Dynamics Simulation of Remotely Operated Vehicle-Fiber Optic Micro Cable System

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***Abstract* –This paper presents an approach of modeling for Fiber Optic Micro Cable (FOMC), constructs a coupled nonlinear model for Remotely Operated Vehicle(ROV) connected with FOMC, and makes computer simulation at last. The model of FOMC takes use of the lumped mass method in which FOMC is considered to be a system of micro units connected by elastic non-mass spring. Four order Runge-Kutta method is used to work out the equation of FOMC and ROV kinematics and dynamics. Simulation includes tension distribution and shape of FOMC and the motion of ROV under the condition of disturbance of FOMC. The simulation result indicates that the FOMC's influence to ROV can not be neglected while we discuss the control problem of ROV.**

***Index Terms* –ROV,FOMC, dynamics simulation, lumped mass method.**

I. INTRODUCTION

Remotely Operated Vehicle(ROV) connected with Fiber Optic Micro Cable(FOMC) is a new type of ROV arisen in recent years. It combines the virtue of classic ROV and autonomous underwater vehicle(AUV) and is a good choice for some underwater task because its perfect real-time performance and tactical flexibility, such as local detailed observation of the deep sea shipwreck, large-scale survey of geological features on the ocean floor etc. Japan Agency for Marine-Earth Science and Technology(JAMSTEC) and Woods Hole Oceanographic Institution(WHOI) have done a lot of research work[1][2][3] and designed underwater vehicle UROV7K and HROV(Hybrid Remotely Operated Vehicle) to finish large-scale deep sea exploration. The task of shipwreck's local inspection was completed by micro ROV which is cooperated with HOV(Human Occupied Vehicle). The micro ROV was connected to HOV and communicated with it by a thin FOMC. Now many countries have paid great attention to the research on deep sea micro ROV which is attached to HOV. And the ROV-FOMC system research is an important part for constructing the micro ROV.

In reference [4], S.I.Cowen introduced the characteristics of FOMC in details. Reference [5] provided a method of dynamic modelling for FOMC. Its research was mainly aiming at the FOMC shape and tension distribution under different oceanic conditions but regardless of the influence of vehicle to FOMC. In this paper the ROV and FOMC are investigated as a whole, because FOMC can affect the motion of vehicle while the motion of vehicle could change the motion of FOMC.

The research in this paper is divided into three parts. In the first part we utilize the lumped mass method to model for FOMC. This method is simple but effective, with which the complex partial differential equation about the real FOMC model is avoided. This method has been applied successfully in the towed cable system[6],[7],[8].In the second part the nonlinear model of ROV connected with FOMC will be set up by combining the vehicle model and FOMC model derived in the first part. In the last, based on the model, some computer simulation is done to simulate the FOMC's influence to ROV's motion state and FOMC's tension distribution and shape influenced by the ROV's motion. These research results can be used to guide this type of system's design.

II. FOMC'S DYNAMICS

A. Coordinate System

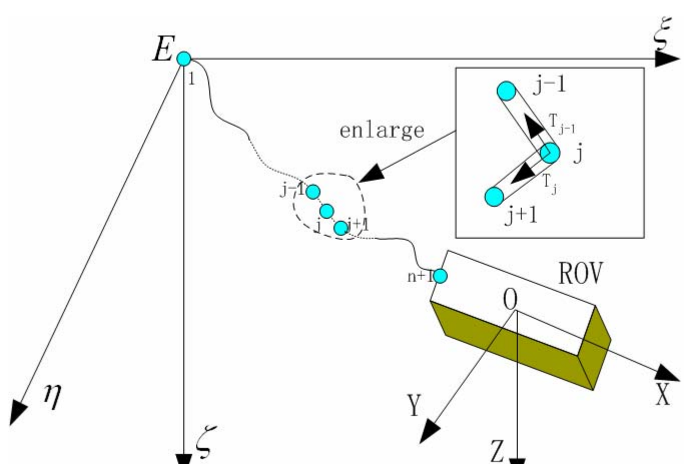

Fig.1:The inertial coordinate system and model of cable ROV(Remotely Operated Vehicle)

In order to develop the model of FOMC, North-East inertial coordinate system is defined. Its origin is located in the released point of FOMC.

B. Dynamics model

The diameter of FOMC is 2mm, and the cable is composed of a single-mode fiber, strengthened epoxy glass and acrylic materials. According to the tether model we can consider the continuous FOMC as a serial of micro unit and define that the connection point between HOV and FOMC is the first unit and the point between FOMC and the ROV is the n+1 unit. The mass and forces are concentrated on the micro units which are connected by linear and non-mass spring. Figure 1 illustrates the inertial coordinate system and lumped mass representation of the tether.

In the inertial coordinate system the j unit model is:

$$\vec{F}_j = m_j \frac{d\vec{v}_j}{dt} \quad (j=1,2,3\ldots n,n+1)$$
$$\vec{v}_j = \frac{d\vec{r}_j}{dt} \quad (j=1,2,3,\ldots,n+1) \tag{1}$$

where $\vec{F}_j$ is the composition of forces on the unit, $\vec{v}_j$ is the velocity vector of unit, $\vec{r}_j$ is the position vector of unit, and m_j is the mass of the unit. The forces on the jth micro unit include the tension of the j and j-1 units, tangential hydrodynamic force $\vec{D}_{tj}$,normal hydrodynamic force $\vec{D}_{nj}$,gravity $\vec{W}_j$ and buoyancy $\vec{B}_j$.

$$\vec{F}_j = \vec{T}_j - \vec{T}_{j-1} - \vec{D}_{tj} - \vec{D}_{nj} + \vec{W}_j - \vec{B}_j \tag{2}$$

where j=1,2,…n+1.

The j unit tension:

$$\vec{T}_j = EA_j \vec{\varepsilon}_j \quad (j=1,2,..n+1) \tag{3}$$

tangential hydrodynamic:

$$\vec{D}_{tj} = -\frac{\rho}{2} C_{tj} A_{tj} \left|\vec{U}_{tavj}\right| \vec{U}_{tavj} \quad (j=1,2,..n+1) \tag{4}$$

normal hydrodynamic:

$$\vec{D}_{nj} = -\frac{\rho}{2} C_{nj} A_{nj} \left|\vec{U}_{navj}\right| \vec{U}_{navj} \quad (j=1,2,..n+1) \tag{5}$$

where E is FOMC's elasticity modulus, ε_j is the axial strain of the j unit, A_j is the cross sectional area, ρ is the seawater density, and $\vec{U}_{tavj}$ and $\vec{U}_{navj}$ is tangential and normal relative velocity to sea current. The tangential resistance coefficient C_{tj} and the normal resistance coefficient C_{nj} are the sectional function of FOMC's Reynolds number[5]. In the sea water FOMC's gravity is considered equal to the buoyancy.

III. ROV'S DYNAMICS AND KINEMATICS

A. *Coordinate system*

Vehicle coordinate system is bound with ROV, and the origin is located in the buoyancy center. The direction of X axis is consistent with principal symmetry axis,Y axis is vertical to X axis and points to the starboard of ROV, and Z axis is vertical to the XY plane and follows the right criteria.

B. *Dynamics and kinematics of ROV*

In this paper the ROV's motion are implemented by principal thruser and rudders, and it's dynamics and kinematics without the disturbance brought by FOMC were derived in reference [9][10].

Kinematics:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} J_1 & 0 \\ 0 & J_2 \end{bmatrix} \begin{bmatrix} u \\ v \\ w \\ p \\ q \\ r \end{bmatrix} \tag{6}$$

where:

$$J_1 = \begin{bmatrix} c\psi c\theta & c\psi s\theta - s\psi c\phi & c\psi s\theta c\phi + s\psi s\phi \\ s\psi c\theta & s\psi s\theta s\phi + c\psi c\theta & s\psi s\theta c\phi - c\psi s\phi \\ -s\theta & c\theta s\phi & c\theta c\phi \end{bmatrix}$$

$$J_2 = \begin{bmatrix} 1 & s\phi t\theta & c\phi t\theta \\ 0 & c\phi & -s\phi \\ 0 & s\phi / c\theta & c\phi / c\theta \end{bmatrix}$$

s(·), c(·),and t(·) mean sin(·), cos(·) and tan(·) respectively, $(x, y, z, \phi, \theta, \psi)'$ is the position and attitude vector of the vehicle in the inertial coordinate system. $(u, v, w, p, q, r)'$ is the velocity vector of the vehicle in vehicle coordinate system.

Dynamics:

$$\begin{aligned}
& m[\dot{u} - vr + wq - x_g(q^2 + r^2) + y_g(pq - \dot{r}) + z_g(pr + \dot{q})] = \sum X \\
& m[\dot{v} - wp + ur - y_g(r^2 + p^2) + z_g(qr - \dot{p}) + x_g(qp + \dot{r})] = \sum Y \\
& m[\dot{w} - uq + vp - z_g(p^2 + q^2) + x_g(rp - \dot{q}) + y_g(rq + \dot{p})] = \sum Z \\
& I_{xx}\dot{p} + (I_{zz} - I_{yy})qr + m[y_g(\dot{w} - uq + vp) - z_g(\dot{v} - wp + ur)] = \sum K \\
& I_{yy}\dot{q} + (I_{xx} - I_{zz})rp + m[z_g(\dot{u} - vr + wq) - x_g(\dot{w} - uq + vp)] = \sum M \\
& I_{zz}\dot{r} + (I_{yy} - I_{xx})pq + m[x_g(\dot{v} - wp + ur) - y_g(\dot{u} - vr + wq)] = \sum N
\end{aligned} \tag{7}$$

where:

(x_g, y_g, z_g) is gravity center vector in vehicle coordinate system, and I_{xx}, I_{yy}, I_{zz} are the moments of inertia.

$$\sum X = X_{HS} + X_{u|u|}u|u| + X_{\dot{u}}\dot{u} + X_{uv}uv + X_{uw}uw + X_{v|v|}v|v| + X_{w|w|}w|w| + X_{wq}wq + X_{qq}qq + X_{vr}vr + X_{rr}rr + X_{prop}$$

$$\sum Y = Y_{HS} + Y_{v|v|}v|v| + Y_{r|r|}r|r| + Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} + Y_{ur}ur + Y_{wp}wp + Y_{pq}pq + Y_{uv}uv + Y_{uu\delta_r}u^2\delta_r$$

$$\sum Z = Z_{HS} + Z_{w|w|}w|w| + Z_{q|q|}q|q| Z_{\dot{w}}\dot{w} + Z_{\dot{q}}\dot{q} +$$
$$Z_{uq}uq + Z_{vp}vp + Z_{rp}rp + Z_{uw}uw + Z_{uu\delta_s}u^2\delta_s \quad (8)$$
$$\sum K = K_{HS} + K_{p|p|}p|p| + K_{\dot{p}}\dot{p} + K_{prop}$$
$$\sum M = M_{HS} + M_{w|w|}w|w| + M_{q|q|}q|q| + M_{\dot{w}}\dot{w} + M_{\dot{q}}\dot{q}$$
$$+ M_{uq}uq + M_{vp}vp + M_{rq}rq + N_{uw}uw + N_{uu\delta_s}u^2\delta_s$$
$$\sum N = N_{HS} + N_{v|v|}v|v| + N_{r|r|}r|r| + N_{\dot{v}}\dot{v} + N_{\dot{r}}\dot{r} +$$
$$N_{ur}ur + N_{wp}wp + N_{pq}pq + N_{uv}uv + N_{uu\delta_r}u^2\delta_r$$

where $(X_{HS}, Y_{HS}, Z_{HS}, K_{HS}, M_{HS}, N_{HS})$ [11] are static forces and moments produced by the gravity and buoyancy of the vehicle., (X_{prop}, K_{prop}) are thrust forces and moments of the principal thruster, and $(Y_{uu\delta_r}u^2\delta_r, Z_{uu\delta_s}u^2\delta_s, N_{uu\delta_s}u^2\delta_s, N_{uu\delta_r}u^2\delta_r)$ are forces and moments brought by the rudders, and other items are hydrodynamic forces.

In the model expressed in (7) the force produced by FOMC is ignored. By adding the force and moment brought by the last unit FOMC we can get the system's integrity model. In inertial coordinate system, the FOMC's last unit force is tension $|\vec{T}_{200}|$.We project it to $E\xi$, $E\eta$, $E\zeta$ axis(the inertial frame) and can get the tension:

$$\vec{T}_{200_i} = (|\vec{T}_{200}| \cdot \frac{r_x(201) - r_x(200)}{dis}, |\vec{T}_{200}| \cdot \frac{r_y(201) - r_y(200)}{dis}, \quad (9)$$
$$|\vec{T}_{200}| \cdot \frac{r_z(201) - r_z(200)}{dis})'$$

where dis is the length of every unit.
The force under vehicle coordinate system is:

$$\vec{T}_v = M_{tr} \cdot \vec{T}_{200i} \quad (10)$$

where M_{tr} is the transferring matrix from inertial coordinate system to vehicle coordinate system[11].
moment is:

$$\vec{M}_v = \vec{R} \times \vec{T}_v \quad (11)$$

where $\vec{R}$ is the position vector of released point on vehicle under vehicle coordinate system.

IV. Simulation Analysis

A. *FOMC's tension distribution and shape simulation*

Simulation condition:

1) The value of position, velocity and acceleration of the first micro unit is 0 (which means HOV is in the station keeping or sitting on the seabed).The last unit's velocity is 0.5m/s(which means vehicle is flying in a constant velocity)
2) The length of FOMC is 100.10m
3) FOMC is divided into 200 units and is 201 micro units.
4) Ocean current is two dimension uniform current
5) Simulation step is 0.05s and time is 20s

In the simulation we obtain the state variables in different ocean condition.

Fig 2 and Fig 3 show the tension distribution and FOMC's shape at 4s, 8s, 12s, 16s and 20s. From the Figures we can see that when there is no ocean current, the tension increases from the first unit to the last unit. However, when there exists low speed current, the status of tension distribution is complex. The tension value varies from 0 to 1N.

B. *ROV's dynamics simulation*

Simulation condition is similar to A but the last unit's position, velocity and acceleration are determined by the vehicle's motion. The initial velocity and acceleration of vehicle is 0, initial position is(0m,0.82m,100.10m), and the thrust force is 20N.

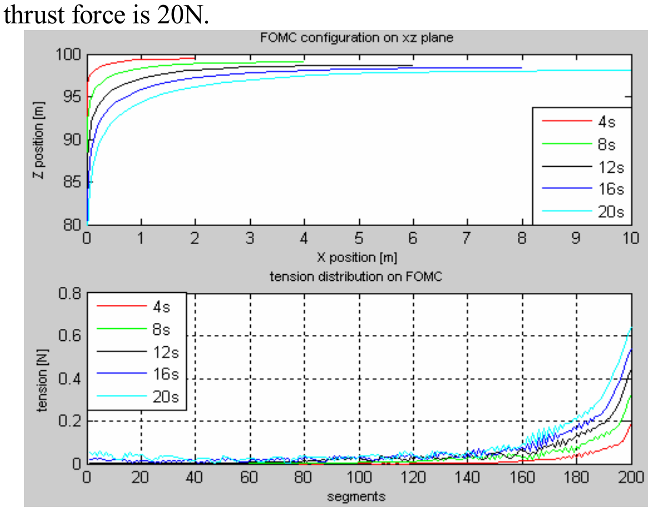

Fig 2. FOMC's tension distribution and shape with no ocean current

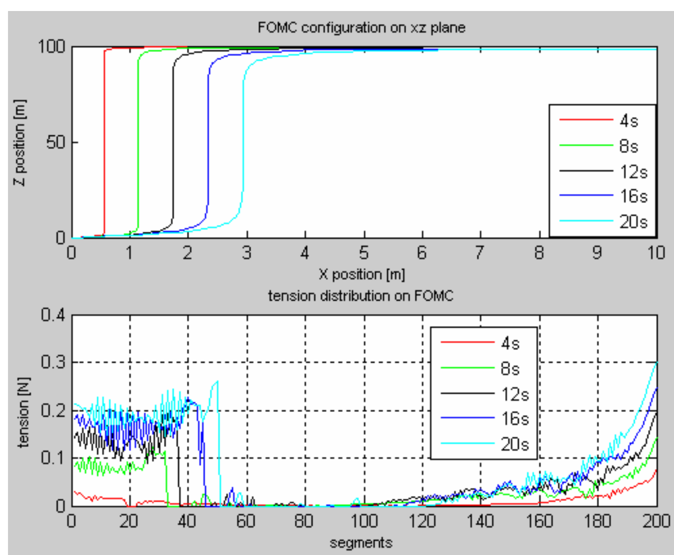

Fig 3. FOMC's tension distribution and shape with velocity of ocean current v = (0.15m/s,0,0)

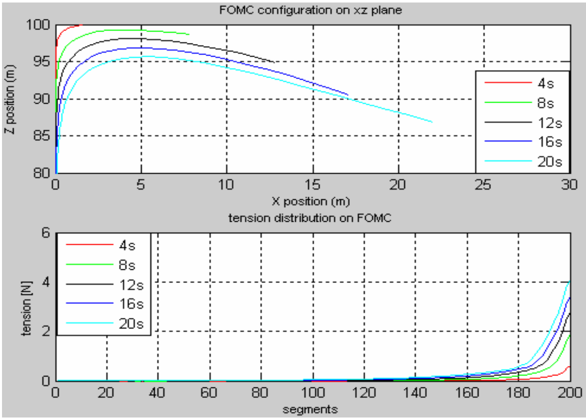

Fig 4. FOMC's tension distribution and shape under no ocean current

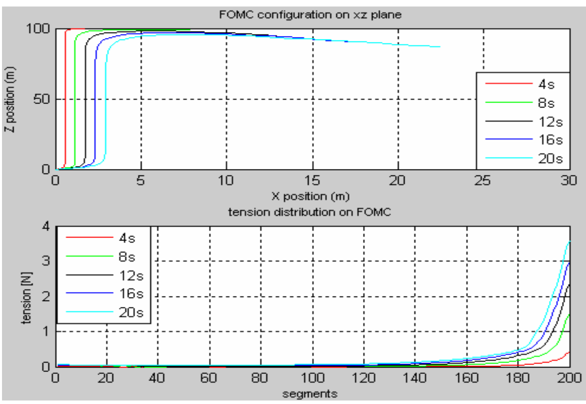

Fig 5. FOMC's tension distribution and shape under velocity of ocean current v = (0.15m/s,0,0)

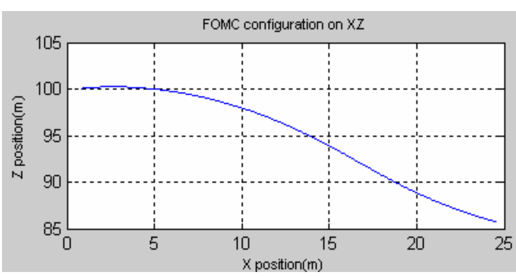

Fig 6. Vehicle dynamic simulation projection on $E\xi\zeta$ without FOMC

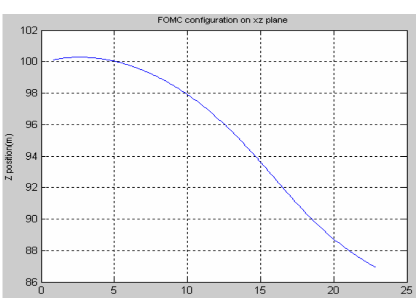

Fig 7 Vehicle dynamic simulation projection on $E\xi\zeta$ with FOMC

In Fig. 4 and Fig. 5, we can get the result as follows: when there is no ocean current or low speed ocean current, the FOMC's tension increases from the first unit to the last unit. The tension's value varies from 0 to 5N. In Fig. 6 and Fig. 7, we can get the result as follows: If we consider the influence produced by FOMC, vehicle's motion state will be different from the state without FOMC. With the FOMC, the vehicle's $E\xi$ and $E\zeta$ value are 1.8m and 0.2m less than that without FOMC after 20 seconds simulation. And the force caused by FOMC can be predicted with the model provided by this paper.

V. Conclusion

In this paper we discussed the FOMC's dynamics, ROV's (connected with FOMC)coupled nonlinear dynamics and kinematics, ROV's motion status and FOMC's tension distribution and shape under the ocean current was simulated. The simulation result indicates that the FOMC's influence to ROV can not be neglected while we discuss the control problem of ROV. In fact actual ROV's operating condition is very complex, i.e. during the course of ROV's release and recovery, the length of cable is variable, so in the next step we will investigate the tension distribution and shape while the length of FOMC is variable.

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