Simulation Experiment Analysis and Verification of Ship Resonance for Shipboard Helicopter

Yan Zhu*, Yuhui Lu, Fengnan Sun, Qiyou Cheng, Siwen Wang, Zhenkun Li
Science and Technology on Rotorcraft Aeromechanics Laboratory, CHRDI, Jingdezhen, China
E-mail: everyanyan@126.com
*Yan Zhu: email: zhuy027@avic.com

Abstract. According to the dynamic characteristics of shipboard helicopter landing, the time-domain load of ship movement on the fuselage under complex sea conditions, the nonlinear dynamic characteristics of rotor damper, and the influence of rotor blade flapping movement and aerodynamic force are considered. The fuselage, rotor lagging damper, blade flapping and lagging movement and aerodynamic model are modeled separately as sub-models, and then the subsystems are integrated according to mechanical principles to finally establish the ship resonance analysis model of helicopter. The method for simulation experiment of ship resonance is put forward. The whole process of ship resonance experiment is dynamically demonstrated by digital simulation technology, which simulates the excitation load on the fuselage caused by the rise and fall and rolling movement of the ship. Actually simulates the lifting collective pitch and conducts periodic excitation by disturbing the control stick. Based on the transient response of the time-domain simulation dynamic system under disturbance, the stability of ship resonance is analyzed. The accuracy of the simulation method is verified through project cases, and the simulation experiment analysis techniques for accurately predicting the unstable boundary of ship resonance are mastered, which provides design and analysis means instead of the experiment that cannot be carried out in model development.

1. Introduction
Ship resonance is an aerodynamic problem that is most likely to endanger the safety of aircraft and ship in the process of helicopter landing. The research on analysis and simulation technology of ship resonance plays an important role in solving the problem of helicopter taking off and landing technologies. Ships in marine meteorological environment will rock when anchoring or sailing under various sea conditions. When the helicopter takes off or lands on the ship, the dynamic characteristics of rotor lagging damper and landing gear are sensitive to environmental changes. The stiffness and damping of rotor lagging damper and landing gear are highly nonlinear, and the dynamic characteristics of rotor and fuselage system will change significantly in ship vibration environment, resulting in the existence or possibility of ship resonance instability caused by the coupling motion of rotor and fuselage. The kinematic relationship between the landing gear and the aircraft and ship, as well as various constraints and dynamic characteristics caused by the landing should also be considered.

Plenty of studies have been done at home and abroad on the model and analysis of coupling stability of ship resonance. William and GC Hu, considering six freedoms of motion, different positions of helicopter on deck and flow field of the ship, established a coupled dynamic analysis...
model of helicopter rotor and fuselage on ship deck. [1][2] For wheel landing gear helicopter, Ming Xu used complex stiffness method to obtain the stiffness and damping of landing gear acting on the fuselage, and analyzed the ship resonance stability under different rotor lifts. [3] The coupled dynamic analysis model of shipboard helicopter and ship motion established by Yang Liu et al. considered the nonlinear and asymmetric characteristics of landing gear system. [4] Chuan Xie et al. adopting the method based on multi-body dynamics, established the dynamic model of rotor/airframe/landing gear/ship coupling, used the state-space eigenvalue method and fourth-order Runge-Kutta method to analyze the dynamic stability of the coupling system, and studied the effects of ship’s roll angle, motion period and rotor hydraulic damper parameters on the ship resonance stability of the helicopter. [5] [6]

In terms of ground/ship resonance stability simulation analysis, AM Ling et al. by establishing a nonlinear dynamic model of rotor/airframe aeroelastic coupling system applicable to the analysis of helicopter start-up on the ground, simulated the transient response of rotor/airframe aeroelastic coupling system during the process the rotor from the speed of zero to the speed after acceleration when the aircraft took off, analyzed the transient response of start-up on the ground, and dynamically simulated the process of ground resonance of start-up experiment on the ground. [7-9] Kianejad et al. adopted nonlinear unsteady computational fluid dynamics simulations to investigate the ship response phenomenon using a container under a sinusoidal roll exciting moment. Simulations were constructed over a range of frequencies to cover the response frequency including lower and higher amplitudes. [10]

On the basis of establishing the digital simulation analysis model of ship resonance experiment considering the nonlinear dynamic characteristics of rotor damper and landing gear, this paper simulates the excitation load on the fuselage caused by the rise and fall and rolling movement of the ship, simulates the effect of the landing gear on the fuselage while landing, actually simulates the lifting collective pitch and conducts periodic excitation by disturbing the control stick. Based on the transient response of time-domain simulation dynamic system under disturbance, the change process of transient response reflects the real state of helicopter under disturbance when taking off and landing on the ship. The resonance stability of the ship is analyzed, and the nonlinear dynamic characteristics of ship motion and components as well as influence of landing gear on ship resonance are revealed. Through the comparison of ship resonance simulation experiment based on nonlinear model with the model linear calculation (linear model), the accuracy of the simulation method is verified by the project cases, and the simulation experiment analysis techniques for accurately predicting the unstable boundary of ship resonance are mastered, which provides design and analysis means instead of the experiment that cannot be carried out in model development.

2. Theoretical Model

In theoretical model, the rotor blade model considers such factors as flap-lag-torsion coupling motion and nonlinear rotor damper. The rotor aerodynamic model will consider the influence of unsteady aerodynamics. Different transverse and longitudinal modal of the fuselage are considered, which is the pitching and rolling modal motion of the rigid fuselage around the instantaneous center on the elastic support system. The time-domain loads of ship motion on rotor and fuselage under complex sea conditions are considered. Based on the principle of mechanics (Lagrange principle, etc.), the equations of rotor blade flapping and lagging motion, and the equations of fuselage pitching and rolling motion are derived, and an analytical model which gives a comprehensive account of various factors affecting the coupling instability of rotor and fuselage when helicopter takes off or lands on the ship is established.

According to the configuration of helicopter models, the coordinate system of fuselage is established, as shown in Figure 1 (n represents the main landing gear and m represents the tail landing gear in the figure). Suppose the fuselage is a rigid body, the landing gear provides elastic support and damping for the fuselage. The six freedoms of rigid-body motion of the fuselage in space are considered, which are \( X, Y, Z, \Phi_X, \Phi_Y, \Phi_Z \) (course, lateral and vertical displacement, and rolling, pitching and yawing motion).
Column-type shock absorber-Wheels and shock absorbers of wheel-type landing gear are connected in series, which has an elastic damping effect on the fuselage. The shock absorbers are simplified as stiffness and damping components, and the wheels are simplified as mass, stiffness and damping components. To explore the influence of ship motion on landing gear, the motion relationship between ship and landing gear is directly taken into account and the force applied on a single landing gear wheel is analyzed, as shown in Figure 2. In Figure 2, Z_1 shows the ship motion, Z_T shows the wheel motion (each wheel is independent from one another), F_S indicates the force of the shock absorber acting on the wheels, M_T indicates mass of the wheel and K and C are the vertical stiffness and damping of the wheel.

If the helicopter uses mooring device (such as harpoon) before taking off or after landing on the ship, the device can be simplified into the pattern shown in Figure 3 by modeling. The joints connecting harpoon device and fuselage are point A, B and C. For the harpoon state upon landing, when the harpoon is locked, that is, after the servo valve is closed, the harpoon rod provides a vertical constraint on the fuselage motion, which has high stiffness.

According to the position of blade infinitesimal mass in the coordinates of non-rotating propeller hub, the position of blade infinitesimal mass in fuselage coordinates and the relative velocity of blade infinitesimal mass caused by flapping β and lagging ζ are derived. Then based on the convected velocity of blade infinitesimal mass caused by fuselage motion, the absolute velocity can be obtained, and the rotor blade energy equation can be established according to D’Alembert principle. The rotor aerodynamic model adopts quasi-steady aerodynamic force and linear inflow model, considering the influence of unsteady aerodynamic force. Figure 4 shows a blade motion model.
There are two types of rotor dampers commonly used in helicopter rotor systems. One is viscoelastic damper and the other is hydraulic damper. According to the type and main design parameters, the two types of dampers are modeled respectively. According to the rotor design parameters, theoretical or empirical formulas, the nonlinear dynamic model of rotor lagging damper is established based on the static compression load data and dynamic stiffness and damping data of model parts. The undetermined coefficients in the formula are fitted by the least square method, which are then checked and modified through relevant experimental data, and finally the nonlinear dynamic model of rotor damper is obtained.

In order to simulate the change of rotating speed during start-up, the author introduced torsional motion equation of the whole power transmission chain including rotor, final reduction drive, engine and drive system, and built the coupling relationship between torsional vibration motion of power transmission system and rotor lead-lag, and fuselage movement.

Finally, the inertia load and aerodynamic load acting on the fuselage caused by the flapping and lagging motion of the rotor blades are added into the motion equation of the fuselage on the landing gear, and the motion equation of the fuselage considering the coupling of the rotor and the fuselage is obtained, namely (1) the fuselage motion equation:

\[
[M] \ddot{X}_F + [M_x(\psi)]\dot{X}_F + [C_x(X_F)]\dot{X}_F + [C_F(\psi)]\dot{\psi}_F \nonumber
\]

\[
+ [C_x(X_F)]\dot{\psi}_F + [K_x(X_F)][X_F] + [K_F(\psi)]\dot{\psi}_F = [F_{ \text{aero}}(\psi) + F_x(X_F)]
\]

(1)

In the equation, the rotor blade matrix coefficients coupled with the fuselage include lagging motion $\zeta$, flapping motion $\beta$ and period coefficient $\cos \Psi$ and $\sin \Psi$. The loads at the right end include aerodynamic load, and load of wheel motion acting on the fuselage through the landing gear. Inertial load caused by ship motion, and aerodynamic load also have periodic coefficient.

(2) the blade motion equation

The lagging motion equations of $N_b$ blades are composed of the lagging equation of kth blade.

\[
I_b \dddot{\xi}_k + F_{\zeta k}^w + M_d(\ddot{\xi}_k, \xi_k) + S_b \Omega^2 \dddot{\xi}_k + S_b (\dddot{\phi} - Z_n \phi_y)(\cos \phi_k - \sin \phi_k \xi_k) \nonumber
\]

\[
- S_b (\dddot{\phi} + Z_n \phi_y)(\sin \phi_k + \cos \phi_k \xi_k) + S_b \dddot{\phi} X + S_b Y, \cos \phi_k + S_b Y, \sin \phi_k \nonumber
\]

\[
= M_{\zeta k} \quad (k = 1, 2, ..., N_b)
\]

(2)

In the equation, \(M_{\zeta k}\) is the aerodynamic load which includes aerodynamic excitation load produced when excitation is applied by periodic variable pitch. \(M_{\zeta}\) is the load of the lagging damper, which is related to the lagging motion of the blade, determined by the nonlinear characteristic curve, and updated in real time in the calculation.

The flapping motion equations of $N_b$ blades are composed of the flapping motion equation of kth blade.

\[
I_b \dddot{\beta}_k + F_{\beta k}^w + S_b \Omega^2 \beta_k L_n + S_b (\dddot{\phi} - Z_n \phi_y - \phi_y) \nonumber
\]

\[
+ S_b (\dddot{\phi} + Z_n \phi_y) \beta_k + M_d (\dot{\beta}_k, \beta_k) \nonumber
\]

\[
= M_{\beta k} \quad (k = 1, 2, ..., N_b)
\]

(3)

In the equation, \(M_{\beta k}\) is the aerodynamic load which includes aerodynamic excitation load produced when excitation is applied by periodic variable pitch. \(M_{\beta}\) is the elastic constraint
load of the flapping hinge, which is related to the flapping motion of the blade and determined by the nonlinear characteristic curve.

(3) the wheels’ vertical motion equation

The vertical motion equation of front wheels and left and right main wheels constitutes equations:

\[
\begin{bmatrix}
M_f \\
C_f \\
K_f
\end{bmatrix}
\begin{bmatrix}
Z_f \\
\dot{Z}_f \\
\ddot{Z}_f
\end{bmatrix}
+ \begin{bmatrix}
C_r \\
K_r
\end{bmatrix}
\begin{bmatrix}
Z_r \\
\dot{Z}_r
\end{bmatrix}
= \begin{bmatrix}
\dot{Z}_{J} \\
\dot{Z}_{T}
\end{bmatrix}
\]

(4)

In the equation, \(Z_J\) indicates the ship motion, \(Z_T\) indicates the wheel motion, and \(M_f, C_f, K_f\) is the wheel mass, vertical stiffness and damping. During balance calculation, motion at the landing point \(Z_J\) is represented by:

\[Z_J = Z_{J0} \sin \omega_J t\]

\(Z_{J0}\) is the amplitude of rise and fall of the landing point, and \(\omega_J\) is the frequency of the ship rise and fall.

After sorting out the above equations and aerodynamic equations, the matrix form of coupled state dynamic equation is obtained:

\[
\begin{bmatrix}
M(\psi) \dot{Y} \\
C(Y,Z,\psi) \dot{Y} \\
K(Y,Z,\psi) \dot{Y}
\end{bmatrix}
+ \begin{bmatrix}
0 \\
1 \\
0
\end{bmatrix}
\begin{bmatrix}
Y \\
0 \\
0
\end{bmatrix}
= \begin{bmatrix}
0 \\
F(Y,Z,\psi)
\end{bmatrix}
\]

(5)

Reduced to first-order equation form:

\[
\begin{bmatrix}
\dot{Y} \\
\ddot{Y}
\end{bmatrix}
= \begin{bmatrix}
0 & I \\
-M^{-1}K & -M^{-1}C
\end{bmatrix}
\begin{bmatrix}
Y \\
\dot{Y}
\end{bmatrix}
+ \begin{bmatrix}
0 \\
F(Y,Z,\psi)
\end{bmatrix}
\]

(6)

3. Simulation Experiment Method of Ship Resonance

For simulation calculation of ship resonance, helicopter driving on the ship from the rotor speed of zero to low speed is simulated. During the whole process from zero speed to rated speed, it simulates the excitation loads of rise and fall and rocking motion of the ship applied on the fuselage, simulates the lifting collective pitch and conducts periodic excitation by disturbing the control stick, analyzes the vibration response history of fuselage and lead-lag response history of blades, calculates the response attenuation damping of fuselage or blades after stopping excitation, and analyzes ship the resonance stability considering the dynamic characteristics of nonlinear components. The specific steps are as follows:

- a) Calculate and determine the collective pitch by a given lift/weight ratio (T/G).
- b) Calculate the static balance of fuselage and landing gear on the ship, and determine the static balance displacement of buffer and wheel.
- c) Under the state of given rotating speed and lift force, the exciting force of the rotor to the fuselage and the rotor lagging is calculated and determined by the given periodic variable pitch value. The periodic variable pitch exciting frequency \(\omega\) is the lead-lag frequency of the rotor.
- d) Simulate the torsion excitation mode in the ship resonance experiment through periodic variable pitch excitation, and the duration of torsion excitation is more than 10 seconds.
- e) Conduct integral calculation of the dynamic response of the fuselage and rotor by Runge-Kutta method.
- f) Change rotating speed, lift force and corresponding excitation frequency, repeat steps from b) to d), simulate and calculate the ship resonance experiment in one weight state, draw the response time history curves of various degrees of freedom of fuselage and rotor lagging, and by analyzing the dynamic response attenuation rate after excitation stops, analyze and determine ship resonance stability of helicopter.
4. Verification and Analysis

For analysis of project cases, through the comparative analysis of results of simulation experiment and ship resonance experiment, the accuracy of simulation calculation results from in terms of frequency and curve fluctuation is analyzed.

Taking the maximum takeoff weight of an aircraft as an example, Figure 5 and Figure 6 show the linear calculation results of ship resonance. Figure 7-9 show the simulation results of ship resonance during free landing, which simulates the whole process of helicopter driving on the ship from rotor speed of zero to low speed and then to rated speed, simulates the excitation loads of rocking motion of the ship applied on the fuselage, simulates the lifting collective pitch, simulates the periodic excitation by disturbing the control stick, and simulates and calculates the fuselage response and the lagging motion of the blade by applying excitation at the 55th second at the rotor speed of 0.62 and the 90th second at the rated speed for 1 second.

Figure 5. Linear calculation of ship resonance stability, T=0.0G, minimum value of ship pitching.

Figure 6. Linear calculation of ship resonance stability, T=0.0G, maximum value of ship pitching.

Figure 7. Response time history of lateral vibration of fuselage (free landing, ship pitching).

Figure 8. Response time history of blades (free landing, ship pitching).

Figure 9. Response time history of lateral vibration of fuselage (free landing, ship rolling) (duration of 100s-110s).
From the figures of response history (Figure 7 to 9), the motion state and stability of the dynamic system in this state can be observed, and its stability measurement adopts moving window analysis, that is:

\[ \varepsilon = \frac{1}{2\pi} \ln \left( \frac{Y}{T} \right), \]
\[ \omega = \frac{2\pi}{T}, \]

\( Y, T, \omega \) are the excited natural frequency of the dynamical system, and \( \varepsilon \) is the attenuation damping ratio of the dynamic system at this vibration frequency. If the damping ratio is greater than 0, it means that the dynamic system is stable. The larger the damping ratio, the higher the stability, and vice versa. If \( \varepsilon \) is a negative value, it means that the response of the dynamic system is not attenuated, that is, it is unstable and divergent.

From Figure 9, it can be seen that the vibration of the whole aircraft in the simulation experiment of free landing includes the low-frequency motion of the fuselage and the high-frequency vibration of the landing gear. The simulation experiment can describe the real helicopter driving on the ship. Under the influence of random transient excitation of ship rocking during free landing and nonlinear constraint load of landing gear, the fuselage vibration is steady (non-divergent) in the working rotating speed range, which means that there will be no ship resonance.

Figure 10 and 11 show the simulation calculation results of ship resonance during landing. On the basis of simulating helicopter free landing, the effect of landing gear on fuselage is simulated, and fuselage response and blade lagging motion are simulated and calculated.

![Figure 10. Response time history of lateral vibration of fuselage (landing, ship rolling).](image)

![Figure 11. Response time history of blades (landing, ship pitching).](image)

By comparing the simulation experiment curves of landing and free landing, it can be seen that after the landing gear is used in the helicopter driving on the ship, the vibration response of the fuselage is reduced, and the lagging response of the blade is also reduced, and the driving stability of the whole aircraft on the ship is better. The simulation curve fluctuates greatly, which just reflects the great influence of nonlinear dynamic characteristics of components on stability of the helicopter.

Based on the comparative analysis of ship resonance simulation experiment based on nonlinear model and the model linear calculation (linear model), the established nonlinear simulation analysis model and analysis method of ship resonance are verified by project cases. The conclusions are as follows:

1. For linear calculation of ship resonance, under the sea conditions that are taken into account, within the rated working speed of the rotor, the helicopter is stable and there will be no ship resonance. Beyond the rated working speed of the rotor, the stability margin of rotating speed is larger and the stability is better.

2. The helicopter driving on the ship during free landing is simulated and calculated. Under the influence of random transient excitation of ship rocking and nonlinear constraint load of landing gear, the fuselage vibration is steady (non-divergent) in the working rotating speed range, which means that there will be no ship resonance.

3. The helicopter driving on the ship during landing is simulated. After the landing gear is used, compared with free landing, the vibration response of the fuselage is reduced, the lead-lag response of the blade is also reduced, the vertical stiffness of fuselage increases, the
frequency of fuselage on landing gear increases, and the driving stability of the whole aircraft is better.

- 4) The simulation experiment results show that the vibration of the whole aircraft includes the low-frequency motion of the fuselage and the high-frequency vibration of the landing gear. The simulation experiment can describe the real helicopter driving on the ship.

- 5) The simulation curve fluctuates greatly, which just reflects the great influence of nonlinear dynamic characteristics of components on stability of the helicopter.

5. Conclusions

Considering factors under complex sea conditions such as ship motion, rotor aerodynamic force, nonlinear characteristics of rotor damper and landing gear, the ship resonance theoretical analysis model with nonlinear dynamic characteristics is established. The method for simulation experiment of ship resonance is put forward, which emulated the whole process of helicopter’s stability when the rotor speed turns from zero to work state, simulated the excitation load on the fuselage caused by the rise and fall and rolling movement of the ship, simulates the aerodynamic influence of rotor, actually simulates the lifting collective pitch and conducts periodic excitation by disturbing the control stick. Based on the transient response of the time-domain simulation dynamic system under disturbance, the stability of ship resonance is analyzed. Through the comparison with model linear calculation (linear model), the accuracy of simulation method is verified, and the following conclusions are obtained:

- (1) The simulation results of ship resonance of free landing are consistent with the model linear calculation results, which shows that the helicopter is steady at working rotating speed and there will be no ship resonance.

- (2) The vibration response of fuselage and lagging response of blades in the simulation experiment of ship resonance during landing are lower than those in free landing, and the stability of ship resonance is better, which is in line with the actual use of helicopters.

- (3) The simulation experiment results show that the vibration of the whole aircraft includes the low-frequency motion of the fuselage and the high-frequency vibration of the landing gear, which reflects the real helicopter driving on the ship. If the curve fluctuates greatly, it reflects the great influence of nonlinear dynamic characteristics of components on stability.

References

[1] William P, Geyer J. (1998) Aerolastic analysis of transient blade dynamics during shipboard engagew/disengage operation. Journal of Aircraft. 35(3): 445-453.

[2] Hu Guo-cai, Sun Jian-guo, Liu Xian-ya. (2008) Analytical Model of Helicopter On-Deck Dynamic Interface. Journal of Naval Aeronautical and Astronautical University. 212.4, 23(5): 481-485.

[3] Ming Xu. (2007) Analytical Method of Ship Resonance for Helicopters with Wheel Landing Gears. Chinese Journal of Aeronautics. Vol.28.

[4] Liu Yang, Xiang Jinwu. (2013) Stability analysis of coupled rotor/fuselage system of shipboard helicopter. Journal of Beijing University of Aeronautics and Astronautics. Vol.39: 442-446.

[5] Xie Chuan, Dong Linghua, Zhou Jinlong, Yang Weidong. (2018) Stability analysis of coupled rotor/fuselage/landing gears/shipboard system for helicopter. The 34th Helicopter Conference. 221-225

[6] Zhao Zeli, Xu Feng. (2020) Dynamic Analysis of “Ship Resonance” for Shipboard Helicopter. Science Technology and Engineering. V226, 20(16).

[7] Ling Aimin, Huang Bingen, Xu Ning. (2009) Simulation Analysis of Helicopter Ground Resonance Test. Helicopter Technique. 25-30.

[8] Yan Zhu, Yuhui Lu, Aiming Ling. (2017) Simulation Analysis of Helicopter Ground Resonance Nonlinear Dynamics. Materials Science and Engineering. Vol.224, 20-24.

[9] Stanislawski. (2019) A Simulation Investigation of Helicopter Ground Resonance Phenomenon. Aircraft Engineering and Aerospace Technology. 91(119).
[10] SS Kianejad. (2020) Investigation of a ship resonance through numerical simulation. Journal of Hydrodynamics, Ser.B. 32(5): 969-983.