Design of 6-DOF Attitude Controller of the UAV Simulator's Hovering Model

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Abstract : For a maneuvering unmanned autonomous helicopter, it is necessary to design a proper controller of each flight mode. In this paper, overall helicopter dynamics is derived and hovering model is linearized and transformed into a state equation form. However, since it is difficult to obtain parameters of stability derivatives in the state equation directly, a linear control model is derived by time-domain parametric system identification method with real flight data of the model helicopter. Then, two different controllers - a linear feedback controller with proportional gains and a robust controller - are designed and their performance is compared. Both proposed controllers show outstanding results by computer simulation. These validated controllers can be used to autonomous flight controller of a real unmanned model helicopter.

Keywords: UAV Simulator, System Identification, Helicopter, Hovering

1. INTRODUCTION

Recently, the core of aerospace industries is moving to UAV(Unmanned Aerial Vehicle), which is better than manned aircraft in some respects such as flight stability for highly dangerous works, physical limits caused by long-time flight or sudden maneuver, enormous time and expenditure cost for pilot training. System design problem is very important since UAV system plays its role as a testbed which fundamental researches such as controller design and system identification can be carried out and evaluated. UAV system design problem itself consists of many study fields, system identification, feedback control system, design and manufacture of sensors, signal processing, real-time control software design.

In developing UAV, many aircraft platforms can be used. Among them, especially, a helicopter is suitable to the application of an intelligent unmanned aerial vehicle since it has various, useful maneuvering that other platforms do not have. Helicopters can perform various missions which fixed-wing aircrafts cannot do because they have abilities such as hovering, vertical takeoff-landing, low-speed cruise, pirouette, etc. Therefore, RUAV(Rotorcraft-based UAV) which has an advantage of various maneuverabilities has been developed for many uses, such as military use, observing forest fires, spraying agricultural chemicals, aerial photographing. Additionally, lately "Pursuit-Evasion" problem, which given missions are accomplished using autonomy and artificial intelligence with a hybrid system including several autonomous UAV or UGVs(Unmanned Ground Vehicle)[6].

When flying in a location, which it is difficult for people to approach, it is impossible to observe the RUAV and dangerousness of crash is increased. Therefore, the automatic control for each flight mode is essential in order to increase helicopter stability and prevent unexpected accidents.

The main subject of this paper is the attitude control of hovering helicopter. Especially, we design a 6-DOF controller for the helicopter that can flight autonomously having sensors and a wireless communication device. In addition, we design controllers of hovering, one of the most important modes for helicopter and validate their performance through computer simulation. As mentioned above, since a model helicopter is sensitive to disturbance and noise, designing goal is a robust controller which can cancel uncertain external effects.

Helicopter model is derived from general full size helicopter model[1]. Nonlinear model obtained is used directly to simulation model and linear model for controller design is derived as simplified form through linearizing. A parametric model for hovering helicopter is identified using collected data by the identification algorithm. After deriving model, two control theories - conventional control theory and linear robust control theory based on state-space - are applied for helicopter stabilization. Proposed controllers, although this paper doesn't treat, should be tested with a fully equipped real helicopter and validated their performance hereafter.

2. HELICOPTER DYNAMICS

Helicopter dynamics is a MIMO time-variant system which has nonlinearity, inherent instability, and strong coupling. And helicopter is exposed to unstable disturbance such as gust or side wind while acting in various modes of vertical takeoff-landing, hovering, and forward flight. Since helicopter's aerodynamic characteristics is very complicated and chaotic, it is actually impossible to obtain exact dynamic equations for all flight modes mentioned previously. The model for simulation and controller design is derived with appropriate accuracy which answers the purpose because a theoretical model usually has somewhat large error and it should be adjusted by experimental data. So, we obtain a nonlinear dynamic model of helicopter through the lumped parameter approach. In this way, a unique dynamics of small model helicopter called "servorotor" is included and general dynamics is simplified to a model valid for hovering and low-speed cruise.

2.1 General Characteristics

Helicopter dynamics follows Newton-Euler equations for translational / rotational rigid body.

Dynamic equations are represented as the body coordinate system. $\boldsymbol{F}_{ext}$ and $\boldsymbol{M}_{ext}$ are the sum of external force and moment which rigid body receives and they describe dynamics of helicopter definitely. The main problem of modeling is finding these terms. Helicopter dynamics consists of following components - main rotor, tail rotor, fuselage, horizontal stabilizer fin, and vertical stabilizer fin - by using the lumped parameter method and is researched by regarding these elements as sources of force and moment. Free-body diagram of helicopter is shown in Fig. 1.

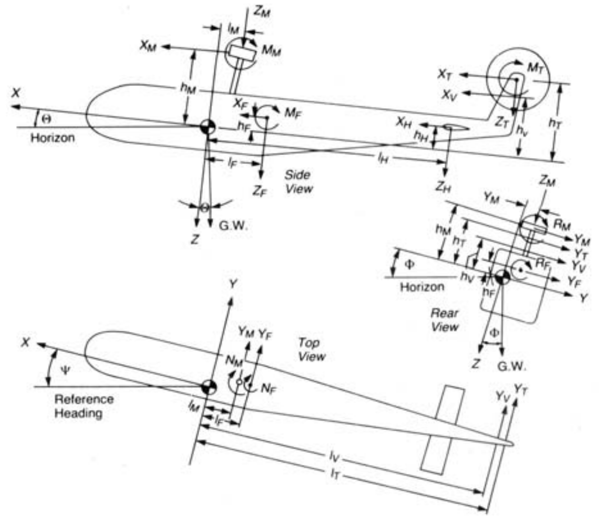

Fig. 1 Helicopter Free-body Diagram

Forces of x, y, z direction are denoted by X, Y, Z respectively and Moment terms of roll, pitch, yaw are denoted by R, M, N respectively. M, T, F, H, V denote main rotor, tail rotor, fuselage, horizontal stabilizer fin, and vertical stabilizer fin respectively. Among rotational inertial moments, we can express force and moment equations neglecting the cross inertia term.

$$\dot{V}_b = \frac{1}{m}\begin{bmatrix} X_M + X_T + X_H + X_V + X_F \\ Y_M + Y_T + Y_V + Y_F \\ Z_M + Z_T + Z_H + Z_V + Z_F \end{bmatrix} + R_{TP\to B}\begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix} + \begin{bmatrix} -vr - wq \\ -ur + wp \\ uq - vp \end{bmatrix} \quad (1)$$

$$\dot{\omega} = I_b^{-1}\begin{bmatrix} R_M + Y_M h_M + Z_M y_M + Y_T h_T + Y_V h_V + Y_F h_F + R_F \\ M_M - X_M h_M + Z_M l_M + M_T - X_T h_T + Z_T l_T - X_H h_H + Z_H l_H - X_V h_V + M_F \\ N_M - Y_M l_M - Y_T l_T - Y_V l_V + N_F - Y_F l_F \end{bmatrix} + I_b^{-1}\begin{bmatrix} qr(I_{yy} - I_{zz}) \\ pr(I_{zz} - I_{xx}) \\ pq(I_{xx} - I_{yy}) \end{bmatrix} \quad (2)$$

In above equations, we evaluate each force and moment term and measure geometrical constants such as location of center of gravity, main rotor, tail rotor, and stabilizer fin. The equation of each force and moment term can be derived according to the result of Prouty[1]. However, since related aerodynamics is very complicated, it is not easy to derive exact equations. When derivation is completed, we can make a simulation model and a control model.

2.2 Helicopter Modeling in Hovering

Since it is usually impossible to find exact force and moment terms in whole flight envelope, in order to obtain more accurate and simple equations, we should divide flight envelope into several flight modes. In this paper, we derive a model equation for hovering mode, one of the most important maneuvers, and design a controller. Helicopter dynamics in hovering is simplified with following assumptions.

- Neglect the effect of fuselage, horizontal / vertical stabilizer fins because helicopter has very low velocity in all direction and attitude deviation is very small.
- Neglect local inflow of other directions and the tail rotor shaft follows +y axis. That is, only lateral thrust, yawing moment, and anti-torque of pitch axis are generated.

According to above two assumptions, derivative equations (1, 2) are simplified as followings.

$$\dot{V}_b = \frac{1}{m}\begin{bmatrix} X_M \\ Y_M + Y_T \\ Z_M + Z_H + Z_F \end{bmatrix} + R_{TP\to B}\begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix} + \begin{bmatrix} -vr - wq \\ -ur + wp \\ uq - vp \end{bmatrix} \quad (3)$$

$$\dot{\omega} = I_b^{-1}\begin{bmatrix} R_M + Y_M h_M + Z_M y_M + Y_T h_T \\ M_M - X_M h_M + Z_M l_M + M_T + Z_H l_H \\ N_M - Y_M l_M - Y_T l_T \end{bmatrix} + I_b^{-1}\begin{bmatrix} qr(I_{yy} - I_{zz}) \\ pr(I_{zz} - I_{xx}) \\ pq(I_{xx} - I_{yy}) \end{bmatrix} \quad (4)$$

Then, with the system equations simplified for hovering, each variable of derived equations(3, 4) is evaluated and overall equations are as following.

$$\dot{V}_b = \frac{1}{m}\begin{bmatrix} -T_M \sin a_{1s} \\ -T_M \sin b_{1s} - T_T \\ -T_M \cos a_{1s} \cos b_{1s} + Z_H + Z_F \end{bmatrix} + R_{TP\to B}\begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix} + \begin{bmatrix} -vr - wq \\ -ur + wp \\ uq - vp \end{bmatrix} \quad (5)$$

$$\dot{\omega} = I_b^{-1}\begin{bmatrix} -\left(\frac{dR}{db_{1s}}\right)b_{1s} - T_M h_M \sin b_{1s} - Q_M \sin a_{1s} - T_M y_M - T_T h_T \\ \left(\frac{dM}{da_{1s}}\right)a_{1s} + T_M h_M \sin a_{1s} - Q_M \sin b_{1s} + T_M l_M - Q_T + Z_H l_H \\ -Q_M \cos a_{1s} \cos b_{1s} + T_M \sin b_{1s} l_M + T_T l_T \end{bmatrix} + I_b^{-1}\begin{bmatrix} qr(I_{yy} - I_{zz}) \\ pr(I_{zz} - I_{xx}) \\ pq(I_{xx} - I_{yy}) \end{bmatrix} \quad (6)$$

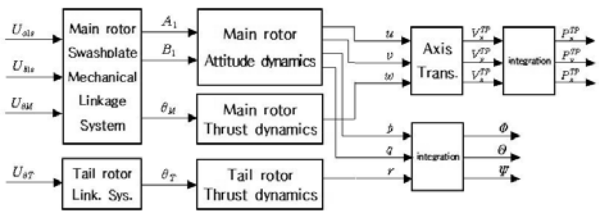

Fig. 2 Block-diagram of Helicopter dynamics

Nonlinear model for hovering is useful as nonlinear simulation model and can be simplified in order to obtain linear model. Linear dynamic model of helicopter is necessary to design linear feedback control system. Now, we define nonlinear helicopter dynamics.

$$\dot{x} = F(x, u) \quad (7)$$

where

$$x = [u \quad v \quad w \quad \Phi \quad p \quad \Theta \quad q \quad \Psi \quad r \quad a_{1s} \quad b_{1s}]^T \quad (8)$$

$$u = [u_{a1s} \quad u_{b1s} \quad u_{\theta M} \quad u_{\theta T}]^T \quad (9)$$

u_{a1s}, u_{b1s} : lateral, longitudinal cyclic pitch input

$u_{\theta M}$, $u_{\theta T}$: main, tail rotor collective pitch input

For nonlinear control model, we can use directly nonlinear simulation model or model which has simplified and approximated thrust and torque terms. In this paper, the main purpose of this research is the design of controller for hovering and linear time-invariant model for hovering. Therefore, we assume as followings.

- The velocity and attitude angles are assumed to be very small so that the following simplifications are valid.

$$\sin x \cong x \quad , \cos x \cong 1 \quad (10)$$

- With the assumption that the rigid body has small velocity and attitude angles in every direction, the Coriolis acceleration terms and gyroscopic terms are ignored.

Applying these assumptions to the original equation, we obtain the differential equation.

$$\dot{x} = F(x,u) = \begin{bmatrix} -\frac{1}{m} T_M a_{1s} - g\Theta \\ -\frac{1}{m}(T_M b_{1s} + T_T) + g\Phi \\ \frac{1}{m}(-T_M + Z_H + Z_F) + g \\ p \\ \frac{1}{I_{xx}}\left[-\left\{ \left(\frac{dR}{db_{1s}} \right) + T_M h_M \right\} b_{1s} - Q_M a_{1s} - T_M y_M - T_T h_T \right] \\ q \\ \frac{1}{I_{yy}}\left[\left\{ \left(\frac{dM}{da_{1s}} \right) + T_M h_M \right\} a_{1s} - Q_M b_{1s} + T_M l_M - Q_T + Z_H l_H \right] \\ r \\ \frac{1}{I_{zz}}\left[-Q_M + T_M b_{1s} l_M + T_T l_T \right] \\ -\frac{a_{1s}}{\tau_f} - q + A_{b1s} b_{1s} + A_{ua1s} u_{a1s} + A_{ub1s} u_{b1s} \\ -\frac{b_{1s}}{\tau_f} - p + B_{a1s} a_{1s} + B_{ua1s} u_{a1s} + B_{ub1s} u_{b1s} \end{bmatrix} \quad (11)$$

The linearized system equation is defined as the Jacobian matrices in the following.

$$\delta\dot{x} = \left[\frac{\partial F_j}{\partial x_i} \right]_{\substack{x = x_{trim} \\ u = u_{trim}}} \delta x + \left[\frac{\partial F_j}{\partial u_i} \right]_{\substack{x = x_{trim} \\ u = u_{trim}}} \delta u \quad (12)$$

The Jacobian, often referred to as the stability derivatives, can be found by the partial differentiation of the system equation ***F(x,u)***. The valuable results on calculating the Jacobian were suggested by Prouty[1]. Using his work, the Jacobian matrices can be computed by simply plugging in the parameters of the target helicopter.

These parameters are geometric, aerodynamic, and special mechanical parameter following helicopter system. Among them, while there exist easily measured parameters, usually it is very difficult to understand these characteristics without special equipments. Moreover, because the airframe is heavy and large, it is also difficult to measure the inertia directly. Therefore, in this paper, without measuring these parameters, we use system identification method to find a system model directly using the flight data.

3. SYSTEM IDENTIFICATION

As explained in the previous section, we use the parameter identification approach instead of using the theoretical model. In the following, the template model for the LTI MIMO parametric identification is given. This model is proposed by Mettler et al in 1999[2].

This model also includes the servorotor(Bell-Hiller Stabilizer) dynamics, which almost all model helicopters adopt, as a first-order approximation. And by having the servomotor PWM input as the control input, we do not need to identify the servomotors and the linkage gains separately and they are identified as a whole in the identification process. In the following, the template model is shown.

$$\dot{x} = Ax + Bu \quad (13)$$

$$x = \begin{bmatrix} u & v & p & q & \Phi & \Theta & a_{1s} & b_{1s} & w & r & \Psi \end{bmatrix}^T \quad (14)$$

$$u = \begin{bmatrix} u_{a1s} & u_{b1s} & u_{\theta M} & u_{\theta T} \end{bmatrix}^T \quad (15)$$

$$A = \begin{bmatrix} X_u & 0 & 0 & 0 & 0 & -g & X_{a1s} & 0 & 0 & 0 & 0 \\ 0 & Y_v & 0 & 0 & g & 0 & 0 & Y_{b1s} & 0 & 0 & 0 \\ L_u & L_v & 0 & 0 & 0 & 0 & L_{a1s} & L_{b1s} & 0 & 0 & 0 \\ M_u & M_v & 0 & 0 & 0 & 0 & M_{a1s} & M_{b1s} & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 & -1/\tau_f & A_{b1s} & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 & B_{a1s} & -1/\tau_f & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & Z_{a1s} & Z_{b1s} & Z_w & Z_r & 0 \\ 0 & 0 & N_p & 0 & 0 & 0 & 0 & 0 & N_w & N_r & N_{rfb} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & K_r & K_{rfb} \end{bmatrix} B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ A_{u_{a1s}} & A_{u_{b1s}} & 0 & 0 \\ B_{u_{a1s}} & B_{u_{b1s}} & 0 & 0 \\ 0 & 0 & Z_{u_{\theta M}} & 0 \\ 0 & 0 & N_{u_{\theta M}} & N_{u_{\theta T}} \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (16,17)$$

$$A = \begin{bmatrix} -0.1257 & 0 & 0 & 0 & 0 & -g & -g & 0 & 0 & 0 & 0 \\ 0 & -0.4247 & 0 & 0 & g & 0 & 0 & g & 0 & 0 & 0 \\ -0.1677 & 0.0870 & 0 & 0 & 0 & 0 & 36.7050 & 161.1087 & 0 & 0 & 0 \\ -0.0823 & -0.0518 & 0 & 0 & 0 & 0 & 63.5763 & -19.4931 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 & -3.4436 & 0.8287 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 & 0.3611 & -3.4436 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 9.6401 & -0.7598 & 8.4231 & 0 \\ 0 & 0 & -1.3300 & 0 & 0 & 0 & 0 & 0 & 0.0566 & -5.5105 & -44.8734 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1.8157 & -11.0210 \end{bmatrix}$$

(18, 19)

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -0.8417 & 2.8231 & 0 & 0 \\ -2.4090 & -0.3511 & 0 & 0 \\ 0 & 0 & 70.5041 & 0 \\ 0 & 0 & 23.6260 & 44.8734 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

A MIMO model like above can be identified with a number of numerical optimization algorithms. In this research, the prediction-error method(PEM) in the MATLAB System Identification Toolbox is chosen[4].

3.1 Real Flight Data

In order to identify each parameter of system matrices, collecting flight data is needed first. For this purpose, UAV platform which hardware and software that can measure pilot's control inputs and aircraft's responses are installed is needed. During experimental flight, pilot gives control inputs for each channel(roll, pitch, yaw, heave) and the responses of aircraft are recorded in the ground computer through the wireless communication device.

In a certain interval, longitudinal and lateral controls are issued in mixed way to capture the cross-coupling of these two channels. In the first stage, the controls in the longitudinal and the lateral channels are given simultaneously, while other channels are controlled to maintain constant value. Next, the main rotor collective pitch or the tail rotor collective pitch is perturbed. Finally, the control signal is issued into all channels simultaneously to check the validity of the cross-coupling terms. It should be noted that, due to the coupled and unstable dynamics, the pilot has to issue a stabilizing command to keep the helicopter in a confined area. This hinders the data collection of a one-channel-at-a-time response.

In this paper, we obtain real-flight experimental results of the helicopter with inertial sensors and wireless communication device.

Fig. 3 Kyosho Caliber 30

The model helicopter used in this experiment is a radio-control helicopter called Caliber 30 made by Kyosho Industry, Japan. This helicopter has the structure with one main-rotor and one tail-rotor. Since it has the Bell-Hiller stabilizer system, helicopter dynamics mentioned before can be properly applied. Additionally, it consists of aluminum body frame, metal linking device, and so on.

In order to give attitude and position information to helicopter stabilizing controller, exact translational / rotational acceleration, position should be measured using inertial navigation system and GPS. In our experiment, we obtain real-flight data with INS produced by MicroInfinity. We use also PCB-based RF module which has properties of 39800 bps and RS-232C to send obtained data to ground station. Obtained real-flight data of the helicopter is shown as Fig. 4.

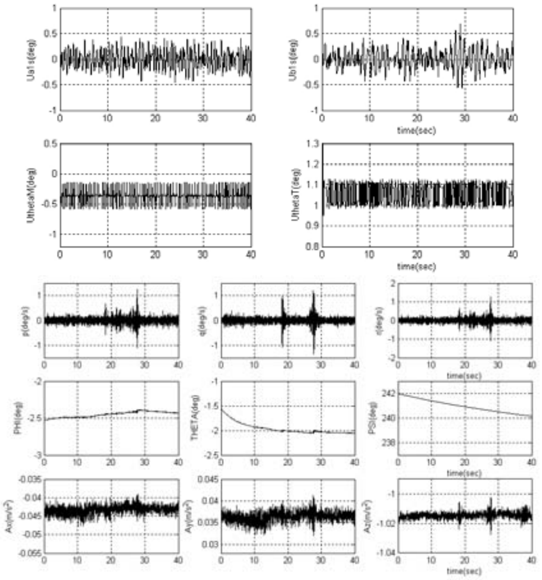

Fig. 4 Real-flight Data

Once adequate flight data has been collected, we identify the parameters in the system matrices using an identification algorithm. Before feeding the data into the numerical tool, the data is preprocessed. The angular rate measurements are filtered by zero-phase non-causal discrete-time filters to filter out high frequency noise without introducing phase delay. The roll and pitch angle measurements are detrended because the helicopter has a trim condition, the equilibrium with certain nonzero states.

3.2 Experimental Hover Model

It should be noted that this method is extremely sensitive to the initial guess of the parameters. It also easily trapped in local minima of the parameter hypersurface. To obtain meaningful results and while avoiding these weaknesses, the following technique is devised[3]. First, the attitude dynamics, which are augmented with the rotor dynamics, is identified using an initial guess. Since the angular rate/rotor dynamics are known to be stable, the derived numerical solution converges to consistent solutions. Then, the horizontal dynamics, the longitudinal and lateral dynamics with linear velocity terms u and v are identified while the parameters for angular dynamics are fixed. This stage is rather challenging due to the unstable linear velocity dynamics. Finally, the heave and yaw dynamics are identified in a similar manner and the cross-coupling terms are estimated.

We can observe that the roll and pitch rate show superb matching because of the explicit servorotor model. However, the model shows rather poor matching in some intervals because the actual dynamics is a very complicated of the engine, the transient lift, and the cross-coupling with the roll, pitch and yaw. In the following, the identified system matrices are shown.

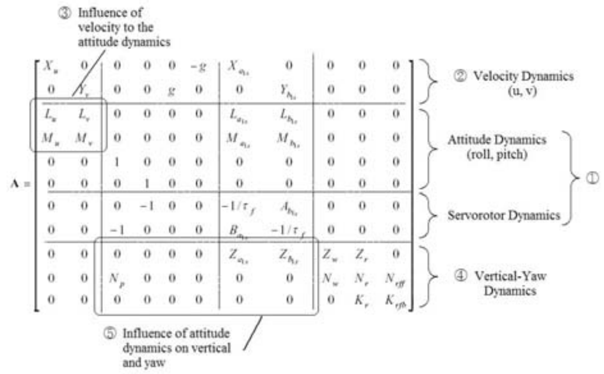

Fig. 5 The procedure of system identification using PEM

The eigenvalues of the identified model are listed in Table 1. The linearized system model has stable eigenvalues except for only one pair of complex conjugate in the right half plane, which renders the whole helicopter dynamics unstable. This unstable mode is the coupled motion in u and v channels and the responses in all other channels are stable. The rotor dynamics is essentially symmetric and the difference between them is generated by the different values of the mass moment of inertia in the roll and pitch axis.

Table 1 Eigenvalues of the identified helicopter system

Mode	Eigenvalue	Mode	Eigenvalue
Phugoid 1	-0.5262±0.0755j	Pitch	-1.8659±8.2757j
Phugoid 2	0.2458±0.0279j	Yaw	-8.2845±8.5845j
Roll	-1.5725±12.2567j	Heave	-0.7223

4. CONTROLLER DESIGN

The helicopter has inherently unstable, complicated and nonlinear dynamics under the significant influence of exogenous disturbances and parameter perturbations. To carry out given missions, the helicopter needs a feedback controller that is consistently reliable. Therefore, in this paper, we seek a suboptimal controller using the model-based approach.

There have been a number of attempts[7, 8, 9] to apply modern control theories to the helicopter control problem because the modern control approach offers many superior features over classical controls such as : decoupling, robustness, and sophisticated performance specification, although it has not won many practitioners in industries yet. Our goal in this research is to design a proper controller for a working autopilot system for our helicopters. Although there are many fancy control theories promising theoretically beautiful results, the reality is, only a handful of these can be actually applied to the complicated helicopter dynamics. Therefore, we choose to deploy the linear control theory for its consistent performance, well-defined theoretical background and effectiveness proven by many practitioners. Especially, to stabilize helicopter in hovering mode, we design the controllers based on the conventional SISO control theory and MIMO state-space control such as H_∞.

4.1 Conventional SISO Controller

The system equation in equations (13~17) represents a MIMO system with moderate coupling among the roll, pitch, yaw, and heave channels. The roll and pitch responses show coupling and the vertical mode agitates the yaw model due to the persistently varying anti-torque of main rotor. However, this system can be considered to be four sub-systems of roll - v_y, pitch - v_x, yaw and heave channels and each can be stabilized by proportional gain controllers.

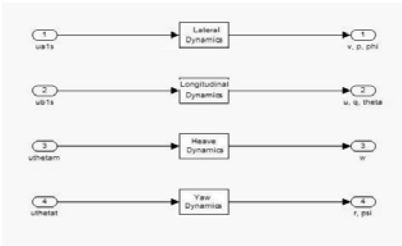

Fig. 6 Decoupling of helicopter dynamics

The control law by the classical SISO approach is established as shown in equation (20). The control law is very simple and static. Dynamics of each channel shows satisfactory performance only by state feedback with proportional gains. Currently, it does not involve any dynamic controllers yet because the static control can maintain a reasonable performance and the measurements for feedback do not require any further filtering[5].

$$u_{a1} = -K_\Phi \Phi - K_v v - K_{p_y} \Delta_{p_y}$$
$$u_{b1} = -K_\Theta \Theta - K_u u - K_{p_x} \Delta_{p_x}$$
$$u_{\theta M} = -K_w w - K_{p_z} \Delta_{p_z}$$
$$u_{\theta T} = -K_\Psi \Psi \qquad (20)$$

Proper gains for each output that can stabilize attitude and translational dynamics of helicopter is derived as following. First, through the root-locus and step response, we determine roughly the interval of gain by trial-error and adapted it in the loop. Then, by adjusting gains slightly related to each direction(lateral, longitudinal, heave, yaw), we obtain them by experience to show stable flight in hovering.

4.2 H∞ Controller

Due to the inherent cross-coupling of the rotor dynamics, MIMO control algorithms are more desirable than SISO which neglect the effect of coupling. Especially, among many MIMO control theories, H_∞ control theory is suitable to helicopter control because it satisfies the robustness specification for unexpected disturbances and the performance specification.

Among many robust control theories, especially the design procedure of H_∞ controller for the mixed-sensitivity problem is briefly explained in the following[10].

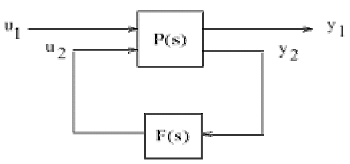

Fig. 7 Robust control problem

As shown in Fig. 7, linear time-invariant plant *P(s)* is mapping external input signal $w(u_1)$, control input $u(u_2)$ to control quantity $z(y_1)$, observed output $y(y_2)$ respectively.

Optimal H_∞ controller design problem is finding a stabilizing controller which makes the closed-loop gain between disturbance w and error signal z smaller than gamma, satisfying $u_2(s)=F(s)y_2(s)$. Gain $T_{y1u1}(s)$ is the transfer function of w to z, and it can be expressed as following equation.

$$\|T_{y1u1}\|_\infty \le \gamma \quad \text{where} \quad T_{y1u1} = \begin{bmatrix} W_1 S \\ W_3 T \end{bmatrix} \qquad (21)$$

H_∞ norm is defined as following[11].

$$\|G(s)\|_\infty = \sup \sigma_{\max}(G(jw)) \qquad (22)$$

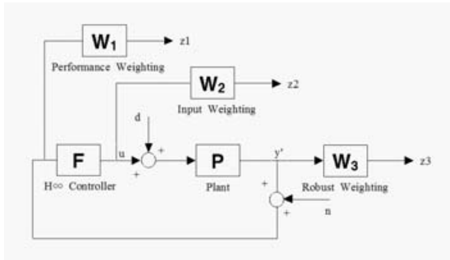

Fig. 8 Mixed-sensitivity problem

In the mixed-sensitivity problem shown as the block diagram like Fig 6, determining W_1 and W_3 is very important. This fact can be confirmed from restraints for mixed-sensitivity H_∞ controller like equation (21)[12].

The choice of weighting function should be preceded in order to design H_∞ controller of the mixed-sensitivity problem. In this paper, weighting functions $W_1(s)$ and $W_3(s)$ of performance specification and robustness specification are defined as followings.

$$W_1^p = \frac{s/100+1}{s+1} I_{2\times 2}, \quad W_1^q = 3\frac{s+1}{s/0.2+1} I_{2\times 2} \qquad (23)$$

$$W_3^{\Phi,\Theta} = 0.006\frac{s+1}{s/10+1} I_{2\times 2}$$

$$W_3^p = \frac{0.371s^2+3.64s+28}{s^2+93.4s+9852}, \quad W_3^q = \frac{0.133s^2+7.05s+60.7}{s^2+181s+21930} \qquad (24)$$

The designed controller shows the result that maximum singular value and minimum singular value are almost same in frequency interval $10^{-3}<w_i<10^5$, control interval. In low frequency range which we can validate the performance specification, the magnitude is 1(0dB) and the slope in high frequency range is maintained at 40dB/sec or more.

5. SIMULATION

Fig. 9 shows the structure of compensator which has SISO multilooped conventional controller. Since this simple structure doesn't need static and complex calculation as we can catch from the control method of equation (20), small realtime-calculation load of CPU is its merit. So it is a very effective controller.

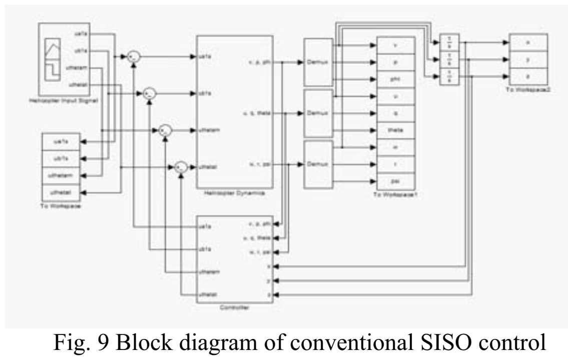
Fig. 9 Block diagram of conventional SISO control

In this paper, the proposed controller is designed, simulated, and validated by using MATLAB / Simulink(Version 6.5). Moreover, using 6-DOF Animation block of Aerospace Blockset, the motion of helicopter can be observed through animation. The hovering helicopter controlled by the proportional gain controller shows comparatively stable motion. The structure of the proposed controller is extremely simple but very effective to stabilize target dynamics in the result of simulation.

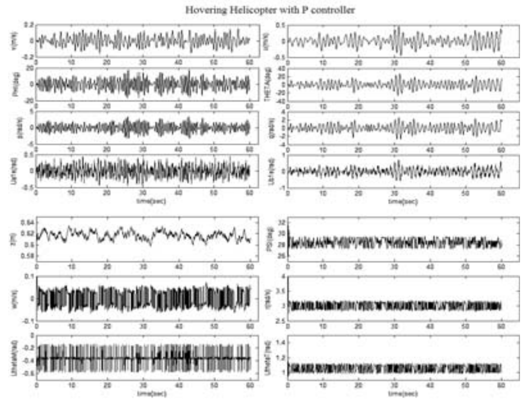

Fig. 10 Hovering result with P controller

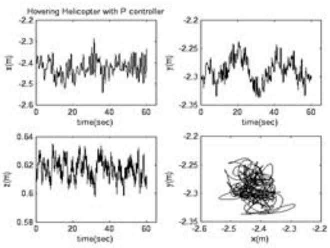

Fig. 11 Position control with P controller

Also, with properly selected weight functions, we derive the controller which satisfies the design requirement and carry out MATLAB simulation using this controller. The simulation result of H∞ controller with the comparison of two proposed controller is shown in Fig. 13. Linear MIMO robust controller like H∞ shows more stable attitude control performance than the proportional controller.

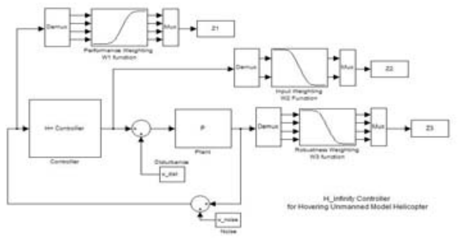
Fig. 12 H∞ control MATLAB simulation

The distribution ranges of attitude angles are similar but the amplitude of H∞ controller is a tenth part of the proportional controller. Despite severe disturbance and plant confusion, the controllers mentioned above show satisfactory stability and tracking performance. While H∞ controller shows robustness, feedback linearization controller has relatively low-level performance because of uncertainty and disturbance.

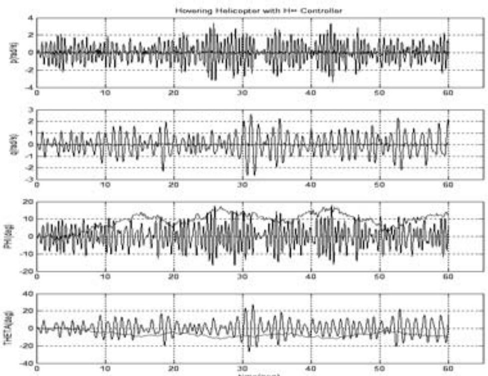

Fig. 13 Comparison of two proposed controllers

6. CONCLUSION AND FUTURE WORK

A system identification and the attitude control of hovering helicopter are accomplished as the first step for autonomous flight of unmanned model helicopter in this paper.

First, we derive nonlinear 6-DOF equation of motion of helicopter and derive state-equations by linearizing with proper assumptions based on this equation. Moreover, we identify the system with real flight data and the conventional SISO multi-loop control and H∞ control for attitude stabilization of hovering unmanned helicopter are applied to this identified model. Both of two proposed controllers show reasonable performances in computer simulation, especially H_∞ controller shows more outstanding performance and robustness against disturbance and uncertainty.

After this research, although the controller for hovering is designed, it cannot be ignored that real maneuver of helicopter contains various maneuvering modes such as forward flight, pirouette, and takeoff-landing with the exception of hovering and we also should design a controller of transposition among these modes. Therefore, the design and validation of controller for each mode should be done. Additionally, real flight tests of designed controllers should be done with unmanned model helicopter with sensors, wireless communication device, FCC(Flight Control Computer) and ground station.

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