless, the proposed approach is intended as an initial step in the proof of concept upon which future refinements can be built. One clear direction for further development is the inclusion of phase information in the modelling process. While the current formulation focuses solely on the amplitude of the transfer function, incorporating the phase component would enable a more complete characterisation of the system dynamics.

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