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Research on the Frequency Aliasing of Resistance Acceleration Guidance for Reentry Flight

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Abstract: According to the special response of resistance acceleration during hypersonic reentry flight, different guidance frequency will result to very different flight and control response. The analysis model for the response of resistance acceleration to the attack angle and dynamic press is put forward respectively in this paper. And the frequency aliasing phenomenon of guidance is revealed. The simulation results to the same vehicle sufficiently substantiate the frequency aliasing of resistance acceleration during reentry guidance.

1 Summary

During the process of large lift-drag ratio flight, Lift-body is usually controlled by given flight profile. Under this background, one of the most classical guidance schemes is space flight reentry guidance [1]. In the guidance scheme of the space shuttle, the resistance acceleration signal is used as the core to control the reentry guidance and the successful implementation of the project is carried out. However, the test results show that there has some defect of using resistance acceleration signal as the controlled quantity. After the opening of the space shuttle test data, a lot of research focused on reentry guidance, which also shows that there is a certain lack in acceleration signal guidance[2].

The traditional guidance design is based on the dynamic equation of a particle. In this method, the assumption of the guidance command and the centroid motion of the aircraft tend to be too idealistic, while the dynamic characteristics of the guidance loop are ignored. It leads to the problem that the guidance loop does not match the control loop, which brings difficulties to the integrated design of the guidance and control. In this paper, the frequency aliasing effect has been considered, and the lack of using drag acceleration signal as the control signal is studied. The study found that high frequency drag acceleration signal is sampled to produce the low frequency interference signal, and this low frequency interference and the low frequency of the guidance are superposed together. It is difficult to eliminate through the filtering process, which will cause serious pollution to the signal and then affect the terminal guidance performance.

2. Frequency aliasing

The frequency aliasing effect can be explained by the following example: a sinusoidal signal with a certain frequency after sampling in different frequencies, the reconstructed signal is directly related to the sampling frequency [3,5]. As shown in Fig.1, the sampling frequency is obviously reduced when the sampling frequency is less than two times of the signal, that is, the low speed rate of the high frequency signal sampling will produce a new low frequency signal. This low frequency signal will seriously affect the performance of the system.

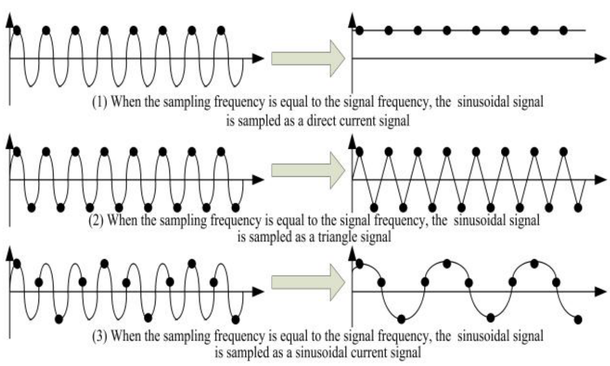

Figure 1. Frequency aliasing

3 Modal analysis of resistance acceleration

According to the dynamic characteristics of reentry flight, the drag acceleration is greatly influenced by dynamic pressure and attack angle. The response of the drag

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acceleration to the attack angle signal is formed by the superposition of two types of oscillation mode, and the response characteristics are relatively complicated. The attack angle and the dynamic pressure are two key factors of the drag acceleration.

As shown in equation (1), $\overline{q}$ is Dynamic pressure, S is Aircraft reference area. C_D refers to Drag coefficient, while it is generally determined by the attack angle and Maher number. D_a is Drag acceleration.

$$D_a = \frac{\overline{q}SC_D(\alpha, mach)}{m} \tag{1}$$

The root locus and modal characteristics indicate that: The transfer function of Drag acceleration-Attack angle has two pairs of conjugate complex roots, which are shown as long-period and short-period mode respectively. Guidance loop design process shows that: The short period motion modes can be improved obviously by the guidance law, but the long period motion mode is attributed to a low frequency response, which influences the guidance characteristics. Fig. 2 is the schematic diagram of open loop root locus.

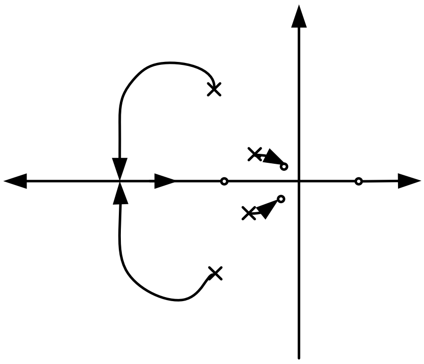

Figure 2. The root locus of drag acceleration and attack angle under typical flight

It is learned from formula (1) that, the drag acceleration is determined by the drag coefficient and dynamic pressure, in which the drag coefficient is greatly affected by the attack angle. It will cause the drag acceleration response to be a short-period motion at initial time. The dynamic pressure is mainly determined by the velocity and altitude, and the response of the velocity to the attack angle is a long-period motion. In the equilibrium state, the moment can be recovered in a relatively short time when the flight vehicle is disturbed by the angle of attack, but the angle of attack caused a negative trajectory angle, leading to the decline of the aircraft, which is gradually accelerated in the tangential direction along the trajectory of gravity force, the velocity increases cause the dynamic pressure increases, and the lift force is also increased. When the lift is greater than gravity, trajectory bend up, and the component of gravity will make airplane slow down, dynamic pressure decreased. When the lift is less than gravity, the trajectory is bent downward, and the dynamic pressure increases with the increase of the velocity. The essence of such alternation is the transformation of the kinetic energy and potential energy，it shows the oscillation motion of the dynamic pressure and the trajectory angle，therefore，dynamic pressure is the physical quantity of long period motion[5].

Fig.3 shows the above discussion about this motion. Above all, when instantaneous changes of attack angle occur, the response of D_a is leaded by C_D at initial time, performing as short period fast oscillation attenuation. Thereafter D_a is mainly influenced by $\overline{q}$, the long-period motion characteristics of $\overline{q}$ makes D_a performance as long-period oscillation.

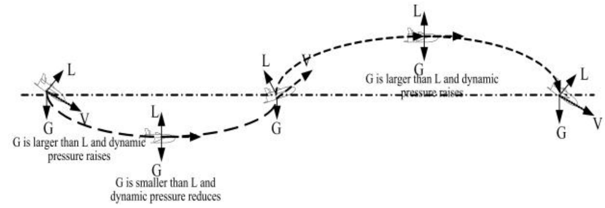

Figure 3. Schematic diagram of the dynamic pressure and long period motion

4 Response characteristic of drag acceleration

4.1 Effect of attack angle on drag acceleration

In the process of high altitude and high speed reentry, the dynamic pressure changes significantly, the sensitivity of the drag acceleration to the angle of attack is different in different dynamic pressure. Fig.5 and Fig.4 shows the response of the drag acceleration during the whole flight when under the condition that, the roll angle is fixed and the attack angle deviation is in $\pm 2^{\circ}$.

Analysis of simulation shows that, under the same attack angle, when the dynamic pressure is small, the resistance acceleration error is very small, about 5%, with the increase of the dynamic pressure, the drag acceleration error is significantly larger, about 20%. It shows that the influence of the attack angle on drag acceleration is related to the dynamic pressure, the greater the dynamic pressure, the more sensitive to the attack angle.

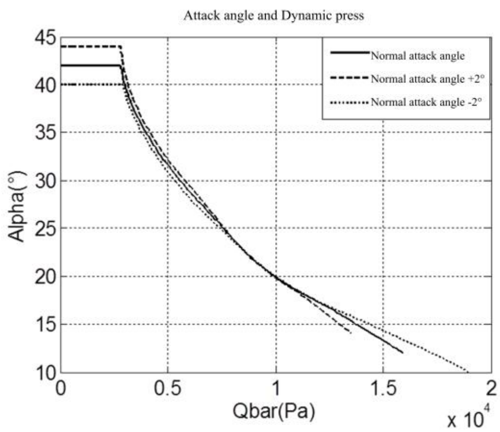

Figure 4. Attack angle-dynamic pressure

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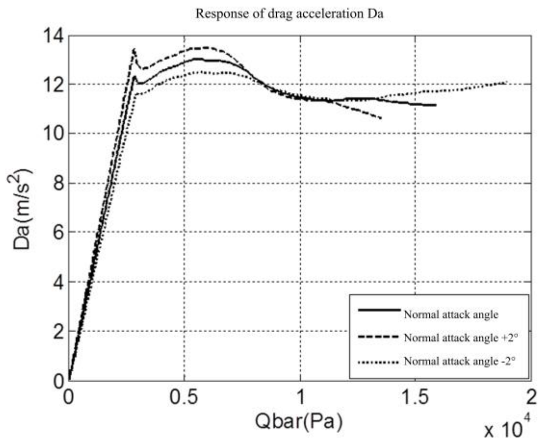

Figure 5. Drag acceleration-dynamic pressure

4.2 Effect of dynamic pressure on drag acceleration

In the guidance loop, the attack angle is the output of the guidance command, but in the control loop, the attack angle is the angular motion. The dynamic characteristics between the attack angle command and the actual attack angle can affect the integrated design of the guidance and control. In order to study the influence of the dynamic characteristic of the attack angle on the drag acceleration, the dynamic characteristics of the attack angle is characterized by a second order system.

$$\frac{\alpha}{\alpha_c} = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \tag{2}$$

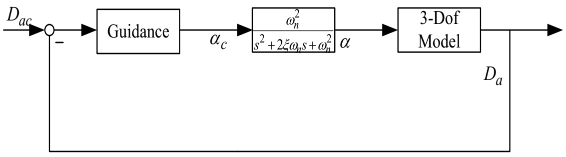

Figure 6. The guidance loop considering the dynamic characteristic of the attack angle

From Fig. 7 to Fig. 10 is the response of the attack angle and drag acceleration under different dynamic link. Considering the dynamic characteristics of the attack angle, as the guidance actual angle command input model, the attack angle command has a certain response time and overshoot. The dynamic characteristic of the attack angle has an influence on the step response of the drag acceleration. When the dynamic pressure is relatively small, due to the dynamic characteristics of the attack angle is poor, the attack angle has a larger overshoot, and the impact of the drag acceleration is also larger. While the dynamic pressure is large, the dynamic characteristic of the attack angle is better, and the influence of the drag acceleration is small.

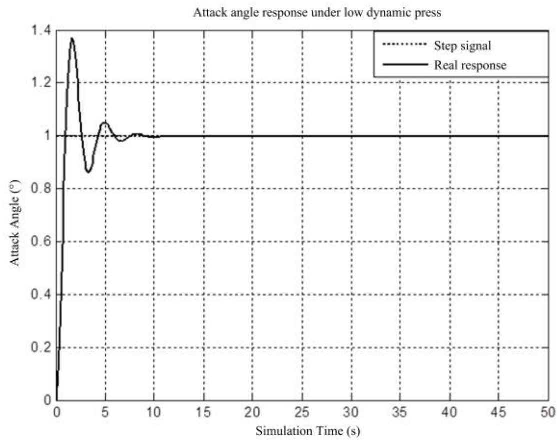

Figure 7. Dynamic characteristics of the attack at low dynamic pressure

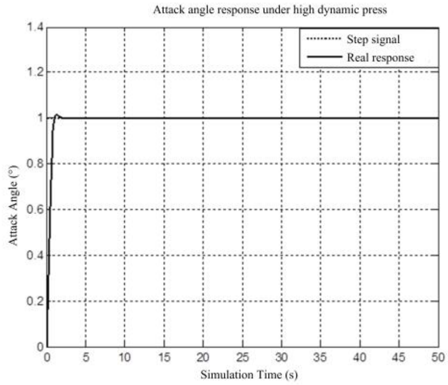

Figure 8. Dynamic characteristics of the attack at high dynamic pressure

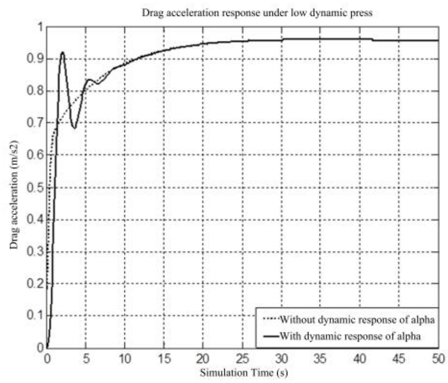

Figure 9. Drag acceleration response at low dynamic pressure

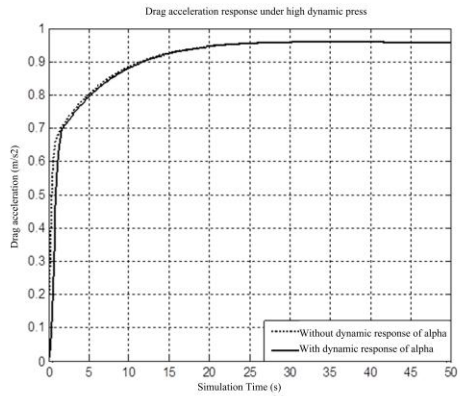

Figure 10. Drag acceleration response at high dynamic pressure

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5 Aliasing phenomenon of drag acceleration

The traditional guidance design is based on the dynamic equation of a particle. In this method, the assumption of the guidance command and the centroid motion of the aircraft tend to be too idealistic, while the dynamic characteristics of the guidance loop are ignored. It leads to the problem that the guidance loop does not match the control loop, which brings difficulties to the integrated design of the guidance and control. In fact, due to the short-period motion of the drag acceleration signal being dominated by the attack angle, the presence of aliasing will produce a new low-frequency drag acceleration signal when using drag acceleration guidance. This low-frequency signal is mixed with the real sensor signal that can be used as an instruction input guidance loop, which affects the precision of the guidance.

The signal of drag acceleration is affected by attack angle and dynamic pressure. The analysis of drag acceleration motion shows that in a short time, the attack angle plays a leading role in the drag acceleration response. Taking into account the engineering practice, the whole reentry attack angle is used as a kind of angular motion, and the attack angle is frequent jitter interference. This is equivalent to a high frequency oscillation signal at the attack angle. With the increase of the dynamic pressure, the shake of attack angle is more obvious. The drag acceleration signal is very sensitive to the high frequency disturbance of attack angle, high frequency drag acceleration response is produced. The guidance process is a long period, and the sampling frequency of the guidance command is low. It equals to sampling high frequency drag acceleration signal with low frequency guidance commands. Drag acceleration signal in sampling process existing aliasing phenomenon, drag acceleration signal, which is sampled after mixed with low drag acceleration signal, resulting in resistance acceleration signal polluted thus affecting the performance of guidance.

In order to verify the aliasing phenomenon after the drag acceleration signal is disturbed by the attack, in this paper, a sinusoidal signal with a frequency of $5\,rad/s$ is chosen to simulate the high frequency interference of the attack angle. In the case of considering the dynamic characteristic of the attack angle, the response of the drag acceleration and the dynamic pressure to the high frequency interference of the attack angle is reflected. Fig.11 is schematic diagram of guidance structure. Fig.12 is Signal of attack angle after adding interference.

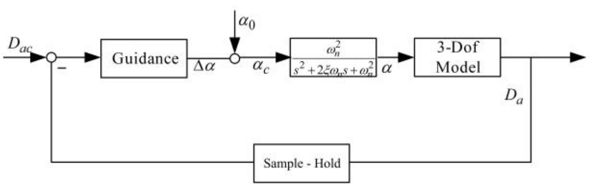

Figure 11. Schematic diagram of guidance structure

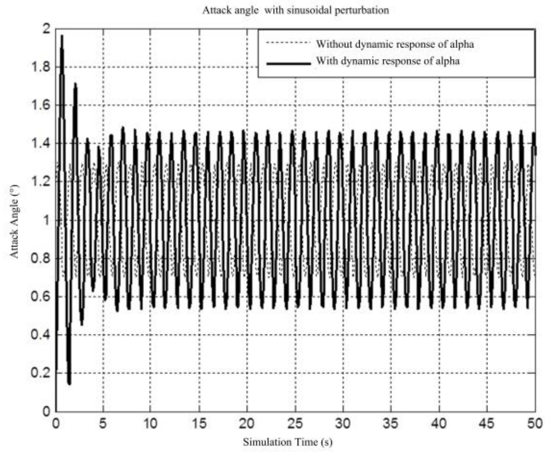

Figure 12. Signal of attack angle after adding interference

The simulation results show that when the sampling frequency is 10Hz, the frequency of the drag acceleration signal after sampling is basically the same as that of the angle of attack. Both of them are shown as high frequency oscillation signals. This is equivalent to the high frequency of attack angle disturbance causes the high frequency drag acceleration of the vibration signal, the drag acceleration of the high frequency oscillation signal can filter out through the high frequency filter. But when the sampling frequency is 1Hz, the low frequency sampling of the high-frequency signal occurs. A new low frequency drag acceleration signal is produced by the aliasing phenomenon and this oscillation signal has a large amplitude. The low frequency drag acceleration signal generated by the high frequency drag of the attack angle can be superimposed on the real resistance acceleration signal, which will cause pollution of the signal. It is difficult to be effectively filtered, because the frequency of new signal is low. In order to avoid this problem, the dynamic pressure can be chosen as the core of the guidance law. Compared with the drag acceleration signal, the dynamic pressure is a long-period change signal, which has little effect by disturbance of attack angle.Fig.13 is the response of 10Hz and 1Hz in the sampling frequency for the drag acceleration. Fig.14 is dynamic pressure response.

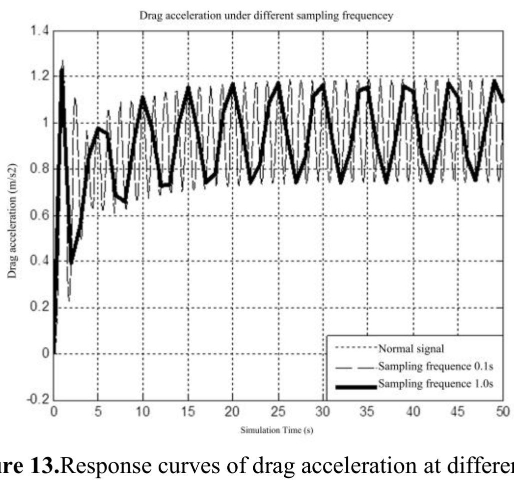

Figure 13. Response curves of drag acceleration at different sampling frequencies

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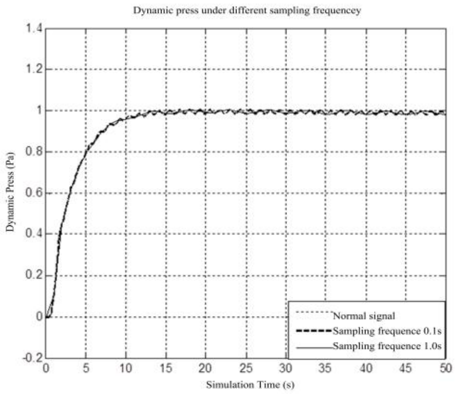

Figure 14. Response curves of dynamic pressure at different sampling frequencies

Fig.13 shows that, due to the drag acceleration being sensitive to the angle of attack, the jitter of the angular signal will result in a larger amplitude response to the drag acceleration. After reducing the sampling frequency, the frequency response of the acceleration signal of the high frequency resistance is mixed, and the new low frequency interference signal is generated. Because the frequency of the guidance loop is low, it is difficult to eliminate the low frequency interference signal through the filter, which will affect the performance of the guidance.

Fig.14 indicates that, dynamic pressure is not sensitive to the attack angle. This is caused by the long period characteristic of dynamic pressure. The dynamic pressure being used as the controlled quantity of the longitudinal direct guidance is relatively well. Even if the sampling frequency is decreased, the dynamic pressure response is very small.

From the above analysis, using drag acceleration as the reentry guidance command has the following deficiencies:

(1) The response performance of the resistance acceleration to the angle of attack is two kinds of motion modes, which are long and short period motion. The initial time of the response is dominated by the angle of attack, which performed short period motion. Then, the dynamic pressure is the main performance for the long period motion, and the response process is complex.

(2) The sensitivity of resistance acceleration to the angle of attack is related to the dynamic pressure, the greater the dynamic pressure, the more sensitive to the angle of attack, and have influence on the integrated design of the guidance and control.

(3) The dynamic characteristic of the angle of attack has great influence on the acceleration of resistance. Resistance acceleration aliasing will be caused after the angle of attack high frequency disturbances. Low frequency resistance acceleration interference is generated by high frequency resistance acceleration signal after aliasing, which can pollution guidance loop and affect the precision of guidance.

6 Conclusion

According to the kinetic law and response characteristics of drag acceleration for high speed reentry vehicle， this paper studies the modal characteristics of the drag acceleration and the response of the guidance command to the attack angle dynamic pressure，It points out the reason that the drag acceleration response is sensitive to the attack angle and objective fact that the frequency aliasing of the guidance commands due to the high frequency attack angle or sampling. Finally, the results of the modal analysis are confirmed by simulation, and it is pointed out that the sampling dynamic pressure guidance can reduce the sensitivity to the attack angle.

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