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DYNAMIC MODEL AND SIMULATION OF ONE ACTIVE JOINT ROBOTIC FISH

ABSTRACT

This study considers the dynamic model of one active joint robotic fish by using Lagrange method and simulation of the robotic fish model in MATLAB/SimMechanics environment. Compared results of these two different models are given in the study. The mathematical model of the system is derived from Lagrange energy equations of the robotic fish inspired from a real carangiform fish. The Computer Aided Design (CAD) model of the robotic fish is designed by using SolidWorks and it is transferred to the SimMechanics environment. The hydrodynamic effects, which are linear and nonlinear drag force, are also adapted and head motion, one active joint, and one passive joint angles found by using MATLAB Simulink environment. Obtained results for joint angles from both dynamic and SimMechanics models are compared and proved with animation video of the robotic fish.

Keywords: Robotic Fish, Dynamic Model, SimMechanics Model, Mathematical Model, Biomimetic Design

BİR AKTİF EKLEMLI ROBOT BALIĞIN DİNAMİK MODELİ VE BENZETİMİ

ÖZ

Bu çalışma Lagrange yöntemleri ile elde edilen aktif bir eklemli robot balığın dinamik modelini ve bu robot balığın MATLAB/SimMechanics ortamında benzetimini içermektedir. Bu iki farklı modelin karşılaştırmalı sonuçları bu çalışmada verilmiştir. Gerçek carangiform türünden bir balıktan esinlenilen sistemin matematik modeli Langrange enerji fonksiyonları yardımı ile elde edilmiştir. Bilgisayar Destekli Tasarım (CAD) modeli Solidworks kullanılarak tasarlanmış ve SimMechanics ortamına aktarılmıştır. Ayrıca lineer ve lineer olamayan hidrodinamik etkiler MATLAB Simulink ortamında bulunan baş hareketine, aktif ekleme ve pasif ekleme uygulanmıştır. Eklem açıları için hem dinamik hem de SimMechanics modellerinden elde edilen sonuçlar karşılaştırılmış ve robot balık animasyonu ile kanıtlanmıştır.

Anahtar Kelimeler: Robot Balık, Dinamik Model, SimMechanics Model, Matematiksel Model, Biomimetic Tasarım

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1. INTRODUCTION

Recently, Robotic fish have been becoming more and more popular topic for researchers. It is known that fish swim by bending their bodies, fins and tails. Fish can achieve more propulsion efficiency and more maneuverability than classic propeller systems. By inspiring from these amazing features autonomous underwater vehicles named robotic fish have been developed since 1990s [from 1 to 7]. To design biological structure of a real fish, an appropriate dynamic model should be derived. The whole dynamic model includes both kinematic and hydrodynamic models. First researches about hydrodynamic of the robotic fish were investigated by Triantafyllou and Hirata [6 and 7]. Zhou et al. derived the mathematic model of robotic fish by using Lagrange method [8]. Suebsaiprom and Lin produced two joint robotic fish based on carangiform motion and three dimensional trajectory tracking was implemented [9]. Wang et al. derived dynamic model of one joint robotic fish and compared with experimental studies [10].

Importance of fish in robotic applications and their swimming abilities are mentioned at previous paragraph. Hence, most of studies about robotic fish have concentrated to obtain smooth fish like motion. In 2000s, various multi joint robotic fish were developed and verified with their dynamic models [11]. For instance, Kumar et al. researched a robotic fish inspired from a carangiform fish. The robotic fish can swim long distance and reach extremely speed [12]. Zhou et al. studied European eel’s swimming locomotion in 2008. They obtained the dynamic model of the fish by using Lagrange Methods. After the model was derived, backward swimming mode of a real fish was mimicked by simulated with the dynamic model [13].

MATLAB/SimMechanics environment can be used to achieve easier dynamic model of the robotic systems than complex mathematical equations. SimMechanics was launched as a toolbox in 2008 by MathWorks Company and many mechanical systems have been modelled by using this toolbox. In the literature, many studies have been given. Dung et al. modelled a robot manipulator by using SimMechanics Toolbox [from 14 to 18]. CAD model of a loader was designed by Liu, which is often preferred for engineering projects such as dam and viaduct construction. This model was also imported to SimMechanics [15]. At the same time, mathematical model of a 3-DOF parallel robot mechanism was obtained by Newton-Euler and compared with *SimMechanics* model. These studies show that the mathematical model of a robotic mechanism can be designed and verified in *SimMechanics* environment [16-18].

2. RESEARCH SIGNIFICATION

In this study, dynamic model of the one active joint robotic fish inspired from a real carangiform fish is derived by using Lagrange method. This dynamic model including both kinematic and hydrodynamic effects is realized in *MATLAB*. Also, a Computer Aided Design (*CAD)* model of the robotic fish is drawn in *SolidWorks* and transferred to *MATLAB/SimMechanics* environment. Finally, comparison results of both dynamics and *SimMechanics* models are given and proved with animations. The rest of this paper is arranged as follows: In Section II, dynamic model of the robotic fish is derived. *SimMechanics* model is given in Section III. Compared results are illustrated in Section IV. Finally, conclusions are given in Section V.

3. PROBLEM DESCRIPTION

3.1. Motion Model

Dynamic model of the robotic fish must be derived in order to control and analysis to this robotic system. Because of this obligation, biological system, which is real fish, is considered as a mechanic system similar to a robot arm. This approach is shown in Figure 1.

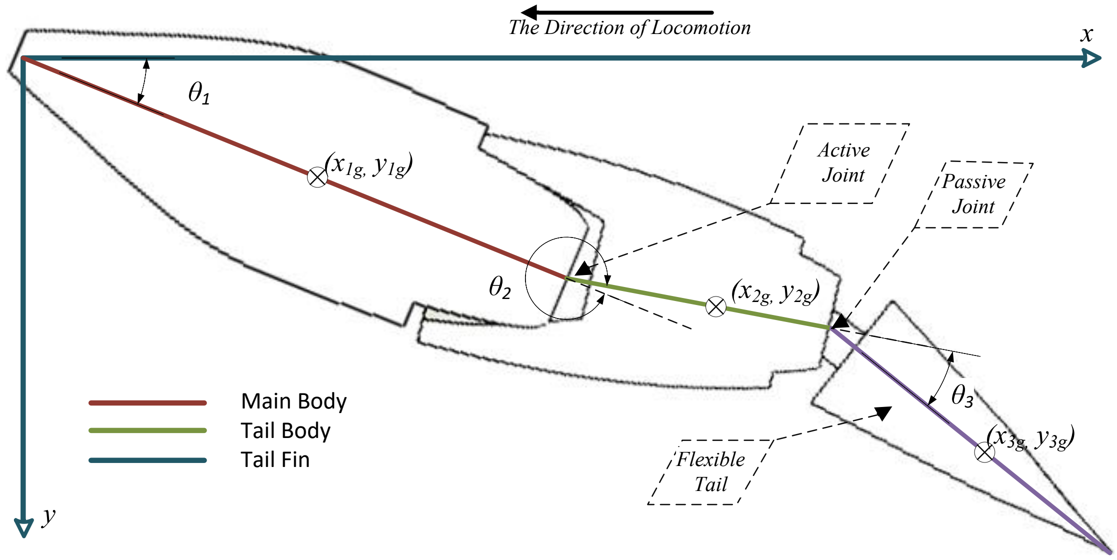

Figure 1. Robotic fish considering as a robot arm

Lagrange method is used to create matematical model of the robotic fish. Thus, center of mass coordinate of every link has to be found. Owing to this reason, Denavit - Hartenberg method is used with Equation (1) which is an translational matrix.

$$ {}^{i-1}Tr_i = \begin{bmatrix} \cos(\theta_i) & -\sin(\theta_i)\cos(a_{i,i+1}) & \sin(\theta_i)\sin(a_{i,i+1}) & A_{i,i+1}\cos(\theta_i) \\ \sin(\theta_i) & \cos(\theta_i)\cos(a_{i,i+1}) & -\cos(\theta_i)\sin(a_{i,i+1}) & A_{i,i+1}\sin(\theta_i) \\ 0 & \sin(a_{i,i+1}) & \cos(a_{i,i+1}) & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1) $$

Where, *i* is link number, *d* and *θ* are displacement and rotation at *z* axis, respectively. *A* and *α* are also displacement and rotation at *x* axis, respectively. Also Tr typifies transformation of axes. After mass center position of every link, are located right column in the matrix, is found, Lagrange equation (*L*) is applied to the robotic system. Equation (2) shows energy function;

$$ L = \frac{1}{2}(m_1\dot{x}_{1_g}{}^2 + m_2\dot{x}_{2_g}{}^2 + m_3\dot{x}_{3_g}{}^2 + m_1\dot{y}_{1_g}{}^2 + m_2\dot{y}_{2_g}{}^2 + m_3\dot{y}_{3_g}{}^2 + J_1\dot{\theta}_1^2 + J_2\dot{\theta}_2^2 + J_3\dot{\theta}_3^2) - V $$
(2)

Where, m is mass of the link and J is inertia of the link. $\dot{x},\dot{y}$ and $\dot{\theta}$ symbolize velocity of x axis, velocity of y axis, and angular velocity, respectively. In Equation (2) the potential energy *V* equals to zero on account of two dimensional motions for the application. In order to obtain Lagrange equation for the system, derivation of the *L* has to be found as below:

$$ \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_k}\right) - \frac{\partial L}{\partial q_k} - \sum_{i=1}^{C}\lambda_i\left(\frac{\partial f_i}{\partial \dot{q}_i}\right) = 0 \quad (3) $$

Here, *q* is each parameter of the system, *k* is current index. *λ*, *f* and *c* symbolize Lagrange multiplier, system constraint and number of system restriction. Thus, the kinematic model of the robotic fish can be obtained.

3.2. Hydrodynamic Force Model

Hydrodynamic force model has vital importance, since this force directly affects the system. There are five hydrodynamic forces on tail fin shown in Figure 2.

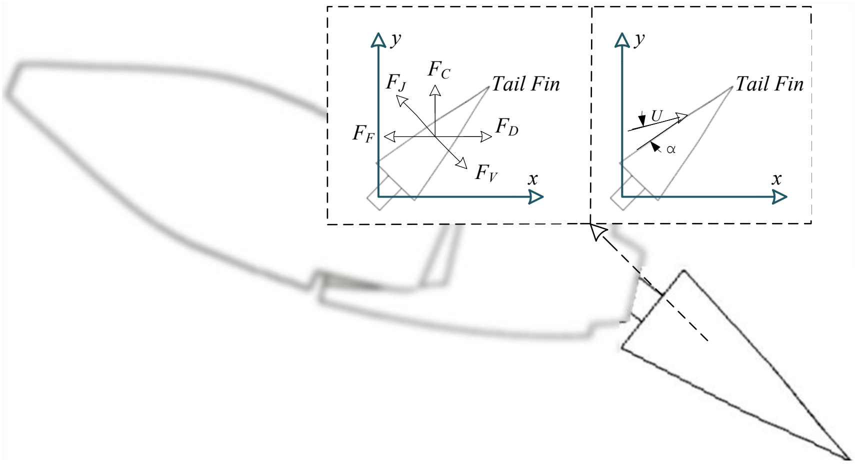

Figure 2. Tail fin and force directions

Fj and Fv are acceleration and lift force, respectively. These forces are given in Equation (4) and (5):

$$F_V = \pi\rho LC^2\dot{U}\sin(a) + \pi\rho LC^2U\dot{a}\cos(a) \quad (4)$$

$$F_J = \pi\rho LCU^2\sin(2a) \quad (5)$$

Where, ρ is density of water, L is length of the fin, C is chord of the fin, U is relative velocity at the center of the fin according to water and α is attack angel of the fin. Forces of the trust (F_F) and yaw angle (Fc) included F_J and F_V are given in Equation (6) and (7).

$$F_F = (F_J(\sin(\theta_1) + \sin(\theta_2) + \sin(\theta_3)) - (F_V(\sin(\theta_1) + \sin(\theta_2) + \sin(\theta_3)) \quad (6)$$

$$F_C = (F_V(\cos(\theta_1) + \cos(\theta_2) + \cos(\theta_3)) - (F_J(\cos(\theta_1) + \cos(\theta_2) + \cos(\theta_3)) \quad (7)$$

F_F provides motion on x axis. F_C provides motion on y axis. Equation (8) shows drag force;

$$F_D = \frac{1}{2}C_D\dot{x}_b{}^2S_x + \frac{1}{2}C_D\dot{y}_b{}^2S_y \quad (8)$$

where, $\dot{x}_b$ and $\dot{y}_b$ are velocity of the body at x and y axes, S_x and S_y are area of the wet surface at x and y axes and C_D is shape coefficient, which are calculated by hydrodynamic analysis method. Five main forces mentioned in this part are added to the system input indicated with τ in motion model.

4. SIMMECHANICS MODELLING OF THE ROBOTIC FISH

The parts of the robotic fish are drawn by using SolidWorks. The CAD model is assembled in this environment as shown in Figure 3.

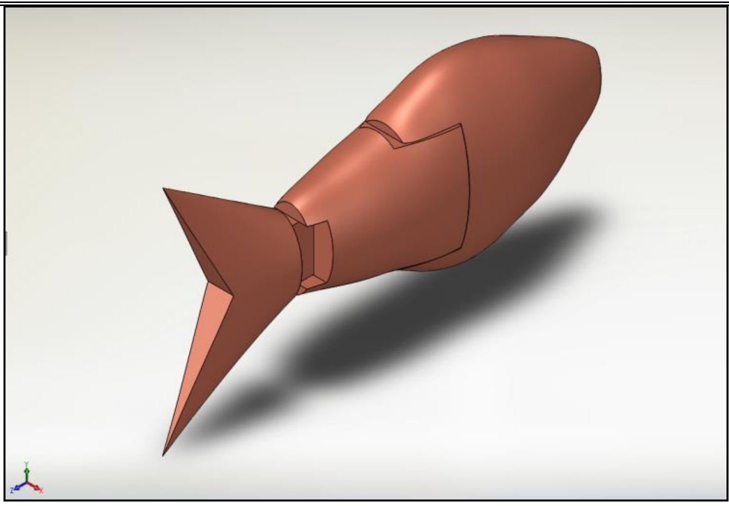

Figure 3. Robotic fish CAD model

After the robotic fish CAD model is designed, this model is transferred to SimMechanics environment as first generation without hydrodynamic effects. The first generation incomplete robotic fish model is illustrated in Figure 4. This model is incomplete, because hydrodynamic forces and motor effects are not applied to the SimMechanics model. Afterwards, these effects are added and whole model shown in Figure 5 is obtained. In this way, the complete model with hydrodynamic effects is also formed.

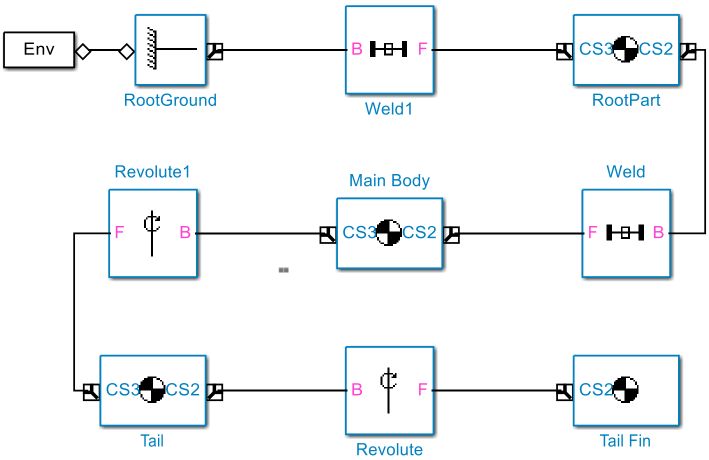

Figure 4. Incomplete Simmechanics model

Multi body simulation for 3D mechanical systems can be designed by SimMechanics environment. Nonlinear engineering models such as robotic and vehicle designs can also be created in this environment. Blocks representing bodies, joints, constraints, and force elements are used in this simulation model. Figure 6 shows the animation of the mechanical model of the robotic fish.

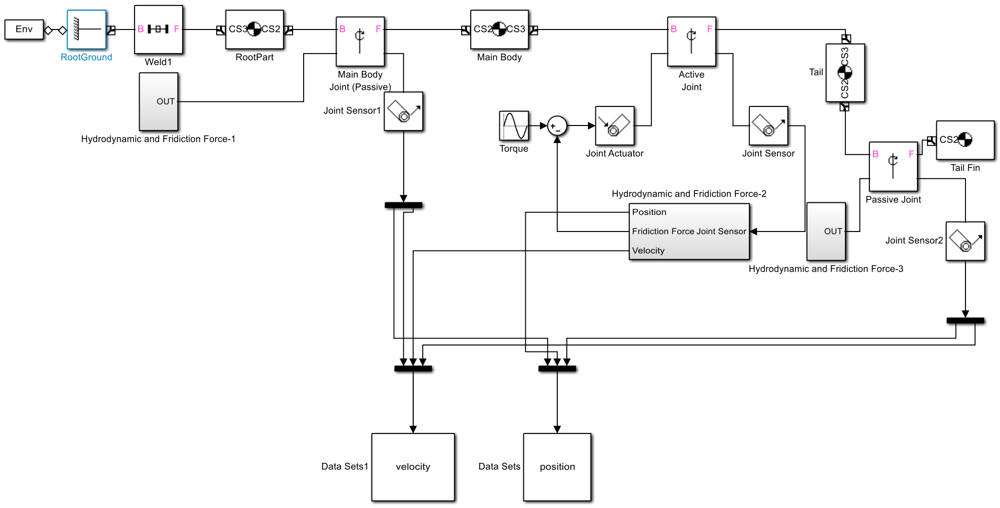

Figure 5. Complete robotic fish SimMechanics Model

CAD model of the robotic fish consisted from mass, joints, inertia and system constants are transferred to SimMechanics to create 3D animation view of the mechanical model.

5. RESULTS

In this study, two individual models, which are given parameter Table 1: dynamic in *MATLAB* and 3D animation in *MATLAB/SimMechanics* are created to compare with each other. Simulation results are shown in from Fig. 6 to 11. Blue and red lines indicate results of the dynamic model and *SimMechanics* model, respectively. From Fig. 6 to 8 present angular velocity of main body, tail body and tail fin of the robotic fish. Since the robotic fish swim by using oscillation of fin, more precise results are obtained with dynamic model from main body to tail. However, *SimMechanics* model of robotic systems can be preferred instead of obtaining dynamic model as it is easy to create for the analysis. Considering all results, the error values between two models are acceptable to design a controller.

Table 1. Simulation parameters

Values of Simulation Parameters			
Symbol	Definition	Value	Unit
m1	Mass of Main Body	0.28826	kg
m2	Mass of Tail Body	0.19552	kg
m3	Mass of Tail Fin	0.15000	kg
J1	Inertia of Main Body	0.0011	kgm^2
J2	Inertia of Tail Body	4.7e-04	kgm^2
J3	Inertia of Tail Fin	1.2e-04	kgm^2
ρ	Density of Fluid	998.2071	kg/m^3
L	Length of Tail Fin	0.075	m
C	Chord of Tail Fin	0.015	m

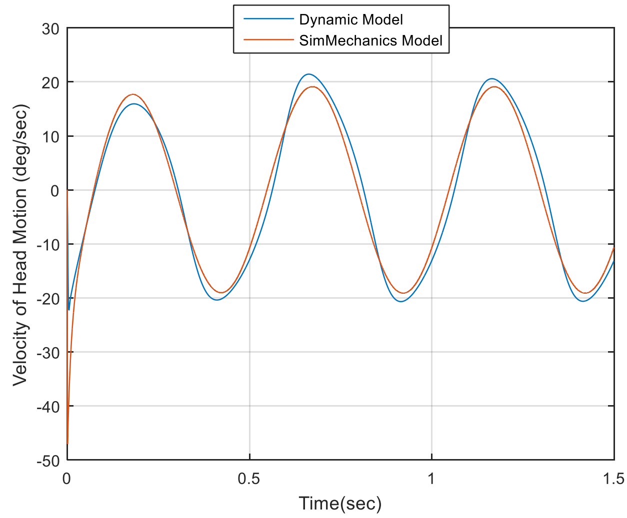

Figure 6. Angular velocity of the main body

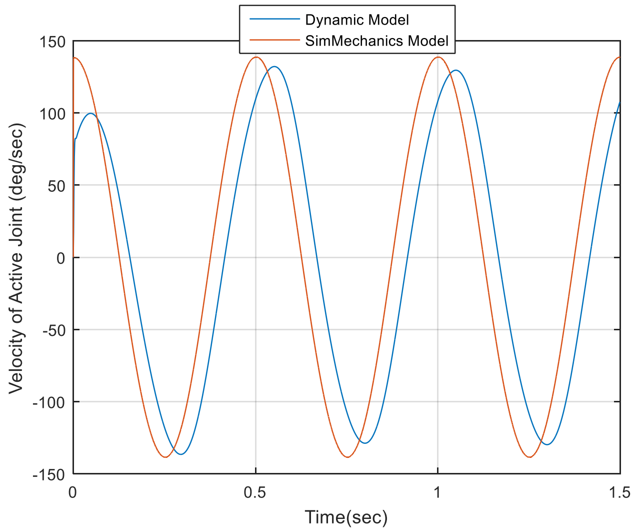

Figure 7. Angular velocity of the tail body

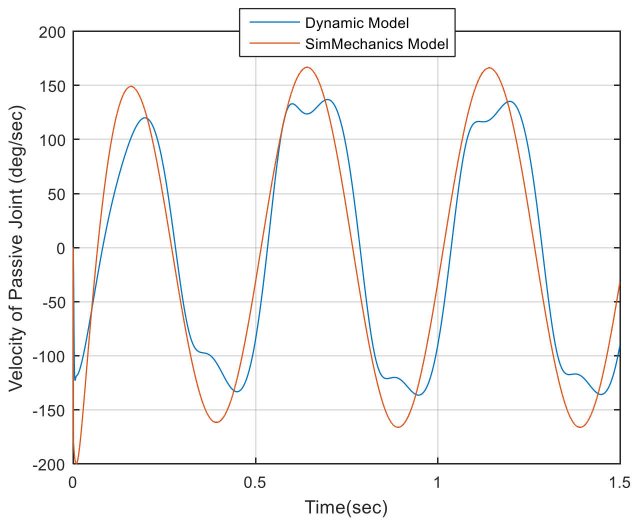

Figure 8. Angular velocity of the tail fin

From Figure 9 to 11 present position of main body, tail body and tail fin of the robotic fish. Acceptable results are also obtained for angles of joints with the SimMechanics model.

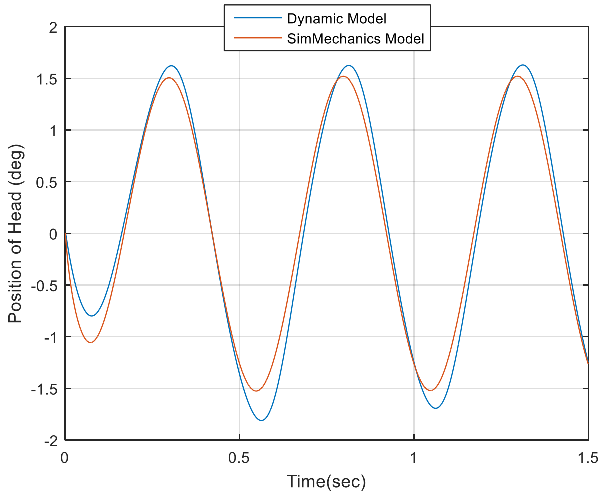

Figure 9. Angle of the main body

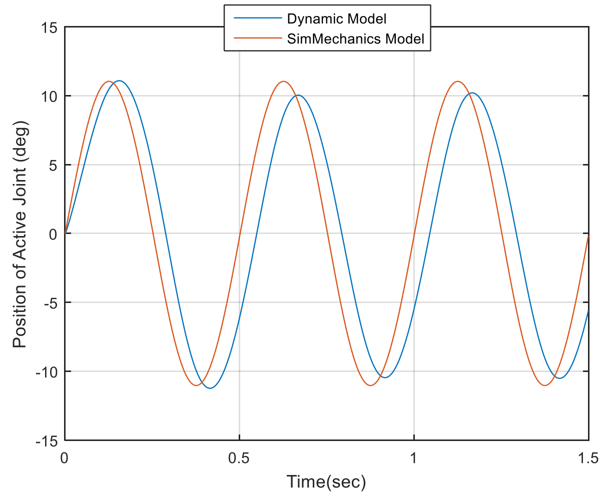

Figure 10. Angle of the tail body

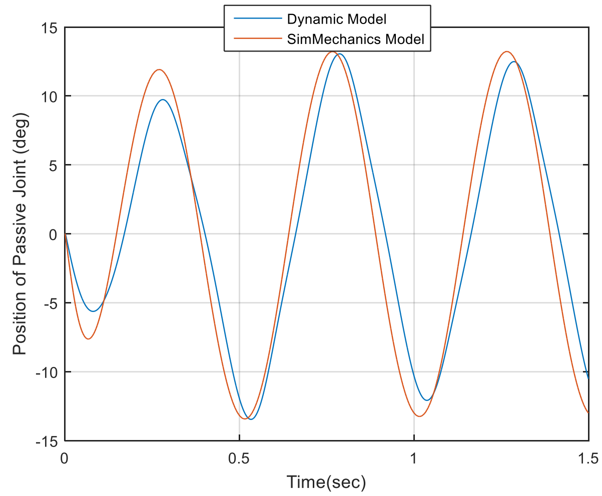

Figure 11. Angle of the tail fin

Animation of the robotic fish is presented in Figure 12 for different times with six images captured from the top view. In detailed animations can be found from *https://youtu.be/IIqG_pAJdwA*. Table 2 shows the joint angles stated in Figure 12 versus different time values.

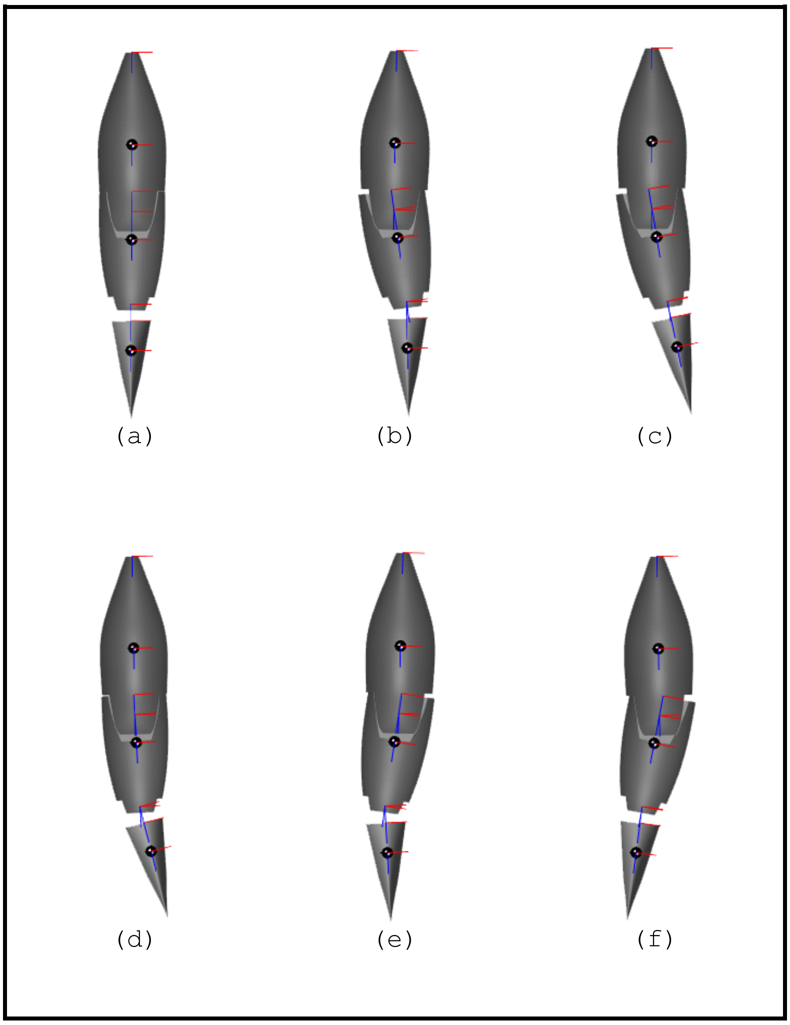

Figure 12. Animation of the robotic fish

Table 2. Animation parameters

Values of the Animation and Picture Locations				
Time (sec.)	θ_1 (deg.)	θ_2 (deg.)	θ_3 (deg.)	Picture
0.00	0.0000°	0.000 °	0.000 °	(a)
0.08	-1.0453 °	9.3151 °	-7.2886 °	(b)
0.16	-0.1370 °	9.9987 °	1.9570 °	(c)
0.23	1.0275 °	2.7612 °	10.491 °	(d)
0.30	-1.5020 °	-6.4717 °	10.839 °	(e)
0.37	0.8920 °	-11.009 °	2.5870 °	(f)

It can be seen from Figure 12 that obtained joint angles from *SimMechanics* model of the robotic fish can animate the robot as a real fish motion in forward swimming mode.

6. CONCLUSION

In this study, two different models which are simple SimMechanics and complex dynamic model of the one active joint robotic fish are designed. The parts of the robotic fish are drawn by using SolidWorks and then CAD model is assembled in this environment. This CAD model is implemented to SimMechanics environment to provide first generation without hydrodynamic effects. The complete SimMechanics model is obtained by adding hydrodynamic forces and motor effects. Dynamic model of the robotic fish is also derived from Lagrange equations. Similar results are provided with two models. Thus, the simple SimMechanics model of the robotic fish can be used instead of complex dynamic model, if one designs a controller for the system. In future works, 3D motion of the robotic fish in x, y, and z axis can be implemented. 3D trajectory tracking can also be provided with this *3D* model of the robotic fish.

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NOTE

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