A hydrodynamic calculation procedure for UV using CFD

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***Abstract*— the paper substantiates the necessity of the CFD analysis of the underwater vehicle. Algorithm of hydrodynamic coefficients computation is presented. The initial conditions and environment model for computation are defined. Authors discuss results of simulation and propose the approach of hydrodynamic coefficients analysis.**

Keywords*— *underwater vehicle; hydrodynamics; mathematical model; polynom approximation; software complex

I. Introduction

An adequate mathematical model of underwater vehicle (UV) is required for the synthesis of its control system [1-7]. The mathematical model, used in this paper, was developed using general and specific laws of nature. Model describes the movement of the underwater vehicle in the viscous environment (water). For synthesis of the precise model, it was necessary to get hydrodynamic dependences with sufficient accuracy. A mathematical model of the underwater vehicle motion was presented in [8]. The vehicle itself is shown in Fig. 1.

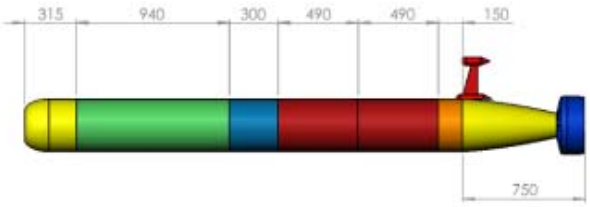

Fig. 1. Appearance of the underwater vehicle

II. Hydrodynamic Calculation Using CFD

Numeca FINE/Hex was used to calculate hydrodynamic coefficients [9]. Hydrodynamic calculation procedure using the software package is as follows:

- Generation of operating conditions.
- Importing of 3D model into NUMECA International.
- Definition of the boundaries and limitation for operating conditions.
- Mesh generation.
- The setting of environment data.
- Selection of continuum mathematical model.
- Setting of the initial condition of the solution.
- Setting of computing parameters (i.e. the values that define the algorithms for computing processes).
- Assignment of output parameters.
- Model simulation in computing unit and the control of the convergence process of the calculation.
- Review of the calculation results using CFView.

Software uses Navier-Stokes equations with Spalart-Almaresu turbulence model to describe the kinematics and dynamics of the continuum. A mesh generation of the operating conditions was produced using HEXPRESS. The following initial conditions were set: angle of incidence of 20 degrees, the sliding angle of 0 degrees, the typical values of the vehicle velocity 1, 3, 5, 7 m/s.

III. Discussion of The Hydrodynamic Calculation Results

After simulation, we got the number of the two-dimensional arrays of the components of hydrodynamic forces and moments that are acting on the underwater vehicle. For further use of the calculated data, it is offered to approximate this data with polynomials. This method allows to integrate the hydrodynamic component into the model in a compact form without tables. The accuracy of the approximation is evaluated by two quantities: an error sum of squares "*SSE*" and a root mean square error "*RMSE*". Fig. 2 shows an example of the two-dimensional approximation of the drag coefficient on the angle of attack and glide at a speed V = 1m/s.

Algorithm for the selection of degree of approximating polynomial is shown in Fig. 3. According to the algorithm, in order to find the degree of the polynomial approximant for hydrodynamic coefficients on the first step, coefficient is approximated by the 2nd degree polynomial. Then, i, the degree of the polynomial is incremented and approximation is carried out again. Now it is necessary to compare the standard deviation $RMSE_i$ with the $RMSE_{i-1}$ and SSE_i with SSE_{i-1}.

If the error for the new polynomial $RMSE_i$ is much smaller than error for the polynomial of "i-1" degree, then the degree

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is incremented by 1. Such increase and comparison is performed in a cycle until the difference between the $RMSE_i$ and the $RMSE_{i-1}$, as well as SSE_i and SSE_{i-1} will be negligible.

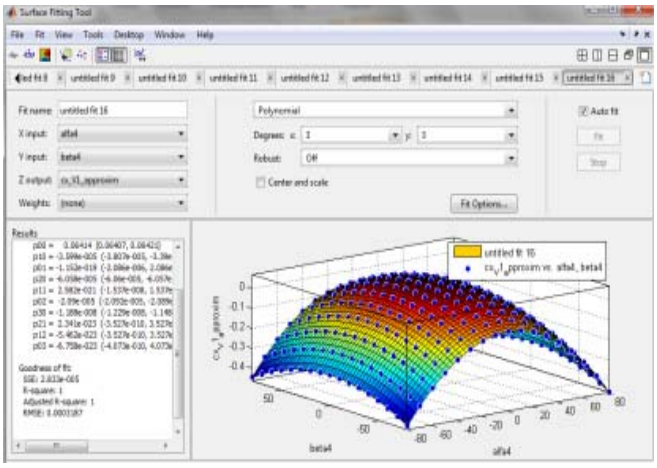

Fig. 2. Two-dimensional approximation of the angles of attack and glide, having velocity V = 1 m/s

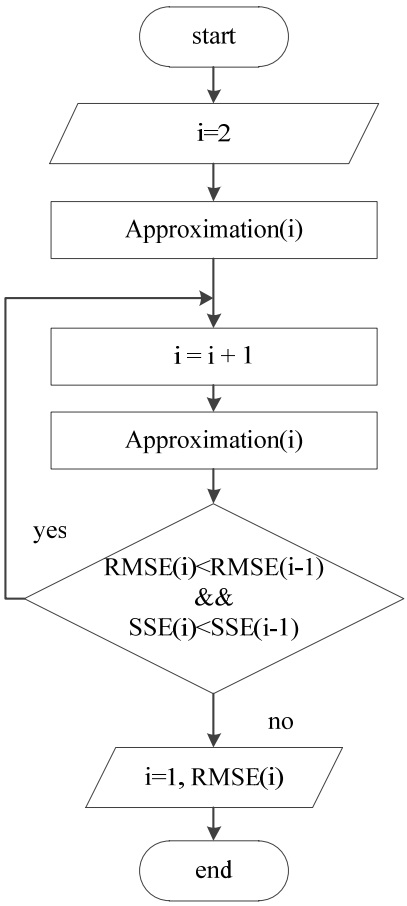

Fig. 3. Block diagram of a polynomial approximation

Let us consider the example of the approximation of m_x coefficient. In the first step, we select the initial degree of approximation, and then then perform approximation of data by polynomials. In this case, polynomial degrees are 3 and 4. The next step is estimation of the accuracy of the approximation using *SSE* and *RMSE*. The error of approximation for different degrees of the polynomial is provided in Table I. Here one can note that SSE_3 and $RMSE_3$ are considerably (one order) higher than the SSE_4 and $RMSE_4$. Therefore, in accordance with the algorithm in Fig. 3, the degree of approximation is incremented, and we compare SSE_4 and $RMSE_4$ with SSE_5 and $RMSE_5$. Now there is only slight difference between the values of errors. Consequently, a polynomial of degree 4 is required for the polynomial approximation of m_x coefficient, as here is a term with a coefficient of 4th degree (p_{13}=1.452e-10) (see. Fig. 4), and the error of this polynomial is much smaller than in the case of 3rd degree polynomial: SSE_3 = 0.00244, $RMSE_3$ = 0.0029; SSE_4 = 0.00067, $RMSE_3$ = 0.00049. The polynomial of the 5th degree does not reduce the approximation error. Table I contains *SSE* and *RMSE* errors of the coefficient for different degrees of polynomial approximation.

TABLE I. CHARACTERISTICS OF APPROXIMATING POLYNOMIAL m_x

Coef.	Degree	SEE	RMSE
m_x	3	0.002438	0.002956
	4	$6.776\cdot10^{-5}$	0.0004973
	5	$6.506\cdot10^{-5}$	0.0004927

Similarly, the approximation for the coefficients m_y, m_z, c_x, c_y, c_z are performed. Characteristics of approximation are given in Table II. The resulting expression for the coefficient of hydrodynamic forces of normal pressure is:

$$c_{xv} = 0.0680 + 3.57\cdot10^{-3}\cdot V + 4.46\cdot10^{-13}\cdot V^2\cdot x + 1.12\cdot10^{-13}\cdot V^2\cdot y - 3.543\cdot10^{-5}\cdot x - 8.98\cdot10^{-19}\cdot y - 6.155\cdot10^{-5}\cdot x^2 + 2.391\cdot10^{-22}\cdot x\cdot y - 2.005\cdot10^{-5}\cdot y^2 - 1.204\cdot10^{-8}\cdot x^3 + 1.62\cdot10^{-23}\cdot x^2\cdot y + 3.044\cdot10^{-23}\cdot x^3\cdot y + 1.222\cdot10^{-22}\cdot y^3 + 1.431\cdot10^{-11}\cdot x^4 - 3.988\cdot10^{-24}\cdot x^3\cdot y + 5.283\cdot10^{-11}\cdot x^2\cdot y^2 + 4.299\cdot10^{-24}\cdot x\cdot y^3 - 8.756\cdot10^{-12}\cdot y^4, \quad (1)$$

where, $x = (180/\pi)\cdot\alpha_0$, $y = (180/\pi)\cdot\beta_0$, α_0, β_0 – angles of attack and slip, V–velocity.

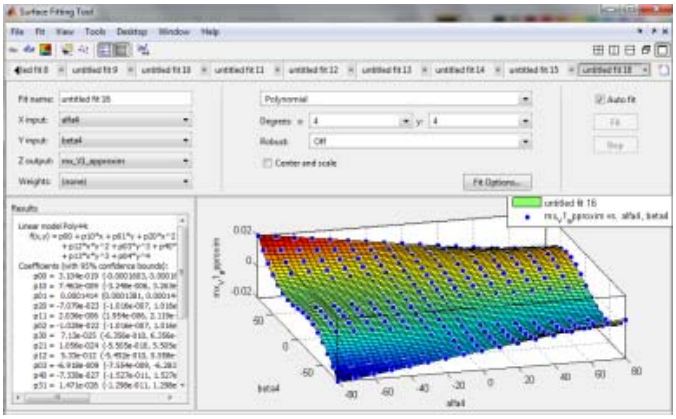

Fig. 4. A two-dimensional approximation mx for angles of attack and glide, having velocity V = 1m/s

TABLE II. CHARACTERISTICS OF APPROXIMATING POLYNOMIAL.

No.	Coef	Degree	SSE	RMSE
1	coefficient of the normal pressure, c_x	4	$2.03 \cdot 10^{-5}$	0.0002939
2	lift coefficient, c_y	3	0.0441	0.01257
3	coefficient of lateral force, c_z	3	0.1141	0.02022
4	moment coefficient, m_x	4	$6.7 \cdot 10^{-5}$	0.00049
5	yaw moment coefficient, m_y	3	0.0006829	0.001564
6	pitching moment coefficient, m_z	3	0.003299	0.003439

IV. CONCLUSIONS

Having the polynomials, calculated by the proposed algorithm, it is possible to obtain approximation expressions for the components of the hydrodynamic forces and moments, acting on the underwater vehicle in motion, which depend on the speed of UV, the angles of attack and slip (Fig. 5-10).

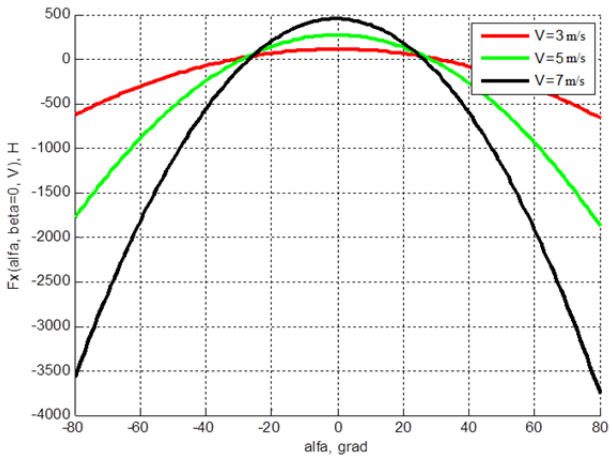

Fig. 5. $F_x(\alpha;\ \beta=0^0, V=3,5,7\ m/s,\ \omega=0)$

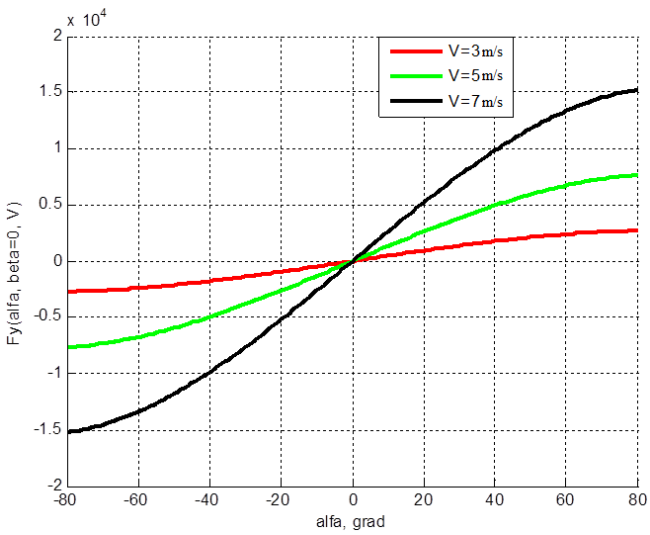

Fig. 6. $F_y(\alpha;\ \beta=0^0, V=3,5,7\ m/s,\ \omega=0)$

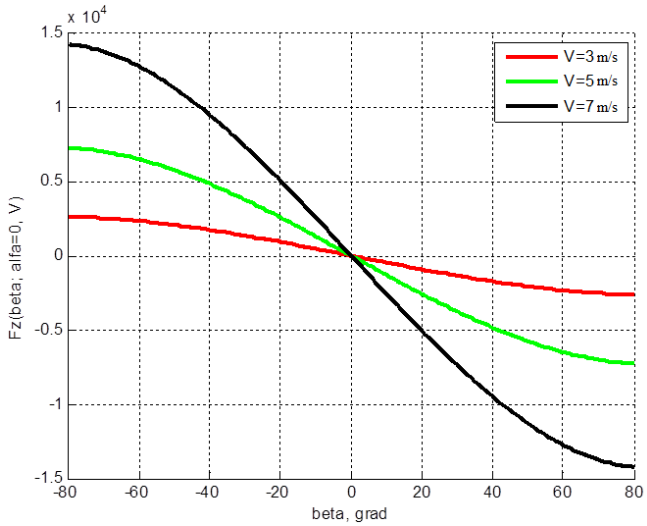

Fig. 7. $F_z(\alpha;\ \beta=0^0, V=3,5,7\ m/s,\ \omega=0)$

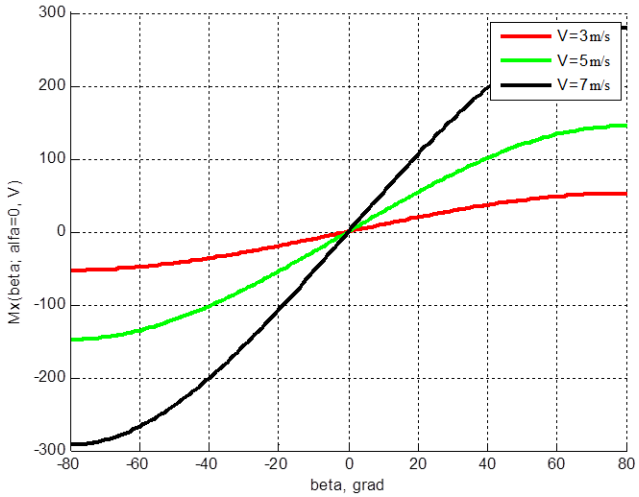

Fig. 8. $M_x(\alpha;\ \beta=0^0, V=3,5,7\ m/s,\ \omega=0)$

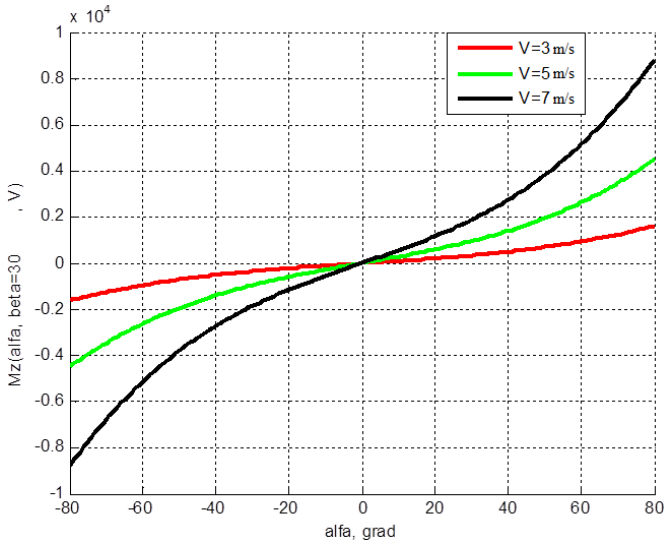

Fig. 9. $M_y(\alpha;\ \beta=0^0, V=3,5,7\ m/s,\ \omega=0)$

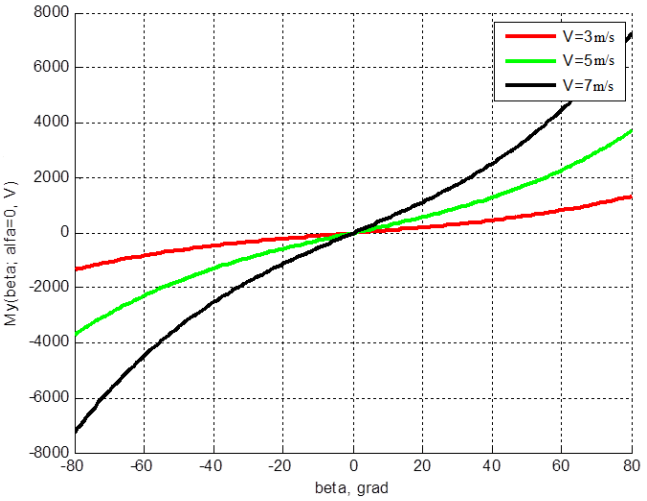

Fig. 10. $M_z(\alpha; \beta=0^0, V=3,5,7\ m/s, \omega=0)$

Choice of the degree of the approximating polynomials is based on the *RMSE* for each coefficient, which depend on the angles of attack, and the drift speed. For the two-dimensional approximation of c_x, m_x, polynomial degree is 4, because shape of the surface is complex. For other coefficients — degree of the approximation polynomials is 3. The criterion for the polynomial degree choice takes redundancy into account and can be formulated as: higher degree should provide significantly more accurate approximations than lower degree polynomial.

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