GUST RESPONSE ANALYSIS IN THE FLIGHT FORMATION OF UNMANNED AIR VEHICLES

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Abstract

Gust response of unmanned air vehicles flight formation was analyzed by using a bio-inspired flight formation simulator and gust models. Two motion parameters, polarity and the nearest neighbor distance, were used to evaluate the gust effect on the flight formation under various mutual interaction conditions. As a result, it was clarified that the polarity was more susceptible to the gust than the nearest neighbor distance, and the gust effect could be attenuated by adjusting the mutual interaction parameters, e.g. by increasing the number of interacting neighbors or by enhancing the tendency of parallel orientation of agents, thus providing important insights to control the stability of flight formation under the gust.

1 Introduction

Flight formation of unmanned air vehicles is a feasible operation for airborne reconnaissance, which enhances the ability of information-gathering by integrating the functions of various sensors on multiple agents. It also enhances the survivability of the system because the malfunction of small number of agents does not affect the total performance of the system. The performance, however, is influenced by the encounter of gust or air turbulence. The position and the moving direction of each agent are disturbed by the gust, causing the degradation of coherence of formation and the sensing quality of agents. In the worst case, the formation can be split into several sub groups losing the interaction and the data link among sub-groups. A countermeasure is then required to solve this problem.

2 Methods

2.1 Interaction Model

The flight formation control in this study is based on a biologically-inspired formation control model which uses simple interaction rules derived from the observed behaviors of the formation of organisms in nature such as flocking of birds or schooling of fish [1, 2]. The model uses three interaction rules, i.e. "approach", "parallel orientation", and "repulsion" rules, each of which is selected depending on the distance between the individual and its neighbour. Namely, the approach is selected when a neighbour is distant, the repulsion is selected when a neighbour is nearby, and the parallel orientation is selected when a neighbour is in an intermediate distance.

To embed this interaction rules into flight control of air vehicles, an interaction field is set around each air vehicle (hereafter called as 'agent') as shown in Fig. 1. The field is divided into three sub-fields with different radiuses. The reaction rules are defined for each sub-field so that the agent approaches to the neighbour in the outermost approach field, moves away from the neighbour in the innermost repulsion field, or moves in parallel with the neighbour when it is in the parallel orientation field between the approach and the repulsion fields as shown in Fig. 2. The vectors $\boldsymbol{\alpha}_{app}$, $\boldsymbol{\alpha}_{para}$, and $\boldsymbol{\alpha}_{repul}$, in Fig. 2 denote the body direction vectors of the agent for the approach, parallel orientation, and repulsion, respectively, where $\boldsymbol{\alpha}_{app}$ and $\boldsymbol{\alpha}_{para}$

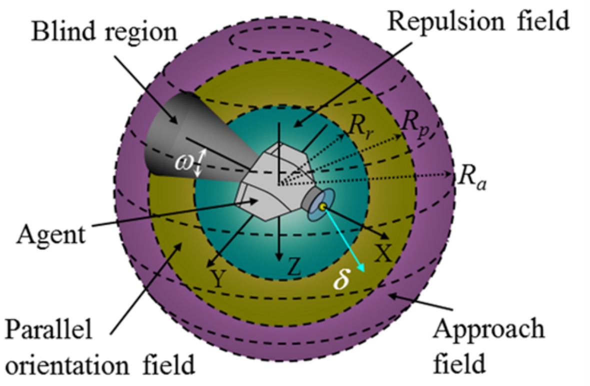
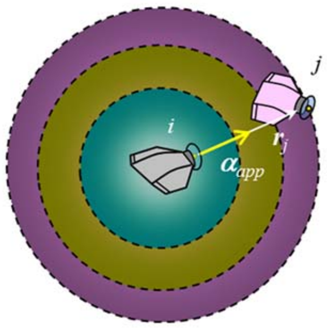
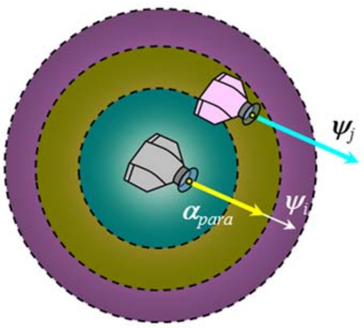


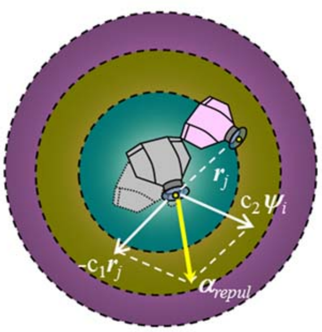
Fig. 1. Interaction field around the agent



(a) approach



(b) parallel orientation



(c) repulsion

Fig. 2. Interaction rules

point to the direction of the neighbor $\boldsymbol{r}_j$ and to the direction in parallel with the body direction of the neighbor $\boldsymbol{\psi}_j$, respectively; $\boldsymbol{\alpha}_{repul}$ points to the direction which is the summation of the counter direction of the neighbor $-\boldsymbol{r}_j$ and the body direction of the agent $\boldsymbol{\psi}_i$ with the weight coefficients c_1 and c_2, respectively, to avoid a collision with the neighbor (here c_1=c_2=1 is used). When multiple neighbors exist in the interaction field, the agent averages the body direction vectors determined by each neighbor and moves in the averaged direction (=$\boldsymbol{\psi}_i^*$). All vectors except $c_1\boldsymbol{r}_j$ and $c_2\boldsymbol{\psi}_i$ are unit vectors used to describe just direction.

The maximum number of neighbors $N_{b,max}$ which can be involved in the interaction with the agent at the same time is considered to assume the performance limit of detection sensor. When the number of neighbors in the interaction field N_b exceeds this limit (N_b>$N_{b,max}$), $N_{b,max}$ neighbors are selected as targets of interaction. This selection is based on the priority of direction where the agent selects neighbors near the specified direction with higher priority than neighbors distant from this direction. This priority (hereafter denoted as "interaction directivity") reflects the property of detection sensor, e.g. microwave or infrared sensor, which usually has the strong sensitivity to the direction where the sensor faces. The vector $\boldsymbol{\delta}$ in Fig. 1 denotes this direction of priority, which usually orients front to detect front neighbors, but can be changed by altering the facing direction of sensor. In addition, the off-sensing area (= blind region) is set at the rear of the agent as shown in Fig. 1 because sensors are generally set around the head and thus the agent is subject to weak sensitivity in rear. The size of blind region is given by the angle ω in Fig. 1. If the agent has rear sensors, ω becomes zero, and if not, ω takes positive value depending on the difficulty of sensing rear objects.

2.2 Motion Calculation

The motion of air vehicle is calculated by using following three dimensional Newton's equation of motion:

for translation,

$$\begin{cases} m(\dot{U}+QW-RV)=-mg\sin\Theta + X_a, \\ m(\dot{V}+RU-PW)=mg\cos\Theta\sin\Phi + Y_a, \\ m(\dot{W}+PV-QU)=mg\cos\Theta\cos\Phi + Z_a, \end{cases} \quad (1)$$

for rotation,

$$\begin{cases} I_{xx}\dot{P}-I_{xz}\dot{R}+(I_{zz}-I_{yy})QR-I_{xz}PQ = L, \\ I_{yy}\dot{Q}+(I_{xx}-I_{zz})RP+I_{xz}(P^2-R^2) = M, \\ -I_{xz}\dot{P}+I_{zz}\dot{R}+(I_{yy}-I_{xx})PQ+I_{xz}QR = N, \end{cases} \quad (2)$$

for the Euler angle of the body,

$$\begin{cases} \dot{\Phi}=P+Q\sin\Phi\tan\Theta+R\cos\Phi\tan\Theta, \\ \dot{\Theta}=Q\cos\Phi-R\sin\Phi, \\ \dot{\Psi}=Q\sin\Phi\sec\Theta+R\cos\Phi\sec\Theta, \end{cases} \quad (3)$$

where m is the mass of the air vehicle and g is the gravity acceleration; (U, V, W) and (P, Q, R) are the velocity and the angular velocity of the vehicle, respectively, determined on the body-fixed coordinates (X_b, Y_b, Z_b); (Φ, Θ, Ψ) are the Euler angle of the body determined on the ground-fixed coordinates (X_g, Y_g, Z_g). The definition of these variables is shown in Fig. 3. The variables (X_a, Y_a, Z_a) denote the force of air and the thrust, and (L, M, N) denote the moments of air acting on the body, both of which are defined on the body-fixed coordinates. The variables I_{xx}, I_{yy}, I_{zz} are the momentum of inertia of the body around $X_bY_bZ_b$-axis, and I_{xz} is the product of inertia of the body with respect to X_bZ_b-plane.

The manipulating variables are the thrust T and the moments L, M, N. The initial thrust T_0 is determined to support the agent weight at a given initial speed V_0, and then it is augmented or attenuated as necessary, e.g. augmented when the agent climbs up, lags behind other agents, or loses height under the minimum allowable height, or attenuated when the agent descends. The moments are added to reduce the error in the body direction, i.e. $\Delta\psi=\psi_i^*-\psi_i$, where ψ_i^* is the new body direction of the agent calculated in the interaction with neighbors as previously mentioned and ψ_i is the current body direction of the agent. Generic PID control is used for these thrust and moment controls. Fig. 4 shows a snapshot of calculated motion of 50 agents.

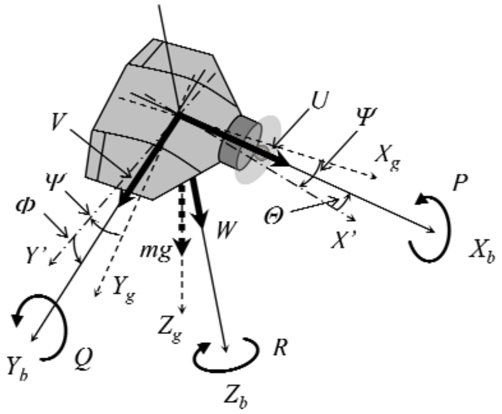


Fig. 3. Definition of variables

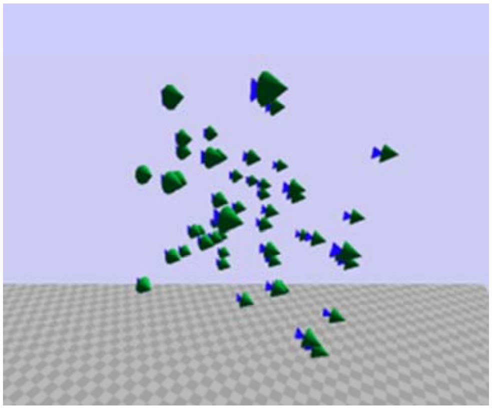


Fig.4. Snapshot of calculated motion

2.3 Gust Model

Two kinds of gust model are used, i.e. isolated gust and Dryden gust models [3], to investigate the effect of simple explicit gust and natural random gust on the motion of flight formation, respectively. The isolated gust is formulated as

$$\begin{cases} (x<0) \\ \quad V=0 \\ (0\leqq x\leqq d_m) \\ \quad V=(V_m/2)\{1-\cos(\pi x/d_m)\} \\ (x>d_m) \\ \quad V=V_m \end{cases} \quad (4)$$

where x is position, V is gust speed, V_m is the maximum value of gust, and d_m is the length of interval where gust grows from zero to V_m. The schematic of gust profile is shown in Fig. 5.

In the Dryden gust model, temporal and spatial change of gust speed (x, y, z-component) is characterized by using the following spectrum distribution:

$$\begin{cases} \Phi_u(\Omega) = \sigma_u^2 \dfrac{2L_u}{\pi} \dfrac{1}{1+(L_u\Omega)^2} \\ \Phi_v(\Omega) = \sigma_v^2 \dfrac{L_v}{\pi} \dfrac{1+3(L_v\Omega)^2}{[1+(L_v\Omega)^2]^2} \\ \Phi_w(\Omega) = \sigma_w^2 \dfrac{L_w}{\pi} \dfrac{1+3(L_w\Omega)^2}{[1+(L_w\Omega)^2]^2} \end{cases} \quad (5)$$

where Ω is the spatial frequency (wavenumber), $\sigma_{u,v,w}$ and $L_{u,v,w}$ are the *x*, *y*, *z*-component of turbulence standard deviation and the turbulence scale length, respectively. The calculation of gust speed (u, v, w) is conducted by using white noise and filters. The details of this calculation can be referred to the reference [3].

2.4 Estimation of gust response

Two characteristic values are used to analyse the gust response of flight formation, i.e. polarity (P) and the nearest neighbour distance (NND). Polarity means the degree of parallelism in the moving direction of agents in the formation and is evaluated by the average deviation of moving direction of each agent from the average moving direction of all agents as follows:

$$P = \frac{1}{N}\sum_{i=1}^{N} \measuredangle(\boldsymbol{v}_i, \overline{\boldsymbol{v}}) \quad (6)$$

where N is the number of agents in the formation; $\boldsymbol{v}_i$ is the velocity vector of i-th agent; $\overline{\boldsymbol{v}}$ is the average velocity vector of all agents; $\measuredangle(\boldsymbol{v}_i, \overline{\boldsymbol{v}})$ is the angle between $\boldsymbol{v}_i$ and $\overline{\boldsymbol{v}}$. The small value of P means the high degree of parallelism in the agent motion, and vice versa.

NND means the distance to the nearest neighbour of each agent and thus indicates the relative position of agents and also the degree of expansion of formation. This value is calculated as the average value of distance to the nearest neighbour of all agents.

In addition, we used two parameters, i.e. the maximum number of interacting neighbours $N_{b,max}$ and the size of parallel orientation field R_p to investigate how these mutual interaction parameters affect the gust response of flight formation.

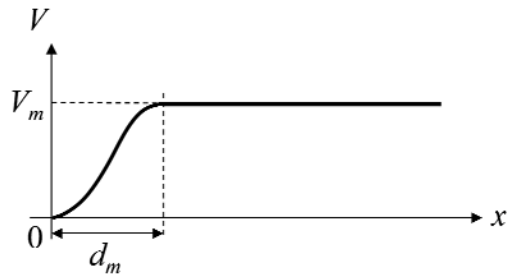


Fig.5. Schematic diagram of isolated gust model

Table 1. Calculation parameters

Radius of attraction field	R_a (BL)	5
Radius of parallel orientation field (standard value)	R_p (BL)	25
Radius of repulsion filed	R_r (BL)	30
Blind-region angle	ω (deg)	30

BL: body length of agent (=0.33m)

2.5 Initial condition and other parameters

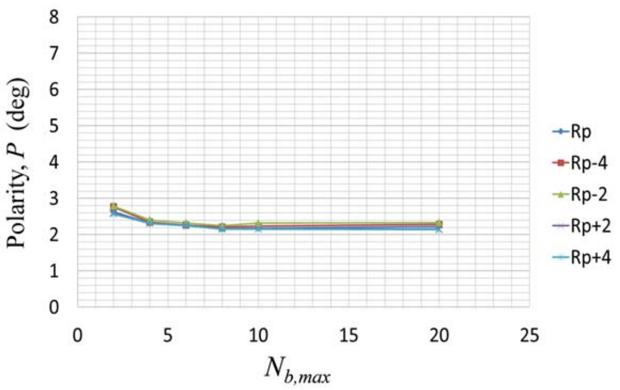
The calculation is conducted by using 50 agents, the body configuration parameters of which are given referring to the real MAV which has 0.27kg mass, 0.33m body length, and 0.6m wing span length [4].

Initially, all agents are positioned randomly in a specified area with the same body direction. The initial speed is V_0=9.7m/s to realize horizontal flight. The motion and the interaction are calculated at intervals of Δt=0.1sec. Other parameters used in the calculation are listed in Table 1.

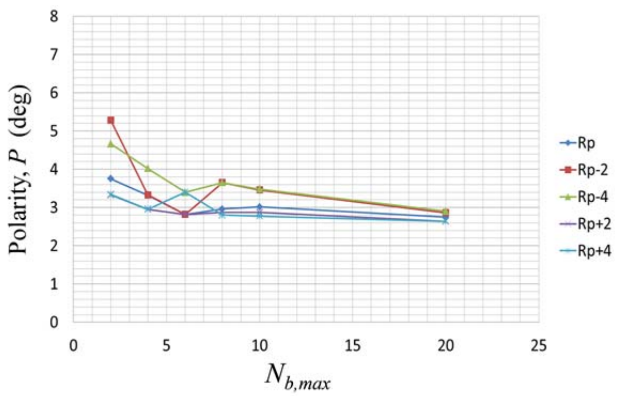
3 Results and discussion

3.1 Polarity

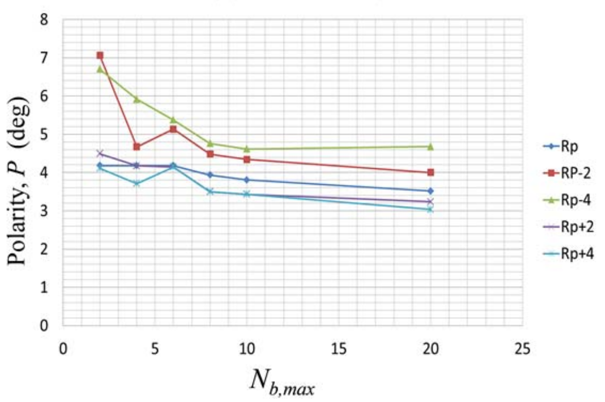
Fig. 6 shows the effect of gust on the polarity P. When the formation flew without gust, P took almost constant value, i.e. about two degrees, for all values of $N_{b,max}$ and R_p as shown in Fig. 6(a), where $R_p \pm 2$ or ± 4 means R_p takes its standard value (=25BL) ± 2BL, or ± 4BL, respectively. This result means the formation was in the considerably stable condition. In contrast, when the formation flew in the isolate gust, P increased significantly at the small value of $N_{b,max}$ or R_p, and decreased as $N_{b,max}$ or R_p increased as shown in Fig. 6(b). When the formation flies in the Dryden gust, i.e. each agent flies in the random and different gust from



(a) no gust (stable cruising condition)



(b) isolate gust



(c) Dryden gust

Fig. 6. Effect of gust on the polarity P

the gust of its neighbours, P further increased at small $N_{b,max}$ or R_p as shown in Fig. 6(c).

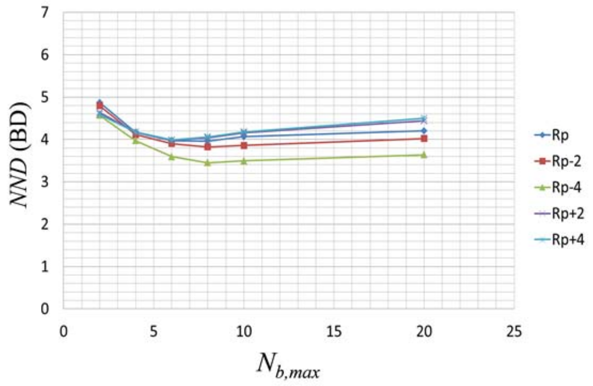
As a result, the polarity P susceptibly increased when the gust was input, and the realistic random gust, i.e. Dryden gust, showed more significant effect than the simple uniform gust, i.e. the isolate gust. In both isolate and Dryden gust, P generally decreased as $N_{b,max}$ or R_p increased. The reason why P decreased as $N_{b,max}$ increased is considered as follows: when each agent interacts with small number of neighbours, the agent becomes susceptible to the change of neighbour's position or velocity. For example, when the agent interacts with a single neighbour, the agent tends to change its position or moving direction frequently to keep appropriate distance or the moving direction, thus increasing the moving direction deviation P. Whereas, when the agent interacts with large number of neighbours, the change of position or moving direction of neighbours becomes small because the agent interacts with the averaged position or moving direction of large number of neighbours, thus decreasing the value of P.

The reason why P decreased as R_p increased can be considered that when R_p increases, the parallel orientation field expands and thus the tendency of agent to orient in parallel with its neighbours increases, resulting in the small deviation of moving direction from the moving direction of other agents, which decreases P.

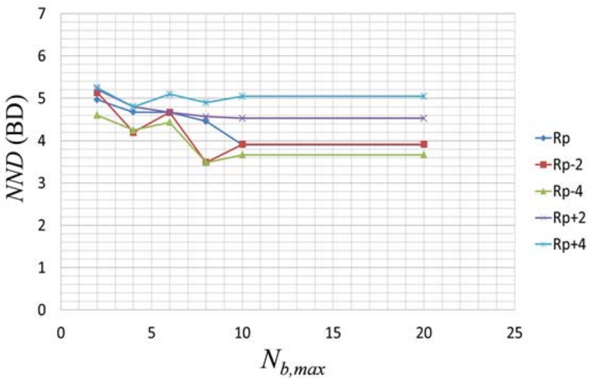
3.2 Nearest Neighbour Distance

Fig. 7 shows the effect of gust on the nearest neighbour distance NND. When the formation flew without gust, NND was relatively constant, i.e. about 4 BL, at large $N_{b,max}$ (> 5), and a little increased at small $N_{b,max}$ (< 5), and it also a little increased as R_p increased as shown in Fig. 7(a). When the formation flew in the isolate gust, each NND was also relatively constant at large $N_{b,max}$ and a little increased at small $N_{b,max}$, but the effect of R_p on NND was larger than that in the no gust condition as shown in Fig. 7(b). The difference between the minimum and the maximum value of NND was about 1.5BL, whereas it was about 1.0BL in the no gust condition. When the formation flew in the

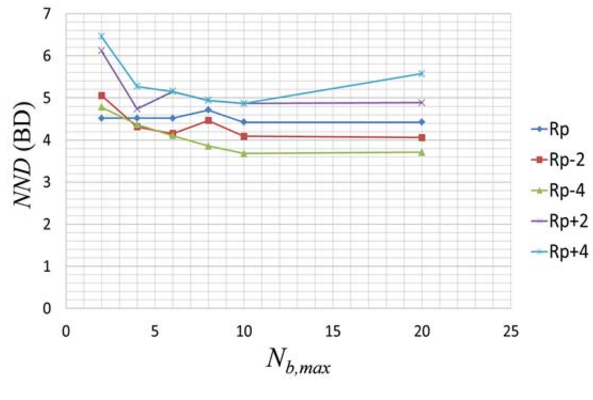
Dryden gust, the change of *NND* with $N_{b,max}$ or R_p became large, showing the difference between the minimum and the maximum value of *NND* was about 2.0BL as shown in Fig. 7(c). The reason why the *NND* increased when R_p increased can be considered that many neighbours, even the nearest neighbour, tend to exist in the parallel orientation field when R_p increases. The agent, then, does not approach to the neighbour in the parallel orientation field, thus resulting in the increase of the distance to the nearest neighbour. The reason why *NND* increased when $N_{b,max}$ decreased can be considered that when the number of interacting neighbours is small, the frequency of neighbours to exist in the approach field decreases, which naturally decreases the agent to approach to the neighbour, resulting in the increase of nearest neighbour distance.



(a) no gust (stable cruising condition)



(b) isolate gust



(c) Dryden gust

Fig. 7. Effect of gust on *NND*

From Figs 6 and 7, it is confirmed that the gust effect on *NND* was smaller than that on the polarity *P*, e.g. *NND* in Dryden gust (Fig.7(c)) is at most about 1.3 times of that in the no gust condition (Fig. 7(a)), while the polarity *P* in Dryden gust (Fig. 6(c)) is at most about 2.3 times of that in the no gust condition (Fig. 6(a)), indicating that the moving direction of agent is markedly susceptible to the gust than the position of agent.

4 Summary

The effect of gust on the motion of flight formation was investigated by using the flight formation simulator and the gust models. The results clarified that the gust causes more effect on the polarity of formation than on the nearest neighbour distance, indicating the larger effect on the moving direction of agent than on the position of agent, and also clarified that these effects depend on the characteristics of mutual interaction among agents such as the number of interacting neighbours or the size of parallel orientation field which represents the tendency of agent to orient in parallel with its neighbors.

In addition, the gust effect depends on the quality of gust itself, e.g. the realistic random gust (Dryden gust) causes larger effect than the simple uniform gust (isolate gust), indicating that Dryden gust is suitable for severe estimation of gust effect. Dryden gust can also simulate the spatial variation of gust speed, and thus suitable for the evaluation of gust response of widely spread flight formation.

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