A review and historical development of analytical techniques to predict aircraft spin and recovery characteristics：

飞机动力学模型：

1. Aerodynamic models based on dynamic wind tunnel tests Aerodynamic coefficient in the aircraft body axes system:

$$C_i = C_{i,static} + \Delta C_{i,steady} + \Delta C_{i,unsteady}$$

$C_{i,static}$: baseline static coefficient

$\Delta C_{i,steady}$： aerodynamic increments because of steady rotations

$\Delta C_{i,unsteady}$： incremental aerodynamic effect because of unsteady and separated airflow conditions

These coefficients are measured in dynamic wind tunnel tests. Different models may cause extremely different simulation results as Reynolds number differs.

2. Aerodynamic models based on real data from flight tests

System identification

neural network

local model networks

locally weighted regression

empirical mode decomposition

3. Analytical prediction of aircraft spin and recovery characteristics

$D : drag \quad W : weight \quad L : lift \quad mr\Omega^2 : balancing\ centrifugal\ force$

Make some simplification so we get the following model of 3 DOFs:

$$\begin{cases} \dfrac{4(I_y - I_z)}{\rho S_w b^3}(\dfrac{\Omega b}{2v})^2 sin(\alpha) sin(2\beta) + C_l = 0 \\ \dfrac{4(I_z - I_x)}{\rho S_w b^2 \overline{c}}(\dfrac{\Omega b}{2v})^2 sin(2\alpha) cos^2(\beta) + C_m = 0 \\ \dfrac{4(I_x - I_y)}{\rho S_w b^3}(\dfrac{\Omega b}{2v})^2 cos(\alpha) sin(2\beta) + C_n = 0 \end{cases} \tag{1}$$

$C_l, C_m, C_n$are the values of rolling,pitching and yawing moment coefficients.There are functions of $[\alpha, \beta, \Omega]$ Facts show that the model is useful in practice and is used by NASA.

4.Bifurcation analysis of aircraft nonlinear dynamics

Have many possibilities of equilibrium states and periodic solutions.Stability characteristics of equilibrium state often change at a bifurcation point.Stabilty may disappear due to bifurcation or jump phenomenon and the state is attracted to a far point to make it steadily spin.This is mature but still have problems to solve further.

4.Prevention and recovery

Describes the method of different types of aircrafts.

尾旋的状态： A spin is defined as an aggravated stall, which results in autorotation of an aircraft while descending in a helical pattern about the vertical spin axis. In an aggravated stall, one wing is stalled more than the other. The more stalled wing experiences less lift and more drag as compared to other and this imbalance of forces initiates autorotation and subsequent rapid decent of the aircraft.

Aircraft Loss of Control Problem Analysis and Research Toward a Holistic Solution

Describes LOC and some statistics of different LOC, with diagrams to intuitively show the facts.、、
Describes an overview of research toward a holistic LOC solution.

Switching Control Architecture with Parametric Optimization for Aircraft Upset Recovery

Upset(Loss-of-Control) Criteria

The prediction of an upset circumstance depends on five quantitative loss-of-control (QLC) envelopes：

1) Adverse aerodynamics envelope:
   [angle of attack α ,sideslip angle β]
2) Unusual attitude envelope:
   [pitch angle θ , roll angle ϕ]
3) Structural integrity envelope:
   [true airspeed V_T , acceleration along the z axis N_Z]
4) Dynamic pitch control envelope:
   [pitch angle θ , pitch rate Q , elevator deflection angle δ_e]
5) Dynamic roll control envelope:
   [roll angle ϕ, roll rate P; aileron deflection angle δ_a]

Recovery Procedures and Recoverability Criteria

Definition of successful recovery:

1) The aircraft should not be stalled, that is, the angle of attack is less than $_{stall}$.
2) The aircraft should be ascending, that is, the pitch angle and the flight-path angle are both greater than zero
3) The aircraft should have regulated attitudes, that is, all three angular rates and derivatives of body angular rates are below a specified threshold.

Mathematical model:Switching Recovery System

Continuous state vector X $X = [V_T, \alpha, \beta, \Phi, \theta, \psi, P, Q, R, N_P, E_P, h]^T$

Model-Predictive Spiral and Spin Upset Recovery Control for the Generic Transport Model Simulation

Piecewise polynomal model

$V_A^T = [u\ v\ w]$:velocity to air

$\omega^T = [p\ q\ r]$:body rates

$\alpha = arcsin(\frac{\omega}{\sqrt{u^2+v^2}})$:angle of attack

$\beta = arcsin(\frac{v}{V_A})$:sideslip angle

$\phi^T = [\phi\ \Theta\ \Psi]$:bank,pitch,heading

Use least square method to model.

$$\mathbf{x}_{8e}^{+} = \mathbf{x}_{8e} + \tau\, \mathbf{f}_{8e}(\mathbf{x}_{8e}, \mathbf{x}_{\delta}), \tag{2a}$$

$$\mathbf{x}_{\delta}^{+} = \mathbf{x}_{\delta} + \tau\, \mathbf{u}_{\delta}, \tag{2b}$$

where $\mathbf{f}_{8e} : \mathbb{R}^8 \times \mathbb{R}^3$ are the continuous time equations of motion and the state and input vectors are

$$\mathbf{x}_{8e}^{T} = [\ u \quad v \quad w \ \vdots\ p \quad q \quad r \ \vdots\ \Phi \quad \Theta\ ] \in \mathbb{R}^8, \tag{3a}$$

$$\mathbf{x}_{\delta}^{T} = [\xi \quad \eta \quad \zeta] \in \mathcal{X}_{\xi} \times \mathcal{X}_{\eta} \times \mathcal{X}_{\zeta} = \mathcal{X}_{\delta}, \tag{3b}$$

$$\mathbf{u}_{\delta}^{T} = [\dot{\xi} \quad \dot{\eta} \quad \dot{\zeta}] \in \mathcal{U}_{\delta}. \tag{3c}$$

The equations of motions $\mathbf{f}_{8e}$ in (2) are the usual rigid body flight dynamics, viz.

$$m\dot{\mathbf{V}}_{\mathrm{A}} = \mathbf{R}^{\mathrm{A}}(V_{\mathrm{A}}, \alpha, \beta, \xi, \eta, \zeta, \boldsymbol{\omega}) + \mathbf{R}^{\mathrm{G}} + m\boldsymbol{\omega} \times \mathbf{V}_{\mathrm{A}}$$

$$\mathrm{I}\dot{\boldsymbol{\omega}} = \mathbf{Q}^{\mathrm{A}}(V_{\mathrm{A}}, \alpha, \beta, \xi, \eta, \zeta, \boldsymbol{\omega}) + \mathbf{Q}^{\mathrm{cg}} + \boldsymbol{\omega} \times \mathrm{I}\boldsymbol{\omega}$$

$$\dot{\underline{\boldsymbol{\Phi}}} = \mathrm{M}_{\omega}(\underline{\boldsymbol{\Phi}})\, \boldsymbol{\omega}$$