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Identification of longitudinal and transversal dynamics of a fast ferry

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Abstract: An analysis of the system identification methods have been carried out and a new alternative approach is proposed in order to estimate models for heave, pitch and roll dynamics of a high speed craft. As starting point, a first approach resolves the identification subject as an optimization problem to fit the best model, and uses genetic algorithms and nonlinear least squares with constraints methods applied in the frequency domain. The second and definitive one suggests a new parameterization which facilitates obtaining high quality starting values and avoids non-quadratic functions in the cost function. At last it is shown an example in which the two approximations are applied and compared.

1. INTRODUCTION

One of the most important steps in the control of process is the identification of an adequate model of a continuous linear system. The suitability depends strongly on the particular application of the system.

The response of a ship advancing in a seaway is a complicated phenomenon involving the interactions between the vessel dynamics and several distinct hydrodynamic forces. The study is focused on a fast ship advancing at constant mean forward speed with arbitrary heading in a train of regular sinusoidal waves. All ship responses are non linear to some extent, but experimental and theoretical investigations have shown that a linear analysis will yield good predictions over a wide variety of sea conditions.

The past decade has seen a growing interest on high speed crafts for both cargo and passenger transportation. Different designs have been considered, and a significant attention has been focused on fast mono-hull displacement ships. One of the objectives in the design is passenger comfort and vehicle safety. Vertical accelerations associated with roll, pitch and heave motions are the main cause of motion sickness. For that reason, a first goal is to damp these three movements.

Therefore, it is necessary to build mathematical models of the dynamical system for the design of a controller which achieves the reduction of the heave, pitch and roll motions, and consequently reduces of the motion sickness index.

As an initial study, previous researches of the work group have studied the longitudinal and transversal dynamics separately. Firstly, heave and pitch motion for the case of head seas (angle of incidence μ=180º) have been studied (Aranda *et al*., 2004a), then actuators are modeled and different controllers are designed (Aranda *et al*., 2002a, 2002b, 2005; Cruz *et a.,* 2004) in order to achieve heave and pitch damping and with successful results. Secondly, in the same way, the rolling response has been modeled, with the design of actuators and controllers for the case of lateral waves (μ=90º) (Aranda *et al*., 2003, 2004b).

In the present work the study has been extended to the analysis of heave, pitch and roll dynamics with different incidence angles between 180 degrees and 90 degrees.

There are many publications related to the ships modelling (Fossen, 2002; Lewis, 1989). In this work modeling is obtained from system identification method (Söderström and Stoica, 1989; Pintelon and Schoukens, 2001), which is based on the observed input-output data.

As a starting point, the ideas set out in (Aranda *et al*., 2004a) to identify continuous transfer functions of heave and pitch modes of a high speed craft with μ=180º are followed, in which the problem is set out as a nonlinear optimization problem with nonlinear constraints. There, the solution is described with a hybrid optimization method (genetic algorithms + nonlinear optimization with constraints from the Matlab toolbox). However, when this technique extends to identification of dynamics with incidence angles different from 180º, the obtained models are not too accurate. In addition, it is shown that the method does not guarantee the best linear approximation, because the non-quadratic functions add computational charge.

Thus, from this first approach, some questions and modifications are raised (following the suggestions of Pintelon and Schoukens (2001)), in order to obtain models more efficiently. There, these new improvements and their application are depicted.

This paper is organized as follows. Firstly it is presented a first approach in system identification method, where the criterion of fitness is developed. Secondly, it is seen the discussion on identification and the new solution of the problem. Finally, an example is shown in order to prove the improvement of the new approach.

2. FIRST APPROACH TO SYSTEM IDENTIFICATION

The system identification problem is to estimate a model of a system based on observed input-output data. This procedure involves three basic steps: the input-output data, a set of candidate models (the model structure), and a criterion to select a particular model in the set, based on the information in the data (the identification method).

2.1 The input-output data

Experiments in CEHIPAR (El Pardo Model Basin, Spain) are made with scaled down replicas (1:25 and 1:40) of the TF120 ferry. Tests with diverse types of waves, ship speeds and different angles of incidence have been made. Also CEHIPAR has a simulation program PRECAL, which reproduces specified conditions and uses a geometrical model of the craft to predict its dynamic behavior. PRECAL solves the physical equations of the dynamic of a ship by using the Band Theory (Fossen, 2002). The program gives amplitude and phase data at different frequencies, and these are the experimental input-output data used for the identification. Simulations are tried with regular waves, with the following characteristics:

- Natural frequency between the rank [0.393, 1.147] rad/s,
- Incidence angle μ= 90º, 105º, 120º, 135º, 150º, 165º, 180º,
- Ship speed 20, 30 and 40 knots.

Tests consist of excitation of the ship system by the sea wave (the input is the wave height (m)). For each type of wave (wave frequency and incidence angle), the ship responses are measured. In this case, the study is focused on heave, pitch and roll modes. Thus, the given outputs are the following (BAZAN, 1995): amplitude and phase of the total force of heave excitation, amplitude and phase of the total moments of pitch and roll excitation, amplitude and phase of the heave motion response, and amplitude and phase of the pitch and roll motion responses. The block diagram of the system to identify is depicted in Figure 1.

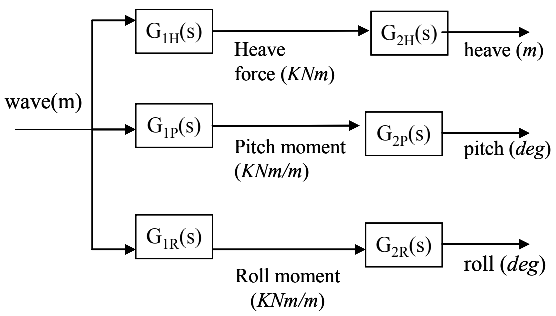

Fig.1. Block diagram of the system.

The transfer functions to be modelled are: $G_{1H}(s)$ from wave height to heave force, $G_{2H}(s)$ from heave force to heave motion, $G_{1P}(s)$ from wave height to pitch moment, $G_{2P}(s)$ from pitch moment to pitch motion, $G_{1R}(s)$ from wave height to roll moment, and $G_{2R}(s)$ from roll moment to roll motion.

Based on the principle of linear superposition, it yields that

$$G_Z(s) = G_{1Z}(s)\cdot G_{2Z}(s); Z = \{H: Heave, P: Pitch, R: Roll\} \quad (1)$$

Therefore, the given input-output data are used to identify directly the transfer functions $G_Z(s)$ whose input is the wave height and the outputs are the heave, pitch or roll motions; and similarly the transfer functions $G_{1Z}(s)$, whose input is the wave height, and the outputs are heave force, pitch moment, or roll moment. The identification of the transfer functions $G_{2Z}(s)$ are made indirectly, by using (1).

2.2 The criterion of fit

Once the experiments with the system to model are designed, and the obtained input-output data are examined, next step is to select and define a model structure and give a criterion of fit so that the best model which reproduces the dynamic of the ship system more suitably is computed.

The system identification gives the mathematical model in the form of transfer function. Data given by the simulator PRECAL are in the frequency domain. Therefore, a parametric estimation of the transfer functions in the frequency domain will be carried out.

In this way, consider the general parameterized transfer function (2). The estimation of the model consists of the fitness of the frequency response or Bode diagram of a transfer function with a fixed number of poles and zeros (model structure) to the actual measured data.

$$G(s,\theta) = \frac{B(s,\theta)}{A(s,\theta)} = \frac{b_{m+1}s^m + b_m s^{m-1} + ... + b_1}{s^n + a_n s^{n-1} + ... + a_1} \quad (2)$$

For the identification of the model it is employed a parametric method, characterized by the adjustment of the collected data to an estimated parameter vector θ,

$$\theta = (b_{m+1}, b_m, b_{m-1}, ..., b_1, a_n, a_{n-1}, ...a_1) \quad (3)$$

The parameter vector θ is determined as the vector that minimizes the sum of squared equation errors. Thus, it is defined the cost function $J(\theta)$:

$$J(\theta) = \sum_{i=1}^{N} \left| G(j\omega_i) - G(j\omega_i, \theta) \right|^2 \quad (4)$$

Thus, the parameter vector is obtained such

$$\hat{\theta} = \arg\min_{\theta} J(\theta) \quad (5)$$

In order to solve the minimization problem, and consequently estimate a transfer function model, the following factors must be considered:

i) A physical insight of the dynamic of the system states that at low frequencies roll and pitch responses amplitudes must tend to zero, while the heave response amplitude must tend to one. That is

- Heave: $G_{1H}(j\omega), G_{2H}(j\omega) \xrightarrow[\omega \to 0]{} 1$
- Pitch: $G_{1P}(j\omega) \xrightarrow[\omega \to 0]{} 0$ (6)
- Roll $G_{1R}(j\omega) \xrightarrow[\omega \to 0]{} 0$

that it is translated for the parameter vector θ:

- $\mathrm{G}_{1\mathrm{H}}(\mathrm{s}), \mathrm{G}_{2\mathrm{H}}(s) \to |a_1| = |b_1|$
- $\mathrm{G}_{1\mathrm{P}}(s) \to |b_1| = 0$ (7)
- $\mathrm{G}_{1\mathrm{R}}(s) \to |b_1| = 0$

ii) The system must be stable. Thus, to ensure the stability of the estimated models the transfer functions are re-parameterized as

$$G(s,x) = \frac{x_{n+m+1}s^m + x_{n+m}s^{m-1} + \ldots + x_{n+1}}{\prod_{i=1}^{npc}\left(s^2 + 2x_{2i-1}s + x_{2i-1}^2 + x_{2i}^2\right)\prod_{i=1}^{nps}\left(s + x_{npc+i}\right)} \tag{8}$$

with $n = nps + npc$ and

$$\begin{cases} x_{2i-1} < -0.005 \text{ for i} = 1, 2, \ldots, \text{npc} \\ x_{npc+i} < -0.005 \text{ for i} = 1, 2, \ldots, \text{nps} \end{cases} \tag{9}$$

Then, the parameters x are obtained by minimizing

$$\sum_{i=1}^{N}\left|G(j\omega_i) - G(j\omega_i, x)\right|^2 \text{ subject to (7) and (9)} \tag{10}$$

Starting values are obtained via a genetic algorithm (Michalewicz, 1999) or generated at random. The solution of (10) is used as initial guess for a multistep procedure, also called alternating variables method (Fletcher, 1991).

The multistep procedure is motivated by the fact that direct measurements of the heave force to heave motion, pitch moment to pitch motion, and roll moment to roll motion dynamics are not available. Therefore, transfer functions $G_{1Z}(s)$ and $G_Z(s)$ are directly estimated by minimizing (10). The solution given is used to identify the transfer function $G_{2Z}(s)$ (Z = H, P or R) by minimizing

$$\sum_{i=1}^{N}\left|G_Z(j\omega_i) - G_{1Z}(j\omega_i, x_a)G_{2Z}(j\omega_i, x_b)\right|^2 \tag{11}$$

subject to (7) and (9). Successively x_a is determined for fixed x_b, and x_b is determined for fixed x_a, with $G_Z(j\omega_i)$ the simulated data and Z = H, P or R.

3. DISCUSSION ON THE IDENTIFICATION METHOD

In this section some suggestions (Pintelon and Schoukens, 2004) are made about the method described in the previous section, which will give out a new improved approach for the identification method. The fundamental questions are raised about: the excitation signal and model structure, the parameterization of the transfer functions, the choice of the starting values, and the multistep procedure.

3.1 Choice of the excitation signal and the model structure

Since the heave, pitch and roll dynamics of a ship are described by nonlinear differential equations (Kenevissi, 2003), it is important the choice of the excitation signal. It is shown that the frequency response of a system depends on the class of excitation signal used.

It is important that the type and power of the waves used for the linear identification experiment (linear approximation of the true nonlinear behaviour) coincides with the type and the power of the waves that the controller or actuators elements should compensate for in real life.

In this particular case the identification and validation are performed with respectively regular (single sines) and irregular (broadband signal) waves. The frequency rank and height of the sinusoidal signal used belong to the frequency spectral and amplitudes of the irregular waves, which are those that the real system could find.

In system identification the determination of model structure is an important aspect, so it is necessary to employ methods to find an appropriate plant model. In practise identification often is performed for an increasing set of model orders. Then one must know when the model order is appropriate. Concerning this problem of choosing the model structure, the following question is raised: In the comparison between the frequency response or Bode diagram of the modelled transfer functions and the data, it is observed that there is a discrepancy in the high frequency range. Thus one can wonder whether these differences are due to the intrinsic nonlinear behaviour of the heave, pitch and roll motions, or to a deliberate simplification of the linear dynamics.

For that reason, it is proposed that one way of guaranteeing that the best (in least square sense) linear approximation has been obtained, and therefore, that all the remaining errors are then due to nonlinear effects, is the utilization of classical model selection criteria such as the Akaike Information Criterion (*AIC*), and the whiteness test of the residual applied to the identification data (Ljung, 1999; Söderström and Stoica., 1989).

Therefore, in the new approach of the identification method, these criterions are applied in order to ensure the best model structure and thus the best linearization.

3.2 Parameterization issues and starting values

Originally, in order to ensure the system stability, a re-parameterization of the transfer functions is carried out (8). Consequently the constraint (7) results in a cost function (10) that is strongly non-quadratic function of the model parameters (for example, the constraint $|a_1| = |b_1|$ is a strongly nonlinear function of x). As a consequence of this parameterization, several disadvantages appear:

- Because of the nonlinear minimization and nonlinear constraints, the generation of starting values is non-trivial, especially for high order systems.

- The selection of the model is more complicated since the number of real *nps* and complex conjugate *npc* poles should be estimated. However, parameterization (2) only needs the number of total poles *n*.

- The classical derivative based nonlinear optimizers (Fletcher, 1991) will degenerate for multiplicities higher than one. On the other hand, parameterization (2) does not impose nor exclude particular pole positions and pole multiplicities.

These problems can be avoided as follows:

- Using parameterization (2), cost function can be written as

$$\sum_{i=1}^{N}\left|G(j\omega_i)-\frac{B(j\omega_i,\theta)}{A(j\omega_i,\theta)}\right|^2 \text{ subject to (7) and (9)} \tag{12}$$

Thus, the nonlinear constraint $|a_1| = |b_1|$ can easily be satisfied by minimizing the cost function two times: first subject to $a_1=b_1$, next subject to $a_1=-b_1$, and finally selecting the solution with the smallest cost function.

- Applying the same trick, high quality starting values for (12) can be obtained via the linear least squares estimate:

$$\sum_{i=1}^{N}\left|A(j\omega_i,\theta)G(j\omega_i)-B(j\omega_i,\theta)\right|^2 \text{ subject to (7)} \tag{13}$$

- Concerning the stability constraint, one possible approach for imposing it is during the minimization, as proposed in the previous method and in Van Gestel *et al.* (2001).

3.3 The multistep procedure

The multistep procedure proposed in previous section to minimize (11) is usually inefficient and is not guaranteed to converge to a stationary point. Hence, another proposed approach is to minimize simultaneously x_a and x_b. If parameterization (2) is used, this scheme will be easier since high quality starting values are available via (13).

4. THE ALTERNATIVE APPROACH TO THE IDENTIFICATION PROBLEM

In this section it is described the alternative procedure developed for the identification of the models, considering all the suggestions raised in previous sections.

4.1. Collecting input-output data

For each particular case of force, moment or motion of heave, pitch and roll responses, initially there are a set of *N* experimental points of amplitude $|G(j\omega_i)|$ and phase $arg(G(j\omega_i))$, for each type of wave, characterized by the natural frequency ω_{0i}, with i = 1..N.

It must be considered that the frequency of oscillation of a ship response when a wave with natural frequency ω_0 reach the ship with an angle μ, is the frequency of encounter ω_e, which is determined by $\omega_e = \omega_0 - (\omega_0^2 / g)U_0 \cos\mu$.

According to this, the starting point are the experimental data, $G(j\omega_{ei})$, i=1…N, that expressed in binomial form are:

$$G(j\omega_{ei}) = |G(j\omega_{ei})|\cdot\cos(\arg(G(j\omega_{ei}))) + j\cdot|G(j\omega_{ei})|\cdot\sin(\arg(G(j\omega_{ei}))) \tag{14}$$

4.2. Criterion of fit

As commented, the identification problem is solved as an optimization problem. The transfer function to be estimated, with *m* zeros and *n* poles is (2), where the parameter vector θ is given by (3).

In order to facilitate calculations in the resolution of the optimization problem, the parameter vector is redefined in terms of the *x* variable:

$$x = (x_1, x_2, ..., x_n, x_{n+1}, ..., x_{n+m}) \tag{15}$$

Thus, the transfer function is:

$$G(s,x) = \frac{B(s,x)}{A(s,x)} = \frac{x_{m+1}s^m + x_m s^{m-1} + ... + x_{n+1}}{s^n + x_n s^{n-1} + ... + x_1} \tag{16}$$

and then the cost function *J(x)* is

$$J(x) = \sum_{i=1}^{N}\left|G(j\omega_i) - G(j\omega_i, x)\right|^2 \tag{17}$$

The problem is solved with the Matlab optimization toolbox.

4.3. Constraints

The constraints of the problem are

i) $|b_1| = |a_1|$ for $G_{1H}(j\omega_e)$, $G_{2H}(j\omega_e)$.This condition is translated for the parameters vector *x* into:

$$|x_{n+1}| = |x_1| \tag{18a}$$

ii) $|b_1| = 0$ for $G_{1P}(j\omega_e)$. In order to ensure that this constraint is satisfied, it is imposed in the parameter vector *x* that

$$x_{n+1} = 0 \tag{18b}$$

iii) System stability. This constraint forces the real part of the poles to be negative.

4.4. Starting values

High quality starting values, i.e., near to the global optimum, are basic to reach the convergence point. In the first approach, starting values are obtained via a genetic algorithm or generated at random. The trouble met in the identification of new models with different angles of incidence is that in many occasions, due that starting values were not adequate or distant from the minimum, the procedure of minimization was long and costly. This was intensified when genetic algorithms were used, since it is a method based on the heuristic that did not give good results in many cases. For that reason, it is developed a new method to obtain the starting values x_0. This method consists of a linear least square estimation. From the cost function *J(x)* expression:

$$J(x)=\sum_{i=1}^{N}\left|G(j\omega_{ei})-G(j\omega_{ei},x)\right|^2=\sum_{i=1}^{N}\left|G(j\omega_{ei})-\frac{B(j\omega_{ei},x)}{A(j\omega_{ei},x)}\right|^2 \quad (19)$$

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$$\sum_{i=1}^{N}\left|A(j\omega_{ei},x)G(j\omega_{ei})-B(j\omega_{ei},x)\right|^2 \quad (20)$$

Therefore, a problem of least squares is set out. For each frequency value ω_{ei}, the denominator $A(j\omega_{ei},x)$ and numerator $B(j\omega_{ei},x)$ are only function of the vector x, and $G(j\omega_{ei})$ is a complex value. Hence, rewriting the above expression leads to an equation of the type of a least squares problem:

$$C\cdot x-d=0 \quad (21)$$

where x is the parameters vector (the starting values) to estimate, C is a matrix with N files and $n+m$ columns, and d is a column vector with $n+m$ size.

4.5. Multistep procedure. Identification of the transfer functions $G_{2Z}(s)$

As commented, an alternative suggested to the multistep procedure in the original approach is to solve simultaneously both transfer functions $G_{1Z}(s,x_a)$ and $G_{2Z}(s,x_b)$, and estimate the parameters vector x_a and x_b at the same time.

Another approach for estimating $G_{2Z}(s)$ is to make a previous hypothesis of linearity and determine the points to fit the transfer function from the linear superposition principle. Thus, for each frequency of encounter of wave ω_{ei}, i =1..N:

$$\left|G_{2Z}(j\omega_{ei})\right|=\frac{\left|G_Z(j\omega_{ei})\right|}{\left|G_{1Z}(j\omega_{ei})\right|}$$
$$\arg(G_{2Z}(j\omega_{ei}))=\arg(G_Z(j\omega_{ei}))-\arg(G_{1Z}(j\omega_{ei})) \quad (22)$$

5. AN ILLUSTRATIVE EXAMPLE

The whole work tries to identify a continuous linear model of heaving, pitching and rolling dynamics. Models of G_{1H}, G_{2H}, G_{1P}, G_{2P}, G_{1R}, *and* G_{2R} are identified for incidence waves between 90 and 180 degrees. Each plant models set have the same number of poles and zeros.

In this section it is shown a practical case of application and comparison of the two approaches commented. Specifically, it is presented the identification of the model corresponding to the wave to heave force plant $G_{1H}(s)$, for the incident angle 135º and ship speed 40 knots. Thus, for each case, the transfer function identified and the Bode diagram in which it is compared with the true data are presented.

Firstly the results from the original approximation are shown. As it has been noted in previous sections, first step is to select a set of candidate model structures. Table 1 shows two of these considered model structures (*m,n,nps*), and the value of the cost function J. Here, m is the number of zeros, n is the total number of poles, and *nps* is the number of simple poles. The parameter vector θ and transfer function are determined for each model structure. These all models give very similar Bode plots in the frequency range of interest, so this is a proof that these must reflect features of the true system. Structure with minimum J is selected as the best model.

Table 1. Model structures, cost function *J*

Model structure (*m,n,nps*)	Cost function *J*
(3,4,2)	0.51
(3,3,1)	0.79

Finally, structure (3,4,2) is chosen, and the estimated transfer function is given by (23). Figure 2 shows the Bode plots of the estimated transfer function and the simulated true data. It can be seen that the model is quite capable of describing the system.

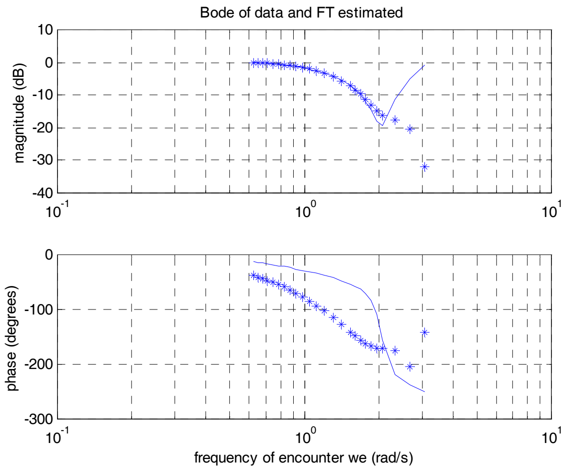

Fig. 2. Bode plot of $G_{1H}(s)$ and experimental data.

$$G_{1H}(s)=9333\frac{76.56s^3-22.21s^2+322.5s-14.92}{s^4+21.26s^3+154.7s^2+289s+14.92} \quad (23)$$

Next, the second approach is proved. Table 2 shows two of the model structures (m is the number of zeros, and n the number of poles) that had been tried, and the respective values of *AIC* and cost function J. According to Akaike's theory, those with the lower value *AIC* is selected. In this case, structure (3,4) gives the best result, so this structure is the chosen one.

Table 2. Model structures, cost function *J* and AIC

Model structure (*m,n*)	*AIC*	Cost function *J*
(3,4)	-63.31	0.0347
(3,3)	-54.71	0.055

Once model structure is fixed, the identification procedure is executed and the following transfer function is estimated:

$$G_{1H}(s)=9333\frac{26.02s^3-22.13s^2+160.9s^1+0.9}{s^4+125.4s^3+149.1s^2+181.3s^1+0.9} \quad (24)$$

Figure 3 shows the comparison between the Bode diagram of the transfer function identified and the actual data. It is shown that the model fits the data quiet good.

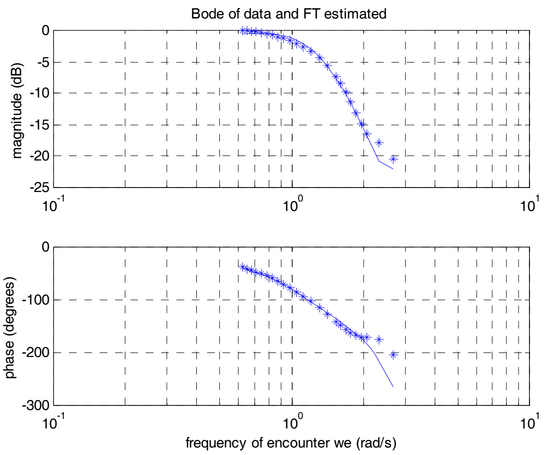

Fig. 3. Bode plot of $G_{1H}(s)$ and data.

Evaluating the results of the two implementations, it is seen in numerical results and graphics that the final approach estimates a transfer function model that fits the data more accurately. In addition, in the Bode diagram of the first $G_{1H}(s)$ it is observed that the amplitudes at high frequencies are too much large, which is translated into a very oscillatory and not proper behaviour in the temporal response.

6. CONCLUSIONS

In this paper an analysis of the system identification methods have been carried out, and a new alternative approach is proposed in order to estimate models for heave, pitch and roll dynamics of a high speed craft.

As a beginning, a first approach uses genetic algorithms and non linear least squares with constraints methods applied in the frequency domain as a criterion of fit to compute the best model. This method has been employed to model the vertical dynamic (heave and pitch modes) for the particular case of waves from directly ahead. However, when the study is extended to the horizontal dynamic (roll mode) and in addition other angles of incidence, it is not obtained such good models. Furthermore, it is observed that the technique does not guarantee the best linear approximation, and involves a lot of computational load due to non-quadratic functions.

For that reason another procedure is suggested. The second approach changes the type of parameterization, in order to facilitate the model selection and avoid non-quadratic functions in the cost function. Moreover and most important, this new parameterization promotes obtaining high quality starting values via a linear least squares estimate.

The paper is concluded with an example in which the two approximations are applied. Finally, it is shown that the second approach obtains more accurate models than the first one.

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