Development of an Automatic Anti Pitching System (APS) Autonomous Surface Vehicle (ASV) for Fish Mapping

Noverdo Saputra¹, Muhammad Arifudin Lukmana², Purwo Joko Suranto¹

¹ Study Program Naval Architecture, Universitas Pembangunan Nasional Veteran Jakarta, Indonesia
² Study Program Mechanical Engineering, Universitas Pembangunan Nasional Veteran Jakarta, Indonesia

arifudin@upnvj.ac.id

Abstract. The common problem occurs in fish mapping using autonomous surface vehicles (ASV) is pitching stability. Some researchers have indicated that problem affects the results of mapping. The target of this system is to design an Autonomous Pitching System (APS) for ASV using numerical simulation software. The simulation is done by implement APS into the system, producing an oscillatory motion from the ASV. For both dynamics of craft in short and long periods, APS with proportional controller (P), proportional-integral controller (PI), and proportional-integral-derivative controller (PID) are developed in order to minimize the oscillatory behaviour. It was found that for the short period dynamics, the APS with PI controller was the optimal controller, followed by the PID controller and then the P controller. For the long period dynamics, the APS with PID controller was optimal.

1. Introduction

ASV has been one of the biggest challenges faced by naval architects and hydrodynamic researchers over the years especially after the discovery of autonomous ship, therefore much thought has been given to finding different methods that can move ships more stable. ASV can be used in various types of operations, one of which is the field of marine mapping. Stability of ASV still becomes concern of researcher, small perturbation mandatory to get good result during recording image of map.

Idris [7] have tried to use ASV for shallow water mapping, where in the early stages of the ASV system design, researchers focused more on ASV stability and maximum payload than travel speed. Recent study [9] was successfully used fully autonomous control rather than used standard remote control for bathymetry measurement in coastal zone, while the author faces a number of difficulties; in accurate GPS, measurement profiles. Therefore in the future development will replace sensor and develop low seakeeping (low perturbation). River monitoring by USV [6] needs improvement in future work. USV will updating the navigation controller that is currently not optimal by conducting a series of straight and zig zag maneuvers with the aim of identifying system model constants.

In this paper try to solve this problem by implement APS with various controller into the ASV. APS is one system to reduce perturbation on ASV by adding stabilizer into the body of ASV. When designing ASV with APS, it is ideal to implement transfer functions of the ASV dynamics. The unique mathematical model, simulation and results will be discussed in this paper. The short-period motion is characterized by heavily-damped longitudinal motion (lasting several seconds) where the assumptions
of constant speed and zero thrust are incorporated. The long period, which lasts 50 or more seconds, is characterized as being only slightly damped (compared to the short period) and the assumption of a constant angle of attack is made.

2. Numerical Formulation

2.1. Numerical equation of motion ASV

Dynamic motion of ASV have developed and corrected in the last one decade [5], [10], and [11]. The factors that influence in dynamic motion are hydrodynamic force, propulsion system, control system, disturbance, gravity and APS. Total Force can be illustrated as:

\[ F = F_h + F_p + F_c + F_g + F_d + F_{APS} \]  \hspace{1cm} (1)

Each force with equilibrium state with subscript \(0\) and perturbation from the datum with apostrophe (') can be expressed as;

\[ F = F_0 + F' \]  \hspace{1cm} (2)

Collu [3], [4] was proposed planning craft hydrodynamic force with “added mass” and “damping coefficients” with respect to the aero-hydrodynamic axis system, where that forces are extended in a “Taylor series” through the “third order equations of motion” and was written as discrepancy equations with steady coefficients with linearization the non-linear scheme of equations of motion and derivatives are separated in restoring coefficients. That equation expressed as:

\[ F^h = F_0^h + F'^h \]  \hspace{1cm} (3)

Where:

\[ F_0^h = (X_0^h Z_0^h M_0^h)^T \]  \hspace{1cm} (4)

\[ F^h = \begin{bmatrix} 0 & X_h^u & X_h^w & X_h^q \\ 0 & Z_h^u & Z_h^w & Z_h^q \\ 0 & M_h^u & M_h^w & M_h^q \end{bmatrix} \begin{bmatrix} u \\ w \\ q \end{bmatrix} + \begin{bmatrix} X_h^u & X_h^w & X_h^q \\ -u & -w & -q \\ M_h^u & M_h^w & M_h^q \end{bmatrix} \begin{bmatrix} u \\ w \\ q \end{bmatrix} \hspace{1cm} (5) \]

In this paper, the thrust from propulsion system equal with total drag ASV. Control force is zero, assuming control system are fixed. Disturbance from environmental, and other disturbance are neglected. Forces are expressed as:

\[ F_p = F_0^p \]  \hspace{1cm} (6)

\[ F_c = F_0^c \]  \hspace{1cm} (7)

\[ F_d = 0 \]  \hspace{1cm} (8)
Contribution force from gravitational force can be expressed as:

\[ F^g = F_0^g + F^{g'} \]  (9)

Where:

\[ F_0^g = (0 \ mg\theta \ 0)^T \]  (10)

\[ F^{g'} = (-mg\theta \ 0)^T \]  (11)

The APS motion can be expressed like equation traditional aircraft motion, after taking into Taylor linear expansion equation can be expressed as:

\[ F^{APS} = F_0^{APS} + F^{APS} \]  (12)

Where:

\[ F_0^{APS} = (X_0^{APS} \ Z_0^{APS} \ M_0^{APS})^T \]  (13)

\[ F^{APS} = \begin{bmatrix}
0 & X_0^{APS} & Z_0^{APS} & M_0^{APS} \\
0 & Z_0^{APS} & Z_0^{APS} & M_0^{APS} \\
0 & M_0^{APS} & M_0^{APS} & M_0^{APS}
\end{bmatrix}
\begin{bmatrix}
u \\
w \\
q
\end{bmatrix}
+ \begin{bmatrix}
X_0 \ X_0^{APS} & X_0^{APS} & X_0^{APS} \\
Z_0 \ Z_0^{APS} & Z_0^{APS} & Z_0^{APS} \\
M_0 \ M_0^{APS} & M_0^{APS} & M_0^{APS}
\end{bmatrix}
\begin{bmatrix}
u \\
w \\
q
\end{bmatrix} \]  (14)

Equilibrium state equation motion an ASV with APS can be reached after under taking equation (5), (6), (7), (8), (11), (14) into longitudinal linearization equations of motion with accelerations are zero and all the perturbations velocities and the perturbation characteristic (RULM standard). So equation can be expressed as:

\begin{align*}
0 &= X_0^{h} + X_0^{p} + X_0^{c} + X_0^{d} + X_0^g + X_0^{APS} \\
0 &= Z_0^{h} + Z_0^{p} + Z_0^{c} + Z_0^{d} + Z_0^g + Z_0^{APS} \\
0 &= M_0^{h} + M_0^{p} + M_0^{c} + M_0^{d} + M_0^g + M_0^{APS}
\end{align*}  (15)

Where longitudinal linearization equations of motion (assume system equation is decoupled) can be expressed as (apostrophe (‘) representing the perturbation state will be omitted):

\begin{align*}
X &= mu'' \\
Z &= m(w' - q'V_0) \\
M &= I_\theta \ q'
\end{align*}  (16)
After undertaking equation (15) into equation (16) and eliminating the insignificant conditions, the numerical equation of motion an ASV with APS can be shown as:

\[
\begin{bmatrix}
A & [B] & [C]
\end{bmatrix}
\begin{bmatrix}
\dot{u} \\
\dot{w} \\
\dot{q}
\end{bmatrix}
= 0
\]

Where, matrix [A] is the amount of the mass matrix, the hydrodynamic added mass and APS added mass derivatives, Matrix [B] defines as the damping matrix, and Matrix [C] defines as the restoring matrix.

2.2. Transfer Function and Control System

In this system, the transfer function is needed to deflect the ASV dynamic control surface, which is idealized as a motor. This function is a servo control surface control function. First, the given input voltage is applied to the motor (servo) which produces proportional torque which rotates the motor shaft to a certain angle position. From here, the angle position is connected to the control surface. The control surface servo transfer function is given as follows [1], [2]:

\[
\frac{\Delta \delta(s)}{\Delta \delta_e(s)} = \frac{k_a}{s + \frac{1}{\tau}}
\]

Where \( k_a \) is the gain for the motor (generally having an order of magnitude of 10) and is the time constant for the servo motor (0.05 – 0.25 s). The general block diagram for a pitch attitude autopilot was given as follows [1], [2]:

![Figure 1 ASV with APS Control System](image)

As shown \( \theta_c \) is the commanded pitch attitude change (the initial disturbance to the aircraft), \( e \) is the voltage applied to the controller, \( \delta_e \) is the incremental voltage applied to the servo, \( \delta_v \) is the incremental elevator angle, and finally \( \theta \) is the final resulting change in pitch (to compensate for initial disturbance).

The following table lists the P, PI, and PID controllers and their respective forms [1], [2]:
### Table 1. Transfer Function controller

| Controller | General Form of the Transfer Function |
|------------|---------------------------------------|
| P          | $K_p$                                  |
| PI         | $K_p[1+1/(K_i*s)]$                     |
| PID        | $K_p[1+1/(K_i*s)+s*K_d]$               |

Where $K_p$ is the proportional gain, $K_i$ is the integral time constant, and $K_d$ is the derivative time constant.

### 3. Numerical Formulation

The first step in this research was to derive the transfer functions for both the short period and long period motion directly from the state-space equations. For the short period motion, the following transfer functions were derived: $\Delta w(s)/\Delta \delta_e(s)$ and $\Delta q(s)/\Delta \delta_e(s)$. For the long period motion, the following transfer functions were derived: $\Delta u(s)/\Delta \delta_e(s)$, $\Delta w(s)/\Delta \delta_e(s)$, and $\Delta \theta(s)/\Delta \delta_e(s)$. Next, numerical simulation algorithm was developed in order to plot the open loop response (without APS), APS with P-controller response, APS with PI-controller response, and APS PID-controller response for both the short period and long period dynamics. For the proportional (P) controller, the value for $K_p$ was found using the Root-Locus method. The initial guess for the values of $K_i$ and $K_d$ were equivalent to the period of the initial open-loop response. Once the initial guesses for these values were made, the two constants were “tweaked”. The value of $K_i$ was incrementally increased above the initial open-loop response period and each time the response was observed. The value of $K_d$ was incrementally decreased in the same fashion until an acceptable output response was observed for the controllers.

### 4. Result and Discussion

After follow procedure in section 3, effects APS with controller into ASV will be expressed in figures below:

![Figure 2 Short Period ASV Dynamics](image-url)
Figure 2 displays the open-loop short period dynamics response along with the corresponding APS system with P, PI, and PID controllers. As shown, for the short period response, the APS system with PI controller was optimal. Figure 3 displays the open-loop long period dynamics response along with the corresponding APS system with P, PI, and PID controllers. As shown, the APS system with PID controller seemed to be optimal, as it corresponded with the lowest maximum percent overshoot (0.2). However, in this case both the APS with P and PI controllers tended to have lower settling times (~300 s), compared with the PID: 350 s.

5. Conclusion
In this paper the problem pitching stability has been tried to be solved by adopting APS with controller. Results show about 15 % of perturbation reduction at beginning of APS system with PI controller was applied (at 2 sec) for short periodic, while 80% perturbation was decrease at 50 sec after running the system (APS with PID was optimal). However further experimental investigations is required to validate new equation of ASV with APS and to find type of stabilizer and controller to optimize the result.

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