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UNDERWATER MANIPULATORS

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Abstract: The study presented by this paper depicts the differences between the kinematics and dynamics of a grabber mechanism when it operates in atmospheric or underwater environment. The grabber we refer to is attached to an underwater vehicle/robot. The modification in angular acceleration of the fingered mechanism is caused by the enhanced underwater friction and hydrodynamic forces that oppose to the movement. The mechanism operation analysis in both environments offers engineering design information about efforts and about how tests developed at surface may be concluding for underwater operation accuracy.

1.INTRODUCTION

Manipulators equip a large number of industrial, space or underwater mobile system applications. Remote control underwater vehicles are one of these applications, of great interest for those whose work consists of underwater life research, deep sea control or, especially, deep sea industrial installations. These vehicles are usually equipped with manipulators constructed in a various kind of solutions.

We developed the project for the construction of such a vehicle/robot of small dimensions which can operate down to 300m depth under sea. Its propulsion is achieved by four actuators, that allow the movement both in horizontal and vertical planes. It is provided with movement and depth sensors, a video camera and a manipulator with changeable grippers.

2.THE VEHICLE MANIPULATOR AND ITS GRIPPERS

The manipulator is an articulated mechanism mounted on a fix or mobile base, conceived to handle things. It is electrically, hydraulically or pneumatically actuated by a number of actuators, usually equal to its degrees of freedom. The reaction forces developed as the manipulator accelerates may disturb the base dynamics and result in poor performance and accuracy of the base, mainly in environments with diminished gravity. The dynamic performance of a manipulator is characterized by the inertial and acceleration properties of its end-effector. The gripper is the manipulator's tool, by which the manipulated object is gripped and hold, moved or cut. Grippers of various kinds exist in use, from ferromagnetic grippers with no moving parts and no degrees of freedom to complex grasp force sensitive mechanical grippers. Grippers essentially have part of the human hand functions. If the gripping abilities of a mechanical five-finger hand are denoted with 100%, then a four-finger hand has 99% , a three-finger hand has 90% and a two-finger hand has about 40% of its abilities [1].

The end effector is part of a mechanical gripper and according to the construction solution adopted by the designer its movement may be an axial, rotational or plan-parallel one.

The manipulator attached to the considered underwater vehicle is a very simple one, composed of an electrical actuator, a mechanical arm and a gripper, fig.1. We adopted this solution taking into account the hard underwater operation conditions and a low cost for execution and exploitation.

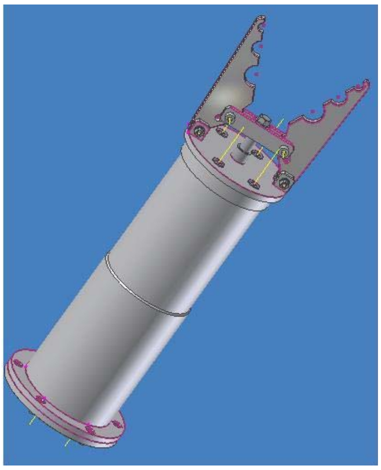


Fig.1.Manipulator with two-finger removable gripper

The mechanism consists of a leading screw actuated by an electrical c.c. motor, which rotates without axial possibility of moving. It imposes an axial movement to a nut which cannot rotate. A rod attached to the nut symmetrically links to the fingers of the gripper. The fingers are in fact levers rotating around a fix point, the finger's joint on the gripper support. The joint between the rod and a finger is mobile. The mechanism has only one degree of freedom. This reduced number doesn't affect the positioning abilities because the manipulator is attached to a mobile base: the remote controlled vehicle.

The changeable tools that may be attached are: a two-finger gripper, a three-finger gripper or a cutting two finger, fig.2. Whatever is the tool, the rod acts symmetrically on the fingers.

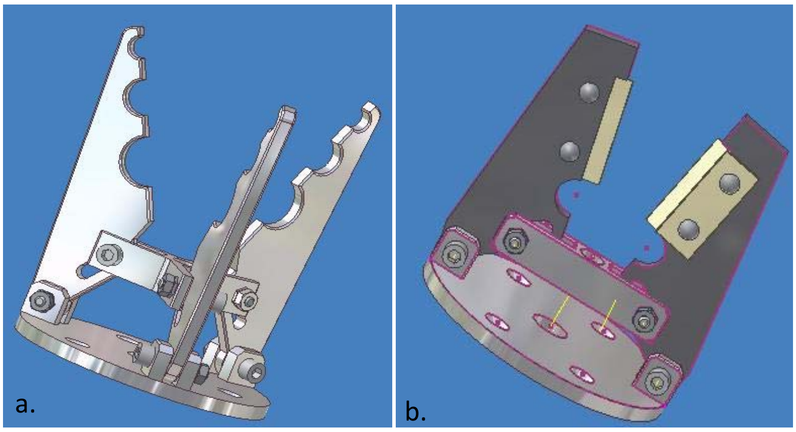


Fig.2.Changeable tools: a. three-finger gripper; b. two-finger cutting tool

3.CONSIDERATIONS ON THE DYNAMICS OF THE MECHANISM

The main objectives of the engineering design were:

- from the quantitative point of view:
  - -the force developed by the fingers, according to the motor torque;
  - -the displacement of the driving rod, and consequently the opening between fingers.
- from the qualitative point of view:
  - -the quick response of the mechanism at the actuator movement;
  - -accuracy in operation.

The dynamic equations for a complex manipulator with a rotating end-effector, operating at surface, in atmospheric environment, are [1]:

$$\mathbf{M} = \mathbf{I}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{V}(\mathbf{q},\dot{\mathbf{q}}) + \mathbf{G}(\mathbf{q}) \tag{1}$$

were $\mathbf{M} = [\mathbf{M_1}, \mathbf{M_2}, \mathbf{M_3}]^\mathbf{T}$ the vector of actuator torque;
$\mathbf{I}(\mathbf{q}) = [\mathbf{I_1}, \mathbf{I_2}, \mathbf{I_3}]^\mathbf{T}$ the inertia mass matrix of the mechanism;
$\mathbf{q} = [\mathbf{q_1}, \mathbf{q_2}, \mathbf{q_3}]^\mathbf{T}$ the vector of generalized coordinates;
$\mathbf{V} = [\mathbf{V_1}, \mathbf{V_2}, \mathbf{V_3}]^\mathbf{T}$ the vector of centripetal forces;
$\mathbf{G} = [\mathbf{G_1}, \mathbf{G_2}, \mathbf{G_3}]^\mathbf{T}$ the gravity vector.

At surface, the action of the air resistance to the movement may be neglected.

On the contrary, the water resistance to the movement and the pressure forces acting on the unbalanced mechanism parts must be taken into account, thus the dynamic equations for the same manipulator operating underwater become:

$$\mathbf{M} = \mathbf{H}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{V}(\mathbf{q},\dot{\mathbf{q}}) + \mathbf{G_a}(\mathbf{q}) + \mathbf{F_r}(\mathbf{q},\dot{\mathbf{q}}) \tag{2}$$

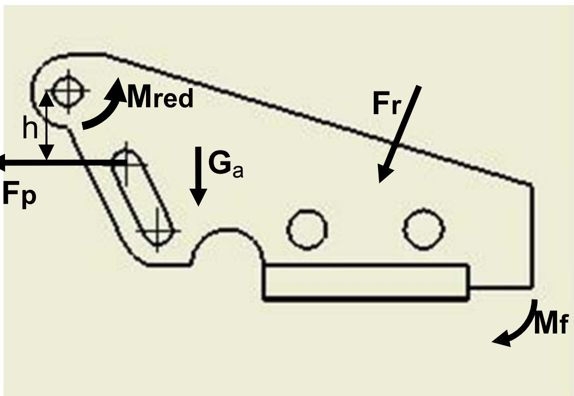
were $\mathbf{F_r} = [\mathbf{F_{r1}}, \mathbf{F_{r2}}, \mathbf{F_{r3}}]^\mathbf{T}$ the vector of resistance generalized forces;
$\mathbf{G_a} = [\mathbf{G_{a1}}, \mathbf{G_{a2}}, \mathbf{G_{a3}}]^\mathbf{T}$ the apparent gravity vector.

Taking into account the simplicity of our mechanism, the equations (2) become less complex. Even if it is a spatial mechanism, with a superior pair (leading screw-nut), we assumed it to be a planar one. The mechanism has one degree of freedom, so the assumption is justified. We obtain a single dynamic scalar equation [4]:

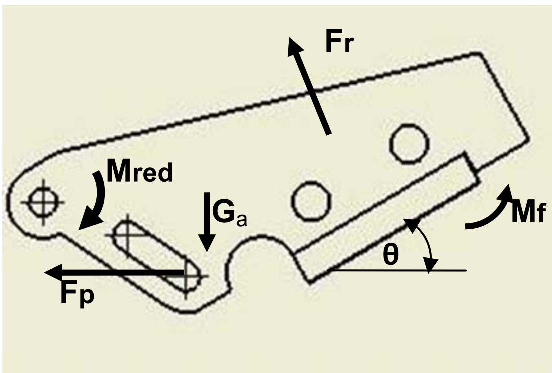
$$\mathrm{M_{red}} = \varepsilon \cdot \mathrm{I_{red}} \qquad 3)$$

were $\mathrm{M_{red}}$-the torque reduced at the end-effector;
$\mathrm{I_{red}}$-the inertia momentum reduced at the end-effector;
ε- angular acceleration of the end-effector.

Both $\mathrm{M_{red}}$ and $\mathrm{I_{red}}$ are dependent of the underwater vehicle depth of operation. The reduced torque was calculated as a function of the rotation angle, θ. The loads on the finger, in underwater environment, are represented in fig. 3.



a.



b.

Fig.3 Loads on the finger: a. Opening of the closed mechanism; b.Closing of the opened mechanism

The relationship for the reduced torque is

$$\mathrm{M_{red}} = \mathrm{M_m}\frac{2\cdot\pi\cdot h}{s} \pm \mathrm{G_a l_G cos\theta} \pm \mathrm{F_r} \cdot \mathrm{l_C} - \mathrm{M_f} \pm \mathrm{F_p} \cdot \mathrm{h} \tag{4}$$

were M_m-the motor torque, [Nm];

G_a-apparent gravity force of finger, [N];
F_r-hydrodynamic resistance force on the finger, [N];
F_p-pressure force on the front face of the rod, transmitted to the finger, [N];
M_f-friction torque on both faces of the finger, [Nm];
h-distance between the rod axis and the rotation point of the finger, [m];
s-leading screw pitch, [m];
l_G-distance between the rotation point of the finger, and the application point of gravity force [m];
l_C-distance between the rotation point of the finger, and the application point of resistance force [m].

The sign $\pm$ depends on the movement orientation.

The motor torque depends only on the rotation angle, θ. The apparent gravity force, G_a does mechanical work only when the grabber is mounted in vertical plan and it depends only on the depth of the water. These dependence was calculated considering the compressibility of water. Thus, the density variation of the sea water is given by the relationship:

$$\rho = \rho_o[1 + \beta \cdot \Delta p] \tag{5}$$

were ρ-sea water density at operation depth, [kg/m^3];
$\rho_o = 1025$ [kg/m^3], sea water density at surface [3];
$\beta = 4{,}55 \cdot 10^{-7}$ [kPa^{-1}], compressibility coefficient for the sea water;
Δp-static pressure variation with the sea water depth, [kPa]

The hydrodynamic resistance force is a distributed force on the finger's length, L. The elementary resistance force is:

$$dF_r = \frac{1}{2} C \cdot A \cdot \rho \cdot (\omega r)^2 \cdot dr \tag{6}$$

were $r\epsilon(0, L)$, L-the finger's length, [m];
C-resistance coefficient, depending on the finger's shape;
A-area of the finger's face opposed to the water; the finger is regarded as a solid moving into still water,[m^2];
ω- angular velocity of the finger, [s^{-1}].

Integrating the relation(6) on the entire length, we obtain a function of angular velocity of the finger, as follows:

$$F_r = \frac{1}{6} C \cdot A \cdot \rho \cdot \omega^2 \cdot L^3 \tag{7}$$

The friction torque, M_f , acts on both faces of the finger. It was evaluated by the formula recommended for a disc rotation in viscous fluid [2]:

$$M_f = \frac{32}{3} \mu \cdot \omega \cdot L^3 \tag{8}$$

were $\mu = 1{,}88 \cdot 10^{-3} kg \cdot m/s$- dynamic viscosity of sea water, variable with the water temperature and depth; the finger was considered a quarter of a disc [3].

According to the above relations, we obtained a variation for the reduced moment of inertia as represented in fig.4. Notice that it decreases rapidly between surface and 50m depth. At greater depth, the variation is insignificant.

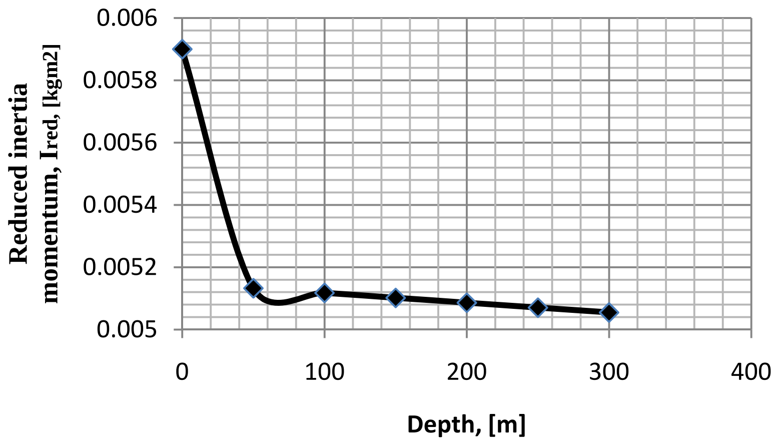


Fig.4.The variation of reduced inertia momentum with the depth

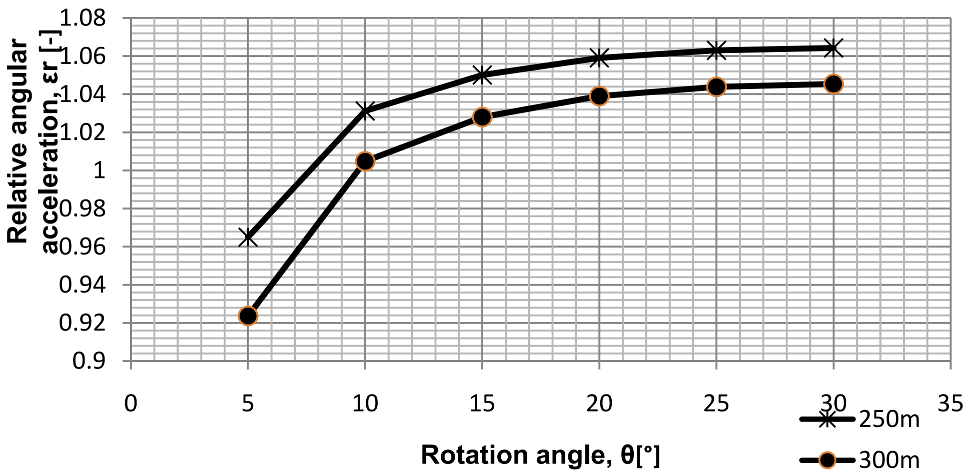


Fig.5.The variation of relative angular acceleration with the rotation angle, at different depths

The reduced torque also decreases when the immersion depth is greater, but its variation is slower. In fig.5 it is represented the variation of the relative angular acceleration, which means the ratio between the angular acceleration at depth and the angular acceleration at surface. It may be noticed that the angular acceleration is smaller at the beginning of finger rotation in water then at surface, which means the opening is more difficult underwater, as the resistance torque and the pressure force are greater.

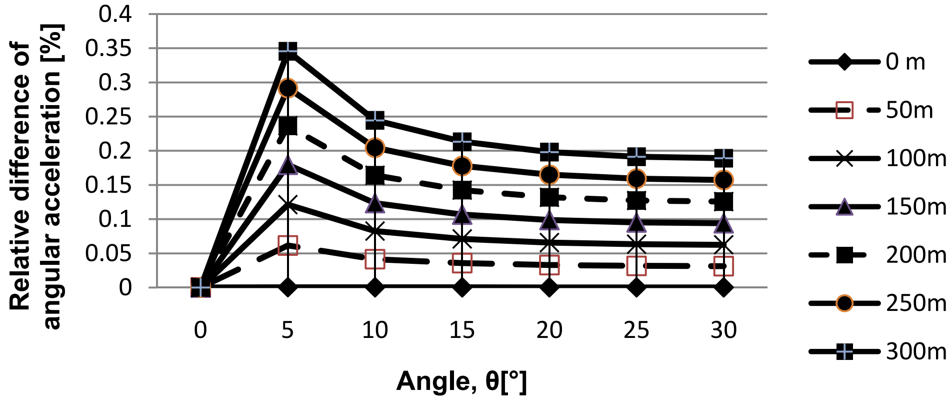


Fig.6.The variation of relative difference of angular acceleration, at different depths

For a two-finger grabber mounted in vertical plane the reduced moment has a smaller variation comparing to the same grabber mounted in horizontal plane. The vertical mounting introduces an asymmetric movement of the fingers, as the angular acceleration of the superior finger is different from the inferior one's. The relative difference of angular acceleration as a function of rotation angle, at different depths, is depicted in fig.6.

This asymmetrical movement, even if weak, may induce vibrations, and affect orientation, especially at great depth of vehicle operation.

The dynamic study offers information about the mechanical parameters (force, displacement) of the manipulator, used in the engineering design and in the resistance calculus of the parts. The results presented above may also considered for the evaluation of the reaction force and torque transmitted by the manipulator to the vehicle. These reaction forces may disturb the accuracy of movement and orientation of the vehicle. The dynamic forces caused by the accelerating links of the manipulator can generate vibrations. The simplest way to lower the reactions (forces and base moments) to within admissible values is a slow movement. Complete reaction force elimination may be achieved by fixing the center of gravity of the manipulator by addition of counterweights or by an appropriate location of the support point of the manipulator. [5]

4.CONCLUSIONS

Usually, the mechanical design of robots has been viewed as a problem of packaging motors and electronics into a reasonable structure. This process relies mostly on the engineering experience. The main mechanical problem is the achievement of a better accuracy of the grabber operation at the requested parameters: gripping/ cutting force and maximal opening between fingers. A good accuracy can be achieved on the basis of a dynamic study of the manipulator.

The water resistance to the movement and the pressure forces acting on the unbalanced mechanism parts, must be taken into calculus relationships. Therefore, the dynamic equations are different for the same manipulator operating at surface or underwater.

Angular acceleration variation with depth revealed that the opening is harder and the movement is slower as depth increases. For the same depth, the opening is slower than at surface, but the movement is faster for a rotating angle between 10^o and 30^o. A weak asymmetry may occur between the movement of the two fingers according to the mounting position of the grabber on the robot structure, which results in vibrations.

The dynamic study is a basis to obtain correction coefficients for the operation parameters measured at surface, such as they may be concluding for the underwater operation parameters

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