Simulation analysis study on the flutter characteristics of control rudder in high speed flight vehicle

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Abstract. This paper dedicates to study on the flutter characteristics of control rudder of high speed flight vehicle, and proposes a novel parameter-tuning method for the flutter characteristics optimization of control rudder at the beginning design stage of flight vehicle by combining parametrized dynamic modeling technology, aerodynamic and aeroelastic flutter analysis methodology. Effects of typical parameters, including leading edge sweep angle, tip chord length, root chord length and span, on flutter characteristics of the control rudder in a high speed flight vehicle are studied. Research results have considerable significance for the design adjustment of the rudder configuration, and can be used to avoid the design reiteration and reduce design cycle.

1. Introduction
The control rudder plays a significant role in the flight dynamics and control of high speed flight vehicle. When the flight vehicle reaches a certain critical speed, the intercoupling of unsteady aerodynamic force, inertial force and elastic force will cause the dynamic unsteady flutter of control rudder vibration, which is serious threat to the flight safety. So control rudder is the significant component in overall design of high speed flight vehicle [1]. An IDF aircraft in Taiwan crashed into the sea with the whole vehicle flutter [2]. An F-117 stealth aircraft crashed in the United States due to the flutter of a control rudder [3]. Therefore, dynamic modeling and flutter characteristics analysis of control rudder is very important in the design and development of the high speed flight vehicle; no flutter is allowed, and the critical flutter speed must be greater than the maximum flight speed and reserves a certain amount of allowance [4-5]. Moreover, with the rapid development of modern high speed aircraft technology and the high requirements on improving the control ability of rudder and reducing the mass of structure, a thinner wing structure has been widely adopted in the control rudder, which leads to higher probability of the rudder flutter.

Traditionally, the flutter characteristic analysis of the control rudder of high speed vehicle is conducted in the middle and later stage of the aircraft design, which is after the detailed design of aerodynamics, structure and load. The flutter speed and flutter frequency of the rudder structure is usually obtained according to aerodynamic calculation, aeroelastic analysis and vibration mode, which is usually calculated by finite element modeling and dynamic analysis. Then the possibility the rudder flutter occurrence is determined by comparison between the flight mechanics and control strategy. Design result is finally verified ground wind tunnel test and flight experiment [6]. Therefore, the flutter of the rudder in the flight state can be avoid to a large degree when the stiffness and mass
distribution of the control rudder of the traditional aircraft is designed according to experience, and the flutter analysis is used to verify and validate the design result.

However, the flight control system of a new type of high speed aircraft requires the control rudder with restrictor performance. The light and thin control rudder structure is able to reduce the natural frequency of the rudder, but cause the aeroelastic problem, namely, the flight has greater flutter risk in the condition of higher flight height and Mach number. When there is no relevant design and test experience, if the flutter analysis of the rudder is considered at a later design stage, the flight condition exceeds the flutter boundary and does not meet the requirements of control and trajectory design, in this case, the structure and even the shape of the rudder have to be revised significantly, which will waste wind tunnel test resources seriously and have a significant impact on both the overall progress of aircraft and the design of related majors.[7-8]

In order to consider the influence of flutter characteristic on rudder design at the beginning stage of high speed aircraft development, this paper proposed novel parameterized analysis method to analyze flutter characteristics of high speed aircraft. In Section 2, the parameterized dynamic modeling of the rudder structure surface is achieved firstly by plane projection of 3D rudder surface and the modeling technique of the 3D model reconstruction based on the plane grid. Then by combining parameterized aerodynamics and aeroelastic analysis, a novel method is proposed to optimize flutter characteristics at the beginning stage of high speed aircraft design by adjusting typical characteristic parameters of the rudder structure. In Section 3, simulation studies are carried out to investigate the influence of structure parameters of a high speed aircraft control surface on the flutter characteristics including leading edge sweep angle, tip chord length, root chord length and rudder span. Some conclusions are conducted in Section 4. The study results provide an important reference for the optimization and adjustment of the structure and shape of the rudder surface, and are benefit to avoid effectively the repeated design of the rudder surface.

2. A novel parameterized analysis method for the flutter of control rudder

The flutter phenomenon of control rudder of the high speed flight vehicle is caused by the interaction of unsteady aerodynamic forces, inertial forces and elastic forces. Thus, the vibration characteristics and unsteady aerodynamic load of the rudder face structure in the flight state should be obtained firstly before flutter analysis.

The system dynamic equation for control rudder structure can be expressed as:
$$\begin{align*}
[M_{nn}][\ddot{X}_n(t)] + [B_{nn}][\dot{X}_n(t)] + [K_{nn}][X_n(t)] &= F_n(t) \quad (1)
\end{align*}$$

where $M_{nn}$, $K_{nn}$ and $B_{nn}$ is the mass matrix, stiffness matrix and damping matrix of the rudder surface structure, respectively; $X_n(t) = [x_1(t), ..., x_n(t)]^T$ is the displacement column vector of the structure; $F_n(t) = [f_1(t), ..., f_n(t)]^T$ is aerodynamic load on the structure and $n$ is the system degree.

When the system damping and loads are not considered, equation (1) becomes:
$$\begin{align*}
[M_{nn}][\ddot{X}_n(t)] + [K_{nn}][X_n(t)] &= 0 \quad (2)
\end{align*}$$

The normal vibration frequencies and vibration modes can be obtained by solving the characteristic equation of equation (2).

Aerodynamic load of flight vehicle is usually calculated by harmonic gradient method at low supersonic stage, and van Dyke piston theory[9], Newton impact theory[10], van Dyke/Newton shock mixing theory[11] and unified hypersonic lifting surface theory[12] are usually adopted in the hypersonic stage. When aerodynamic load is calculated by finite element method, aerodynamic surface is generally divided into several aerodynamic surface elements. The deformation of the structure will cause the deformation of the aerodynamic surface, so the element downwash $\{W_j\}$ can be expressed as[13]:
$$\{W_j\} = \left[D^1_{jk} + i\omega b/V D^2_{jk}\right]\{u_k\} + \{W^g_j\} \quad (3)$$

where $D^1_{jk}$ and $D^2_{jk}$ are the real part and the imaginary part of the Jacobian matrix, respectively; $\omega$ is natural frequency; $b$ is half of the reference chord length; $V$ is the flow velocity; $u_k$ is the
displacement of the aerodynamic surface at the grid node; \( W_j^\theta \) is static dynamic downwash on the \( j \) th aerodynamic element.

Classic flutter analysis methods include eigenvector orientation approach \([14, 15]\) and envelope function \([16, 17]\). The P-K method, proposed by Hassig in 1971, is an alternative flutter analysis method for aircraft control rudder surface, and its flutter motion equation can be expressed as \([13]\):

\[
\left[ M_{hh} p^2 + (B_{hh} - 1/4 \rho \bar{c} V Q_h^i / k) p + (K_{hh} - 1/2 \rho V^2 Q_h^R) \right] \{ u_h \} = 0
\]

where \( Q_h^i \) is the imaginary part of the influence coefficient matrix of the generalized aerodynamic force, namely, modal aerodynamic damping matrix; \( Q_h^R \) is the real part of the influence coefficient matrix of the generalized aerodynamic force, namely, modal aerodynamic stiffness matrix; \( M_{hh} \) is modal mass matrix; \( B_{hh} \) is modal damping matrix; \( K_{hh} \) is modal stiffness matrix; \( p = \omega (\gamma + i) \) is characteristic value; \( \gamma = g/2 \) is transient attenuation coefficient; \( g \) is structural damping; \( \rho \) is air density; \( \bar{c} \) is reference chord length; \( k = \omega \bar{c}/2V \) is reduction frequency. The criterion for the critical point of flutter is structural damping \( g = 0 \).

Based on above structural dynamics analysis methods, aerodynamic analysis method and aeroelastic flutter analysis method, a novel the parameterized flutter characteristics of the control rudder can be proposed and shown in figure 1 which can be used to analyze the flutter characteristics of typical structural parameters of rudders. The control rudder is used to control the vertical and horizontal flight attitude, including both vertical rudders and elevators in this paper. The control rudder of a high speed aircraft shown in figure 2, which consists of skin and spar, holds typical light and thin structure characteristics of control rudder. Thus, it is served as an example to illustrate the proposed method as shown by encircled portion in figure 1.

In the term of parameterized finite element modeling, according to the method shown in figure 1, Projection plane of the 3D control surface structure is firstly divided into four areas as shown in figure 3, namely, front area of the rudder, external frame area of the rudder, internal frame area of the rudder and rudder axis area of the rudder. Then each area is meshed by 2D flat plane grids. The structure can be described by typical parameters such as root chord length, tip chord length, rudder span, leading edge sweepback and so on. Then, the parameterized 3D reconstruction of the rudder is carried out by taking the thickness of rudder plane chord and the height of the middle are line as characteristic parameters. 3D finite element model of the rudder is reconstructed by extending 2D structure at all nodes to form skin, longitudinal wall and wing rib as shown in figure 4.

In the term of the unsteady aerodynamic calculation of the rudder, the parameterized aerodynamic grid is divided firstly on the parameterized 2D plane projection of the rudder as shown in figure 5. The unsteady aerodynamic force theory is chosen according to the flight Mach number state and then used to calculate the unsteady aerodynamic force of the control rudder. In the design of high speed vehicle, subsonic dipole grid method can be adopted in subsonic speed range, while the ZONA51 supersonic lift surface theory \([12, 18]\) is used in supersonic speed range.
The initial structure model of the rudder surface

Plane projection of three-dimensional rudder surface

Reconstruction of 3D model of plane grid

Parameterized simulation model of rudder surface

Material parameters

Building model Elements

Parameterized iteration based on control and ballistic requirements

Structural parameterization

Typical plane parameters

Topology partition

Planar projection of 3D rudder skin model

3D expansion of grid

Typical spatial parameters

Parameterized mesh division

Unsteady aerodynamic force on the parameterized rudder

Unsteady aerodynamic calculation

Aerodynamic analysis network model

Parameterized aerodynamic division

Parameterized aerodynamic calculation

Outer surface profile of rudder

Aerodynamic parameterization

Figure 1. Simulation analysis flow chart of parameterized flutter characteristics of control rudder.

1. Front area
2. External frame area
3. Internal frame area
4. Rudder axis area

1. 2D plane projection
2. Sections along the span direction
3. 3D rudder skin model
4. 3D rudder frame model

Figure 2. A high speed flight vehicle and its control rudder.

Figure 3. Plane projection partition of control rudder structure.

Figure 4. 3D model reconstruction of plane mesh of rudder plane.
Finally, parameterized analysis and optimization of the flutter characteristics of the control rudder can be achieved with the aid of the aeroelastic analysis software on the basis of parameterization of the rudder surface structure and aerodynamic grid as shown in figure 1.

3. Simulation studies
In order to verify the feasibility of parametrized control rudder surface modeling and flutter characteristics analysis method proposed in Section 2, the normal mode and flutter characteristics of the control rudder structure of a high speed vehicle, as shown in figure 2, are investigated. The rudder sweepback angle is set as $\alpha = 60^\circ$, root chord length is set as $L_g = 500\text{mm}$, span is set as $L = 300\text{mm}$, tip chord is set as $L_s = 400\text{mm}$. The alloy material with modulus of elasticity $E = 60\text{GPa}$ and density $\rho = 5 \times 10^3\text{kg/m}^3$ are selected as the material of control rudder.

The first 3 normal vibration modes can be obtained by parameterized programming modeling and simulation solution in MSC.Patran and Nastran software according to the analysis process shown in figure 1, and results are shown in figure 6. This natural frequency is compared with the modal experiments as shown in table 1. It can be indicated by figure 6 and table 1 that the simulation results of the control rudder mode characteristics obtained by using the plane projection subdivision and the reconstruction technology of planar mesh model are almost the same with the experimental results, which can meet requirement of controlling rudder design at the beginning stage of high speed aircraft.

**Table 1.** Comparison between simulation and experimental results of first 3 order natural vibration modes of a high speed flight vehicle control rudder.

| Order | Mode description                  | Simulation Frequency (Hz) | Experimental Frequency (Hz) | Simulation Error (%) |
|-------|-----------------------------------|---------------------------|-----------------------------|----------------------|
| 1     | 1st Bending mode                  | 50.2                      | 51.7                        | 2.9                  |
| 2     | 1st torsional mode                | 81.2                      | 84.1                        | 3.4                  |
| 3     | 1st vibration mode by steering engine | 92.7                      | 95.1                        | 2.5                  |
Figure 6. First 3 order natural vibration modes of a high speed flight vehicle control rudder (a) First order natural vibration mode (b) Second order natural vibration mode (c) Third order natural vibration mode.

After above modal analysis of the rudder structure, the parameterized unsteady aerodynamic force is calculated in by Nastran software, and the classical flutter analysis is carried out by P-K method. When the height is at sea level (atmospheric density is 1.225kg/m$^3$), flight Mach number $Ma = 1.5$, and ZONA51 method is used to calculate the unsteady aerodynamic force, the results of control rudder flutter characteristics are shown in table 2, flutter curve of $V$-$g$ and $V$-$f$ shown in figure 7(a) and figure 7(b), respectively, which indicate that the coupling of the rudder flutter is the 1st and 2nd order modes, namely, the classical bending and torsional coupling flutter.

Table 2. Flutter analysis results of control rudder.

| Flutter Speed (m/s) | Flutter Frequency (Hz) | Coupling modes                  |
|---------------------|------------------------|----------------------------------|
| 635                 | 65.7                   | 1$^{\text{st}}$ bending mode and 1$^{\text{st}}$ torsional mode |

Figure 7. Flutter characteristics of control rudder at sea level with flight $Ma=1.5$.

In order to study the influence of typical parameters on the flutter characteristics of the control rudder, the rudder model and flutter characteristics in the case of different leading edge sweep angle, root chord length, tip chord length and span are obtained according to method as shown in figure 1 and the results are shown in figure 8.
It can be seen from figure 8 that when the leading edge sweep angle, tip chord length or span of rudder increases, the flutter speed decreases gradually; when the root chord length of rudder increases, the flutter speed increases gradually. Except for leading edge sweep angle, tip chord length, root chord length and rudder span, influence of other typical characteristic parameters of the control rudder, such as the material properties, wing rib direction, on the flutter characteristics can also be obtained. The analysis results can provide an important reference for the adjustment and optimization of the rudder design at the beginning stage of the high speed flight vehicle design.

4. Conclusions
A parameterized flutter characteristics analysis method is proposed in this paper by combining parameterized finite element modeling method of the control rudder structure, unsteady aerodynamic and aeroelastic flutter analysis. The effectiveness of the proposed method on flutter analysis of the control rudder is verified by simulation case studies. Effects of typical parameters of the rudder surface on the flutter characteristics of the control rudder are obtained including leading edge sweep angle, tip chord length, root chord length and rudder span. When the leading edge sweep angle, tip chord length or span of rudder increase, the flutter speed decreases gradually, but when the root chord of rudder becomes longer, the flutter speed increases gradually. The conclusions provides an important reference for optimizing and adjusting the rudder structure and shape at the beginning stage of the high speed aircraft design, which can effectively avoid the repetition of rudder design in the middle and later stage of aircraft design.

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