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Application of the Feedback for the Sideslip Angle Change in Hypersonic Vehicle

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Abstract

This paper designs the $\dot{\beta}$ feedback controller for the unstable Dutch Roll and severe kinematic coupling of the hypersonic vehicle at high angle of attack and large mach number. This paper deduces the mechanism of improving the stability of the Dutch Roll and illustrates the mechanism of restraining the kinematic coupling using $\dot{\beta}$ controller based on the linear small perturbation equations. And an easy analysis is made about the signal of $\dot{\beta}$ controller. Finally, the relational tests are conducted in simulations using $\dot{\beta}$ controller. The simulation result shows that the $\dot{\beta}$ controller can improve the damp of the Dutch Roll, weaken the influence of kinematic coupling, restrain the variety of sideslip and improve the equality of sideslip.

Keywords: *Hypersonic Vehicle; Dutch Roll; Kinematic Coupling; Feedback Controller*

1. Introduction

Flight of the Hypersonic Vehicle is of large envelope, strong coupling, serious nonlinearity and bad modal characteristic of the Dutch Roll [1-3]. Therefore, in rolling maneuvers, the problems of serious kinematic coupling and the interconversion of sideslip angle and attack angle arise [4-8]. So the research of suppression techniques of sideslip angle is rise in response to the proper time and conditions.

The suppression techniques of sideslip angle are applied in the simulation phase of X-15 Vehicle. In aileron control, sideslip angle of X-15 Vehicle is unstable [9]. It vibrates acutely and diffuses. The application of $\dot{\beta}$ control successfully addresses this kind of issues but is not applied in actual flight. Whereafter, due to the problem of controlling, in the United States space shuttle, $\dot{\beta}$ control is used in the heading channel of space shuttle and has achieved good results [10]. $\dot{\beta}$ feedback control is used in both the Boeing 757 and 767.And the related research of being yaw damper of heading channel has been done.

This paper designs the $\dot{\beta}$ feedback controller for the unstable Dutch Roll and severe kinematic coupling of the hypersonic vehicle at high angle of attack and mach number. The feedback of rate of sideslip angle change is researched. This paper deduces the mechanism of rate of sideslip angle change based on its controlling and the related simulation is done.

2. Mathematical Model

Regarding the air vehicle as a rigid body, linearize the motion equation and the normal linear state equation 1 can be obtained as:

$$\dot{X} = AX + BU \tag{1}$$

Linear small disturbance equations are built at airflow coordinate system.Taking no account of longitudinal state, only the lateral state is analyzed. The equation 2 provides the quantity of state X and control lateral input U .

$$\begin{aligned} X &= [\Delta\beta \quad \Delta\phi \quad \Delta p_w \quad \Delta r_w]^T \\ U &= [\Delta\delta_a \quad \Delta\delta_r]^T \end{aligned} \tag{2}$$

The corresponding matrix A and B are showing as equation 3, of which the parameters all are defined at the airflow coordinate system.

$$A = \begin{bmatrix} \frac{Y_\beta}{V} & \frac{g\cos\mu_e}{V} & \frac{Y_p}{V} & \frac{Y_r - V}{V} \\ 0 & 0 & \frac{\cos\mu_e}{\cos\theta_e} & \frac{\sin\mu_e}{\cos\theta_e} \\ L'_\beta & 0 & L'_p & L'_r \\ N'_\beta & 0 & N'_p & N'_r \end{bmatrix} \quad B = \begin{bmatrix} \frac{Y_{\delta_a}}{V} & \frac{Y_{\delta_r}}{V} \\ 0 & 0 \\ L'_{\delta_a} & L'_{\delta_r} \\ N'_{\delta_a} & N'_{\delta_r} \end{bmatrix} \tag{3}$$

3. The Mechanism of $\dot{\beta}$ Feedback Control

The main idea of feedback control law design of sideslip angle change rate is that the $\dot{\beta}$ feedback directly improves the sideslip motion of hypersonic flight and dynamic quality of the sideslip angle.

Because of the large envelope, strong coupling, serious nonlinearity and bad modal characteristic of the Dutch Roll at high angle of attack and mach number, the motion coupling of hypersonic vehicle is very obvious during roll maneuver. The feedback of sideslip angle change rate can improve the Dutch Roll and motion coupling effectively.

3.1. $\dot{\beta}$ feedback Stability Augmentation the Dutch Roll

The turbulence of sideslip angle of air vehicle results in transverse lateral oscillation. So the $\dot{\beta}$ feedback can be introduced in heading channel for increasing the damping to improve the lateral oscillation. The controller of sideslip angle change rate is the sideslip angle damping, which can improve the dynamic behaviour of sideslip angle change and restrain the change trend of sideslip angle. The Dutch Roll reflects the oscillation trend of sideslip angle. The Dutch Roll character is the performance parameter of damped frequency of $\ddot{\beta}$ quadratic equation[11-12].It can be considerate to improve the Dutch Roll character by feedback of sideslip angle change rate.

The equation 3 provides the lateral small disturbance equation. The control law of sideslip angle change rate feedback to rudder is $\delta_r = k\dot{\beta}$, which is brought in equation 1 and the equation 4 can be obtained:

$$\begin{aligned} \delta_r = k\frac{Y_\beta}{V}\Delta\beta + k\frac{g\cos\mu_e}{V}\Delta\phi + k\frac{Y_p}{V}\Delta p \\ k\frac{Y_r - V}{V}\Delta r + k\frac{Y_{\delta_a}}{V}\Delta\delta_r + k\frac{Y_{\delta_r}}{V}\Delta\delta_a \end{aligned} \tag{4}$$

The rudder after feedback is brought in the linear state equation. So the feedback of sideslip angle change rate contained gain matrix A is the equation 5 which is shown as:

$$A1=\begin{bmatrix} \frac{Y_\beta}{V}+k\frac{Y_{\delta_r}Y_\beta}{V^2} & \frac{g\cos\mu_e}{V}+k\frac{Y_{\delta_r}g\cos\mu_e}{V^2} & \frac{Y_p}{V}+k\frac{Y_{\delta_r}Y_p}{V^2} & \frac{Y_r-V}{V}+k\frac{Y_{\delta_r}(Y_r-V)}{V^2} \\ 0 & 0 & \frac{\cos\mu_e}{\cos\theta_e} & \frac{\sin\mu_e}{\cos\theta_e} \\ L'_\beta+kL'_{\delta_r}\frac{Y_\beta}{V} & kL'_{\delta_r}\frac{g\cos\mu_e}{V} & L'_p+kL'_{\delta_r}\frac{Y_p}{V} & L'_r+kL'_{\delta_r}\frac{Y_r-V}{V} \\ N'_\beta+kN'_{\delta_r}\frac{Y_\beta}{V} & kN'_{\delta_r}\frac{g\cos\mu_e}{V} & N'_p+kN'_{\delta_r}\frac{Y_p}{V} & N'_r+kN'_{\delta_r}\frac{Y_r-V}{V} \end{bmatrix} \tag{5}$$

In the process of deducing the characteristic root of $A1$, the gravity is ignored, Y_p is usually equal to zero and $Y_r \ll V$ .All Y_p/V and Y_r/V can be ignored. Besides, the cross derivative N'_p caused by rolling angular velocity also can be ignored. At high angle of attack and mach number hypersonic vehicle is of low rudder efficiency and high speed. Apart from Y_{δ_r}/V and only take account of the moment, we can get the equation 6.

$$\Delta_{LD}=s(s-L'_p)[(s-\frac{Y_\beta}{V})(s-(N'_r-kN'_{\delta_r}))+(N'_\beta+kN'_{\delta_r}\frac{Y_\beta}{V})] \tag{6}$$

So the Dutch Roll characteristic is acquired further as equations 7.

$$\begin{aligned} \omega_{nd}^2 &= \frac{Y_\beta}{V}N'_r+N'_\beta \\ \xi_d &= -\frac{(N'_r-kN'_{\delta_r}+\frac{Y_\beta}{V})}{2\omega_{nd}} \end{aligned} \tag{7}$$

Seen from the equation 7, $\dot{\beta}$ feedback mainly changes the Dutch Roll damping characteristic. So the $\dot{\beta}$ feedback contributes to change the Dutch Roll characteristic of vehicle. In a similar way, the Dutch Roll characteristic of $\dot{\beta}$ feedback to aileron is deduced as equation 8.

$$\begin{aligned} \omega_{nd}^2 &= \frac{Y_\beta}{V}N'_r+N'_\beta \\ \xi_d &= -\frac{(N'_r-kN'_{\delta_a}+\frac{Y_\beta}{V})}{2\omega_{nd}} \end{aligned} \tag{8}$$

From the foregoing, no matter feedback to aileron channel or rudder channel, it is effective to better the Dutch Roll character of the air vehicle.

Choose the state point of a air vehicle, 30km as height, 6 as the mach number, 35°as the angle of attack. The Table 1 gives the Dutch Roll character of rudder of $\dot{\beta}$ feedback. The Table 2 gives the Dutch Roll character of $\dot{\beta}$ feedback to aileron.

Table 1. The Dutch Roll Charater of $\dot{\beta}$ To Rudder Channel

$k_{\dot{\beta}}$	Character value	Damping	Frequency
0	5.11e-002±6.71e+000i	-7.61e-003	6.71e+000
-1	-1.32e+000±6.66e+000i	1.95e-001	6.79e+000
-2	-2.77e+000±6.29e+000i	4.04e-001	6.87e+000
-3	-4.32e+000±5.46e+000i	6.20e-001	6.97e+000
-4	-5.99e+000±3.77e+000i	8.46e-001	7.07e+000

Table 2. The Dutch Roll Charater of $\dot{\beta}$ To Aileron Channel

$k_{\dot{\beta}}$	Character value	Damping	Frequency
0	5.11e-002±6.71e+000i	-7.61e-003	6.71e+000
1	-4.91e+001±1.88e+001i	9.34e-001	5.26e+001
1.5	-4.94e+001±4.28e+001i	7.56e-001	6.53e+001
2	-4.95e+001±5.73e+001i	6.54e-001	7.58e+001

A comparison between the Table 1 and Table 2 can prove that $\dot{\beta}$ feedback to both rudder and aileron can improve the Dutch Roll damping character and the change of frequency is not obvious.

3.2. $\dot{\beta}$ Feedback Eliminates the Kinematic Coupling

Kinematic coupling happens when a vehicle is rolling. With the rolling, sideslip angle and attack angle can converted to one another, which is one of most typical kinematic coupling [13].

Aerodynamic configurations of hypersonic vehicle make the rotational inertia of an air vehicle transverse lateral small. The longitudinal static stability and directional static stability are bad. When the aileron is deflection, it is easy to reach a large rolling angular velocity in a short time. But there is a transient process of the effect of longitudinal and righting moment. So the longitudinal stability torque and heading stability torque has no enough time to deflect the roll shaft obviously. So the actual rolling shaft coincides exactly with the vertical axis of the vehicle body and the air vehicle may occur serious kinematic coupling.

The equation 9 is the mathematical expression of mutual transformation of attack angle and sideslip angle in kinematic coupling[14].

$$\begin{cases}\dot{\alpha} = -p\cos\alpha\tan\beta - r\sin\alpha\tan\beta \\ \dot{\beta} = p\sin\alpha - r\cos\alpha\end{cases} \tag{9}$$

From the mathematical expression above, the degree of kinematic coupling of air vehicle mainly depends on the attack angle and roll rate. When the attack angle and roll rate are large, the kinematic coupling is more serious. When the attack angle and roll rate are small, the kinematic coupling is relatively unconspicuous.

When actual rolling, the longitudinal and heading static stability moment hinder the change of attack angle and sideslip angle, which makes the roll shaft deviate the body axis. When the attack angle and roll rate is relative small, and static stability is good, the longitudinal and heading static stability moment hinder the change of attack angle and sideslip angle. The roll axis will roll around the speed axis and the attack angle and the sideslip angle are invariable, which lead the kinematic coupling eliminate.

To eliminate the kinematic coupling in the rolling process, the essence is to roll around the speed shaft. The key of rolling around the speed shaft is in restraining the change of sideslip in the rolling process.

From the equation 9, it can be seen that the feedback of change of sideslip angle of the kinematic coupling can restrain the kinematic coupling. Take account of the complete signal of rate of sideslip angle change, the equation 10 is shown as:

$$\dot{\beta} = p\sin\alpha - r\cos\alpha + Y/(mV) + G_{ya}/(mV) \tag{10}$$

The signal of the rate of sideslip angle change consists of three parts: kinematic coupling $p\sin\alpha - r\cos\alpha$, lateral force Y/mV and force of gravity G_{ya}/mV.

The speed of the hypersonic vehicle is too fast, and the $\dot{\beta}$ mainly acts on the rolling movement. The kinematic coupling plays a leading role. The lateral force and force of gravity is relatively small and can be ignored. $\dot{\beta}$ can be reduced to the equation 11.

$$\dot{\beta} \approx p\sin\alpha - r\cos\alpha \tag{11}$$

The equation 11 is the kinematic coupling. For stabilizing the speed of yaw angle, when the speed of yaw angle is stabilized as zero, namely roll rate and yaw rate meet the equation $r = p\tan\alpha$, the air vehicle rolls around the speed shaft. At this moment, the impact of kinematic coupling can be eliminated. $\dot{\beta}$ feedback can effectively improves the rolling performance of the air vehicle.

3.3. $\dot{\beta}$ Signal Analysis

Because in practical engineering application there are no sensors directly obtaining the $\dot{\beta}$ signal, it is recommended to take account of the signal of sideslip angle high-pass filter and the rate of sideslip angle change, so the $\dot{\beta}$ expression can be written as:

$$\begin{aligned} \dot{\beta} &= \frac{s}{\tau s + 1}\beta \\ \dot{\beta} &= p\sin\alpha - r\cos\alpha + \frac{Y}{mV} + \frac{G_{ya}}{mV} \end{aligned} \tag{12}$$

The feedback of sideslip angle change rate is mainly used to improve the performance of sideslip angle. In the equation 12, high-pass filter $\tau = 0.02$.The Figure 1 shows the sideslip angle differential signal and sideslip angle high-pass filter signal and sideslip angle kinematic coupling, namely the simplified sideslip angle change rate. The small disturbance comparison diagram is like following:

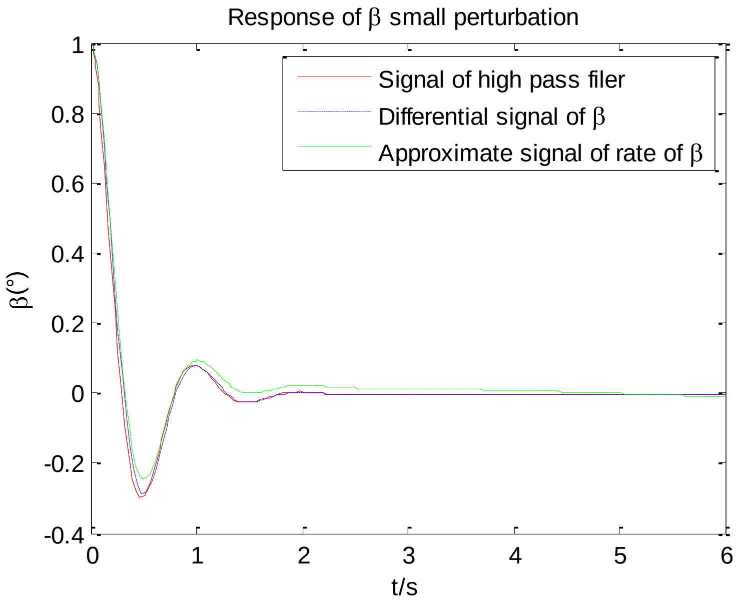

Figure 1. Sideslip Angle Disturbance Response Achieved By Different Sideslip Angle Change Rate

From the Figure 1, the sideslip angle disturbance response achieved by different sideslip angle change rate is basically same. Among the response, the sideslip angle differential signal is $\dot{\beta}$ accurate signal. The high-pass filter signal is the nearest but is sensitive to noise in actual motion, so it is not recommended. Ignoring the gravitational force and side force, the simplified signal of sideslip angle change rate has some differences, which are not obvious.

But in the process of rolling, for making sure the sideslip angle small, the side force is small and can be ignored. But with the increase of roll angle, the gravity will be more influential. Retaining the gravity, the $\dot{\beta}$ signal can be simplified as equation 13.

$$\dot{\beta} = p\sin\alpha - r\cos\alpha + g\sin\phi\cos\theta / V \tag{13}$$

If the sideslip angle is too large, the proportion of lateral force increases, it can be transformed by lateral overload. But due to the high speed of hypersonic vehicle, more proportion of gravity and side force in $\dot{\beta}$ signal is far less than kinematic coupling. So the equation 11 is more advisable.

It can be concluded from deducing the relation of $\dot{\beta}$ and the Dutch Roll, the feedback to both the rudder channel and aileron channel is OK. Retroacting to the aileron channel, the roll rate caused by aileron can roll around the speed shaft though coordination with yaw rate. Retroacting to the rudder channel, the yaw rate caused by rudder can roll around speed shaft though coordination with roll rate, thus weakening the impact of kinematic coupling in the rolling process.

The Figure 2 is the $\dot{\beta}$ simplified signal feedback diagram.

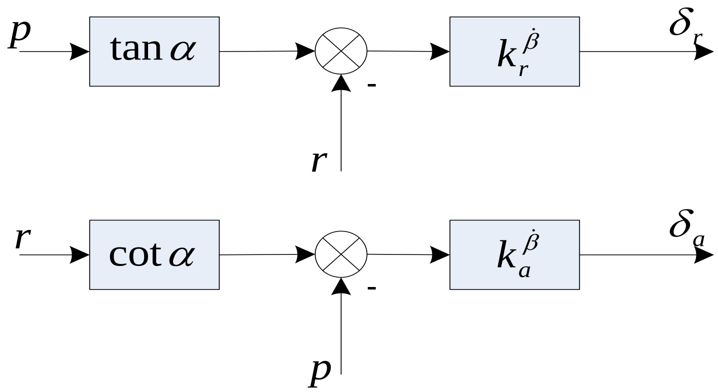

Figure 2. The Feedback Channel Structure Diagram

The analysis above can prove that $\dot{\beta}$ feedback can improve the Dutch Roll character of the air vehicle. At the same time, the air vehicle almost rolls around speed shaft, which restrains the change of sideslip angle in the rolling process.

It can be seen from the Figure 2 that $\dot{\beta}$ feedback is mainly relevant to the attack angle and angular rate and feedback channel. Besides, it is bound up with sideslip angle.

(1) Attack angle

The attack angle directly adjusts the weight of roll rate and yaw rate in $\dot{\beta}$ signal. When the weight of roll rate in the $\dot{\beta}$ signal is weaken, the yaw rate signal can be strengthened. At low angle of attack and large mach number, $\dot{\beta}$ signal can be approximated as $\dot{\beta} = p\alpha - r$. At high angle of attack and large mach number, the $\dot{\beta}$ signal can adopt the equation 11.

The larger the attack, the more effective $\dot{\beta}$ feedback control. This is because with the increase of attack angle, the effect of r feedback will get weakened and the effect p feedback will get strengthened, which meets the change law of $\dot{\beta}$ signal with the attack angle.

(2) Angular rate

The angular rate change also has direct effect on $\dot{\beta}$ signal. When highly maneuvering in the rapid roll, the proportion of roll rate gets bigger. While in the process of small disturbance, the proportion of yaw rate gets strengthened.

The attack angle of the hypersonic vehicle is large, which is almost about 30°. The state is high attack angle and high-maneuver or high attack angle and low-maneuver mostly. $\dot{\beta}$ signal adopts the equation 11 or 13 most of the time. In high-maneuver, the stronger $\dot{\beta}$ signal, the more obvious the effect.

(3) The feedback channel

Based the above analysis, both $\dot{\beta}$ feedback to rudder and $\dot{\beta}$ feedback to aileron are OK. They both can improve the Dutch Roll character and coordinate the angular rate to weaken the impact of kinematic coupling. And all the dynamic characteristics of sideslip angle of the air vehicle can be bettered.

How to choose a proper feedback channel is closely related to the characters of the air vehicle. On the one hand, it depends on the effect of rudder manipulation of the air vehicle. On the other hand, it depends on the control structure. When the $\dot{\beta}$ effect caused by rudder is high, it just needs the feedback to rudder channel. The hypersonic vehicle will suffer high attack angle and mach number, low dynamic pressure region. Because of the cover of body to the rudder, the efficiency of rudder is very low, and the effect of the feedback to rudder channel is very little. So feedback to aileron channel is more advisable. Adopting heading channel to control the roll, the feedback to aileron channel is better. While adopting cross passages to control the roll, the feedback to heading channel is better.

(4) The relation with sideslip angle

Seen from the phase, the phase of rate of sideslip angle advances the sideslip angle 90°. When the sideslip angle pasts zero, the rate of sideslip angle change is the highest and the ability of restraining sideslipping is the strongest, and at a value, the sideslipping's ability of restraining the decreasing trend is relatively weak, which is the expected for controlling.

$\dot{\beta}$ feedback proactively restrains the change of sideslip, which is the damping of sideslip angle and can effectively restrain the change trend of sideslip angle. In the rolling process, because the kinematic coupling and the coupling of aileron to heading make the sideslipping increase, the feedback of sideslip angle change rate can control its increasing trend. At the same time, the appearance of gust results in the coming out of some value in the moment of sideslipping, the feedback of sideslip angle change rate belongs to the process of proactive restraining the change of sideslip angle, which is an advanced link.

$\dot{\beta}$ feedback to rudder or aileron channel mainly improves the dynamic characteristics of sideslip angle and the Dutch Roll damping characteristic of the air vehicle ,and weakens the kinematic coupling of the rolling process. β feedback is used to better static stability and frequency of the Dutch Roll. $\dot{\beta}$ feedback is usually used with β feedback together to better the quality of sideslip angle.

4. Simulation

For testing the validity of the control strategy of the feedback of sideslip angle change rate, the air vehicle nonlinear platform is built in the simulation environment of Matlab/Simulink. The starting condition of nonlinear simulation is:30 as the height, 6 as the mach number, 35°as the attack angle, 0 as the roll angle and the sideslip angle, and control the target to build the 150°roll angle. Adopt aileron to control the rolling and the strategy of sideslip angle change rate feedback to rudder channel. Consider the normal control and the control of sideslip angel change rate and compare them. The sideslip angle change rate uses the simplified signal $p \sin\alpha - r\cos\alpha$, mainly because the hypersonic vehicle is too fast and the gravity and side force is relatively small.

The control scheme of sideslip angle change rate is as the equation 14.

$$\begin{cases} \delta_r = k_{ARI}\delta_a + k_r^{\dot{\beta}}\dot{\beta} + k_r^{\beta}\beta \\ \delta_a = k_a^p p + k_a^{\phi}(\phi - \phi_c) \end{cases} \tag{14}$$

The normal control scheme is as the equation 15.

$$\begin{cases} \delta_r = k_{ARI}\delta_a + k_r^r r + k_r^{\beta}\beta \\ \delta_a = k_a^p p + k_a^{\phi}(\phi - \phi_c) \end{cases} \tag{15}$$

The cross-linking of aileron and the rudder is mainly used to improve the hypersonic vehicle $LCDP$, avoid anti-operating of aileron and weaken the operational coupling of the aileron to the heading. The Figure 3 and 4 respectively give the response curve comparison of the roll rate of 20°/s and 30°/s. The Control One is the control of sideslip angle change rate; the Control Two is the normal control scheme.

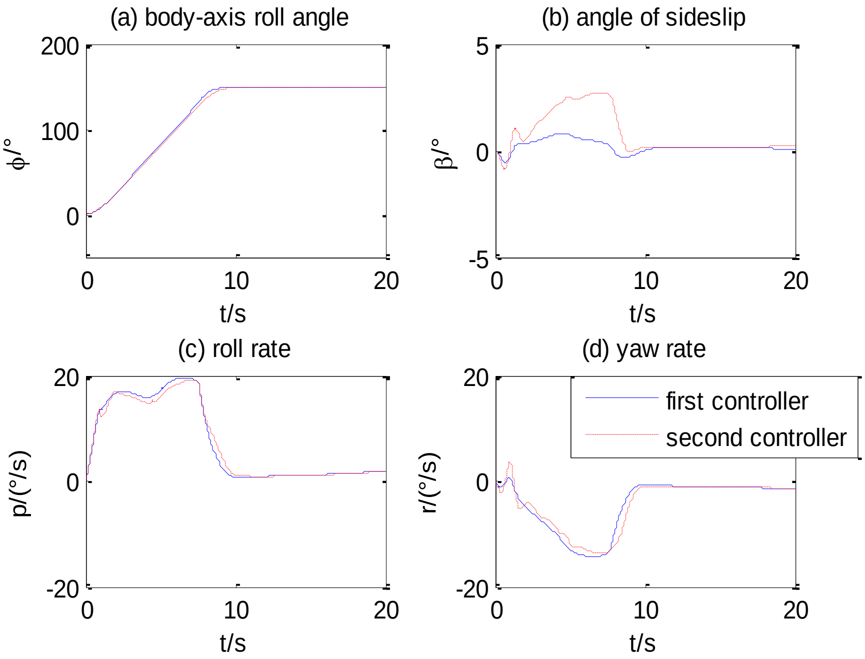

Figure 3. The Response Curve of Roll Rate of 20°/S

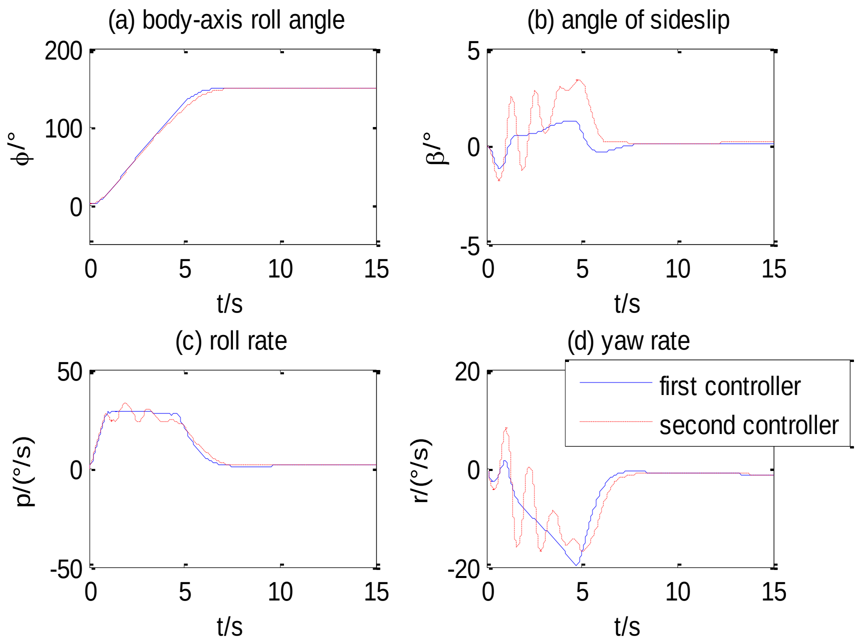

Figure 4. The Response Curve of Roll Rate of 30°/S

Judging from the Figure 3, when the rolling rate is 20°/s, the $\dot{\beta}$ feedback can weaken the sideslip angle. Normal control can realize it as well. The sideslip angle is in the allowed range, but the sideslipping of $\dot{\beta}$ feedback is better. Judging from the Figure 4, when the rolling rate is 30°/s, the control of sideslip angle change rate can still keep the validity. But the normal control has the vibration of sideslip angle. At the same time, angular rate appears the vibration, which must result in the fierce vibration of control plane. The vibration mainly results from two factors. One factor is the worsened Dutch Roll characters in the rapid rolling process. Another one is the kinematic coupling of rapid rolling. So the $\dot{\beta}$ control has better control effect on rapid rolling and improves the dynamic quality of sideslip angle better. Besides it can weaken the sideslip angle effectively.

5. Conclusion

There are two aspects of the restraining side-slipping of feedback of sideslip angle change rate. One aspect is to hinder the change of sideslip angle directly and change the kinetic characteristic, so the Dutch Roll damping characteristic can be improved. Another aspect is to weaken the kinematic coupling of the rolling process. Aiming at the feedback of sideslip angle change rate, this paper analyses the control application. The simulation result proves that the feedback of sideslip angle change rate can improve the Dutch Roll damping characteristic of the air vehicle, which is benefit to restrain the change of sideslip angle in the rolling process to weaken the kinematic coupling especially in the rapid rolling.

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References

[1] H. Lin and Y. Jian-Ying, "Challenges of control science in near space hypersonic aircrafts", Control Theory & Applications, vol. 28, no. 10, **(2011)**.
[2] Q. Naiming and Q. Changmao, "The Six DOF Model of Hypersonic Vehicle and Coupling Characterization Analysis", Journal of Projectiles, Rockets, Missiles and Guidance, vol. 32, no. 1, **(2012)**.
[3] Q. J. Liu, Y. M. Huang and L. N. Wu, "An Analysis of Dutch Roll in High Angle of Attack", Asia-Pacific International Symposium on Aerospace Technology, Xian, PEOPLES R CHINA, **(2010)**.
[4] H. P. Lee, M. Chang and M. K. Kaiser, "Flight dynamics and stability and control characteristics of the X-33 technology demonstrator vehicle", AIAA-98-4410, **(1998)**.
[5] P. Ma, T. Chao and M. Yang, "Modeling and Simulation Methodology of Multifield Coupling for Hypersonic Vehicle", Asia Simulation Conference/International Conference on System Simulation and Scientific Computing, Shanghai, PEOPLES R CHINA, **(2012)**.
[6] L.N. Wu, Y.M. Huang and C.L. He, "Reusable Launch Vehicle Lateral Control Design of Glide Return Phase", Journal of Nanjing University of Aeronautics and Astronautics, vol. 41, no. 3, **(2009)**, pp. 329~333.
A. J. Sinclair and G. T. Flowers, "Coupled Flight-Dynamic and Low-Order Aeroelastic Model for a Slender Launch Vehicle", JOURNAL OF VIBRATION AND ACOUSTICS-TRANSACTIONS OF THE ASME, vol. 135, **(2013)**.
[7] M. Chen and B. Jiang, "Robust Attitude Control of near Space Vehicles with Time-varying Disturbances", International Journal of Control Automation and Systems, vol. 11, no.1, **(2013)**, pp. 182-187.
[8] D. R. Jenkins, T. Landis and S. Crossfield, "Hypersonic:The Story of the North American X-15", Wholesalers: Specialty Press, **(2008)**.
[9] P. Calhoun, "An entry flight controls analysis for a reusable launch vehicle", AIAA-2000-1046, **(2000)**.
[10] N. Ananthkrishnan, "Literal approximations to aircraft dynamic modes", Journal of Guidance Control and Dynamics, vol. 24, no. 6, **(2001)**, pp. 1196-1203.
[11] G. Mengali, "Unified algebraic approach to approximation of lateral-directional modes and departure criteria", Journal of Guidance Control and Dynamics, vol. 27, no. 4, **(2004)**, pp. 724-728.
[12] C. Breitsamter, B. Laschka and G. Sachs, "Lateral-directional coupling and unsteady aerodynamic effects of hypersonic vehicles", Journal of Spacecraft and Rockets, vol. 38, no. 2, **(2001)**, pp. 159-167.
[13] B. L. Stevens and F. L. Lewis, "Aircraft Control and Simulation", New York: John Wiley & Sons, **(2003)**.

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