APISAT 2019

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ENGINEERS AUSTRALIA

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Aeroengine rotor dynamics，design and optimization，squeezed film damper

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Analysis of the Effect of Maneuvering Flight on Flexible Rotor System Dynamics

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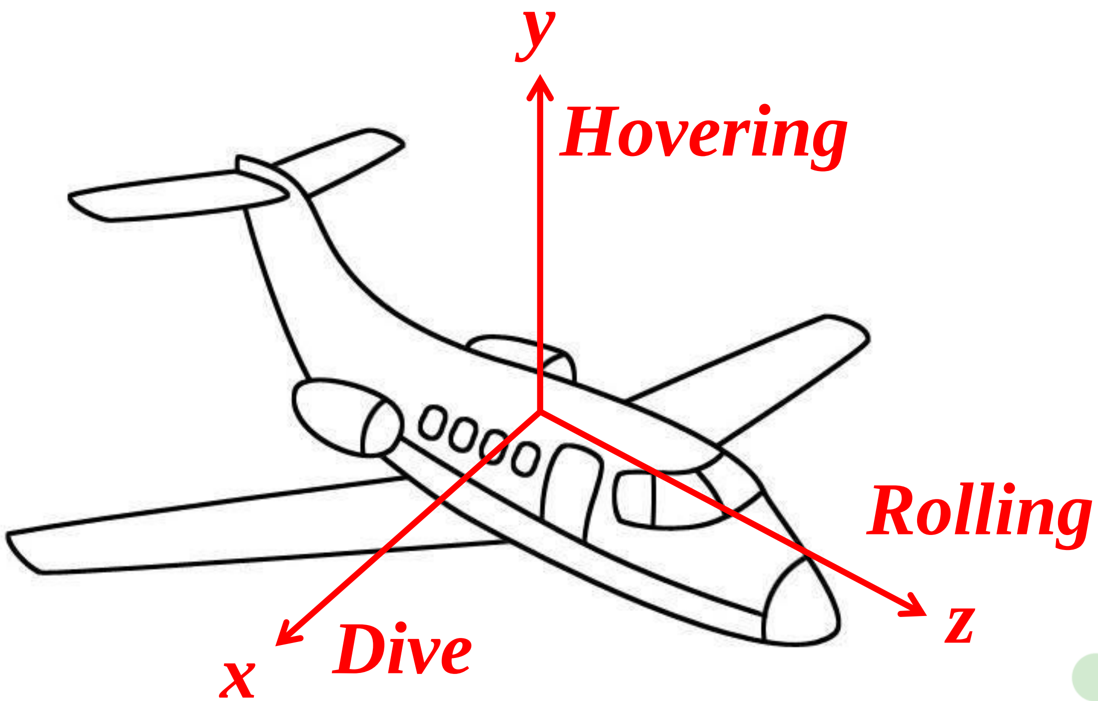
1. What is maneuvering flight

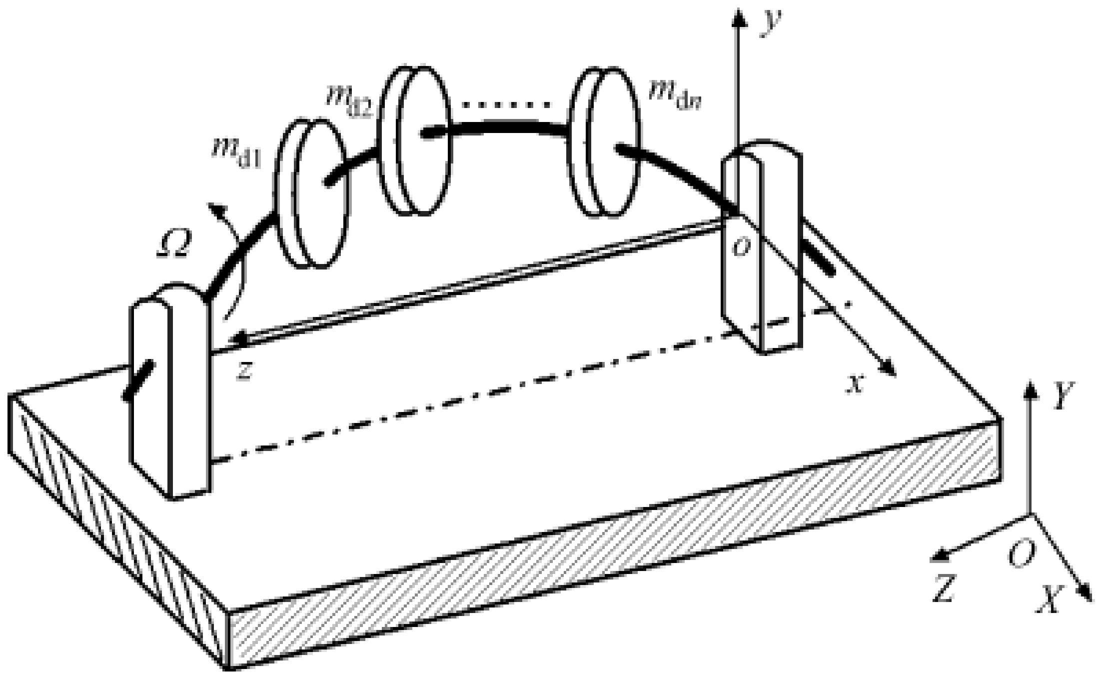
Aircraft changes its speed, direction or altitude when flying



- More than 30% of air combat still retains short-range combat
- An important index to evaluate the performance of aircraft

2. How to describe rotor motion under maneuvering flight

Using the principle of relative motion in the non-inertial system



Fixed coordinate system and the body coordinate system

$$m_i \boldsymbol{a}_{\boldsymbol{ar}} = \boldsymbol{F}_a - m_i \boldsymbol{a}_{\boldsymbol{ae}} - m_i \boldsymbol{a}_{\boldsymbol{ac}}$$

$\boldsymbol{a}_{\boldsymbol{ar}}$ —acceleration of relative motion

$\boldsymbol{F}_a$ —resultant forces acting on the rotor system

$\boldsymbol{a}_{\boldsymbol{ae}}$ —carrier acceleration

$\boldsymbol{a}_{\boldsymbol{ac}}$ —coriolis acceleration

2. How to describe rotor motion under maneuvering flight

$$m_i\ddot{x} - 2m_i\omega_z\dot{y} + c\dot{x} + k_i x - m_i(\omega_y^2+\omega_z^2)x + m_i(\omega_x\omega_y - \alpha_z)y$$
$$= -m_i\left(\frac{dv_{ox}}{dt} + \omega_y v_{oz} - \omega_z v_{oy} + \alpha_y z_i + \omega_z\omega_x z_i\right) + m_i e_i \Omega^2\cos(\Omega t+\varphi)$$

$$m_i\ddot{y} + 2m_i\omega_z\dot{x} + c\dot{y} + k_i y - m_i(\omega_x^2+\omega_z^2)y + m_i(\omega_x\omega_y+\alpha_z)x$$
$$= -m_i\left(\frac{dv_{oy}}{dt} + \omega_z v_{ox} - \omega_x v_{oz} - \alpha_x z_i + \omega_z\omega_y z_i\right) + m_i e_i\Omega^2\sin(\Omega t+\varphi)$$

$$I_{d,i}\ddot{\varphi}_x + I_{p,i}\Omega\dot{\varphi}_y + c\dot{\varphi}_x + k\varphi_x = -\left(\frac{dL^r_{ox}}{dt} + \omega_y L^r_{oz} - \omega_z L^r_{oy}\right)$$

$$I_{d,i}\ddot{\varphi}_y - I_{p,i}\Omega\dot{\varphi}_x + c\dot{\varphi}_y + k\varphi_y = -\left(\frac{dL^r_{oy}}{dt} + \omega_z L^r_{ox} - \omega_x L^r_{oz}\right)$$

Additional load brought by maneuvering:

Additional centrifugal inertia force

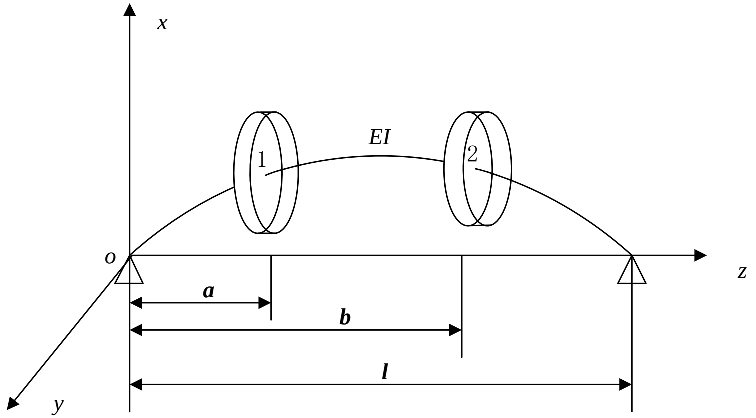
Gyroscopic moment

Inertial moment

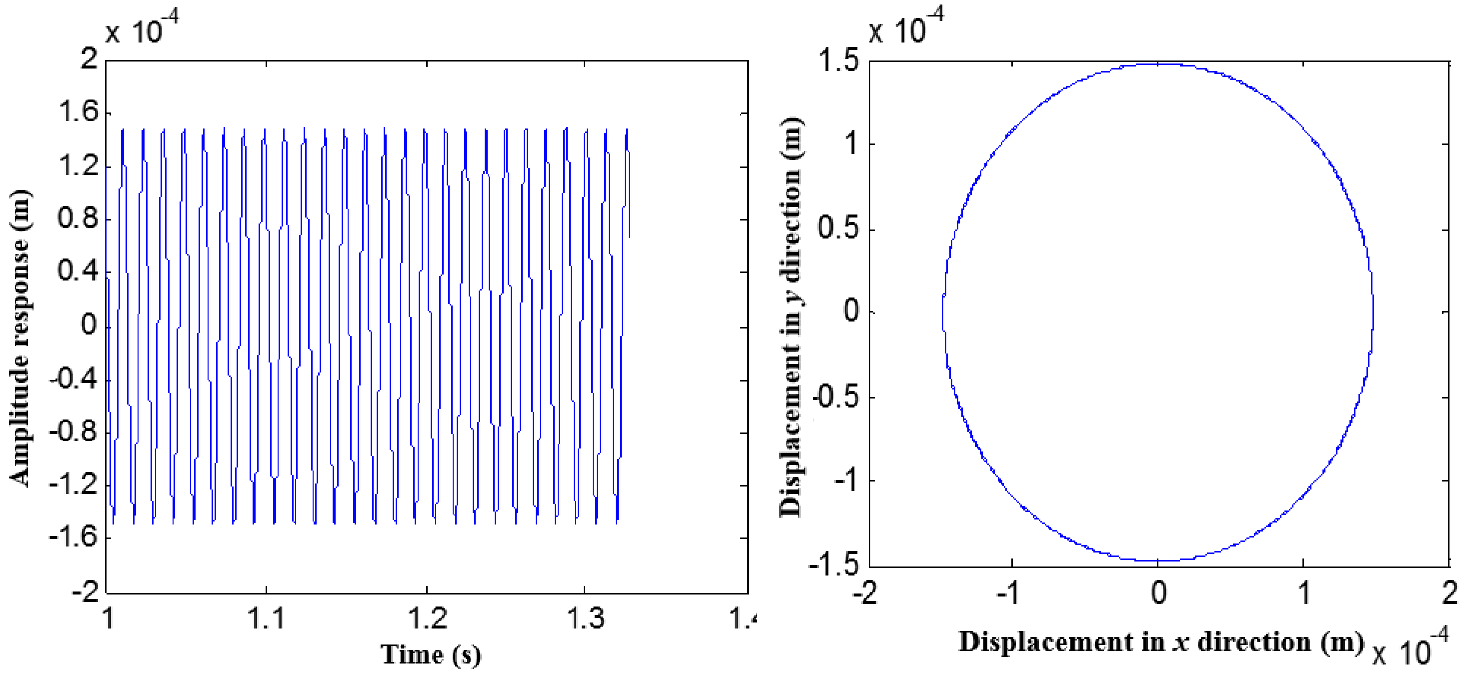
Additional stiffness effect

Additional damping effect

3. How does it affect rotor dynamic characteristics



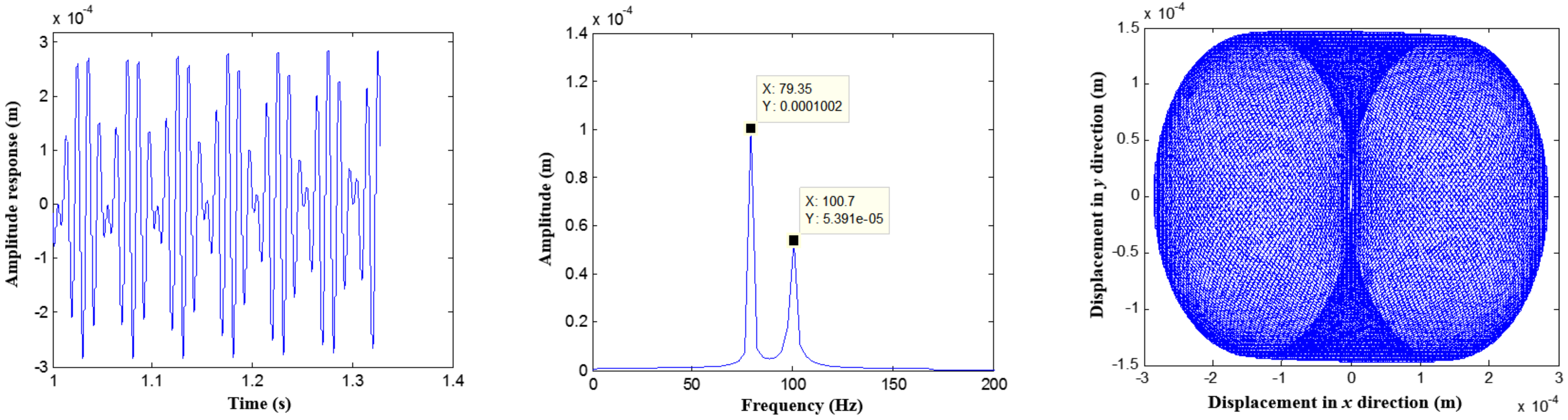
$$
\begin{cases}
m_1\ddot{x}_1 + c_1\dot{x}_1 + k_{11}x_1 + k_{21}\theta_{y1} + k_{31}x_2 + k_{41}\theta_{y2} = 0 \\
J_{d1}\ddot{\theta}_{y1} - J_{p1}\Omega\dot{\theta}_{x1} + c_2\dot{\theta}_{y1} + k_{12}x_1 + k_{22}\theta_{y1} + k_{32}x_2 + k_{42}\theta_{y2} = 0 \\
m_2\ddot{x}_2 + c_1\dot{x}_2 + k_{13}x_1 + k_{23}\theta_{y1} + k_{33}x_2 + k_{43}\theta_{y2} = 0 \\
J_{d2}\ddot{\theta}_{y2} - J_{p2}\Omega\dot{\theta}_{x2} + c_2\dot{\theta}_{y2} + k_{14}x_1 + k_{24}\theta_{y1} + k_{34}x_2 + k_{44}\theta_{y2} = 0 \\
m_1\ddot{y}_1 + c_1\dot{y}_1 + k_{11}y_1 - k_{21}\theta_{x1} + k_{31}y_2 - k_{41}\theta_{x2} = 0 \\
J_{d1}\ddot{\theta}_{x1} + J_{p1}\Omega\dot{\theta}_{y1} + c_2\dot{\theta}_{x1} - k_{12}y_1 + k_{22}\theta_{x1} - k_{32}y_2 + k_{42}\theta_{x2} = 0 \\
m_2\ddot{y}_2 + c_1\dot{y}_2 + k_{13}y_1 - k_{23}\theta_{x1} + k_{33}y_2 - k_{43}\theta_{x2} = 0 \\
J_{d2}\ddot{\theta}_{x2} + J_{p2}\Omega\dot{\theta}_{y2} + c_2\dot{\theta}_{x2} - k_{14}y_1 + k_{24}\theta_{x1} - k_{34}y_2 + k_{44}\theta_{x2} = 0
\end{cases}
$$



(a) Steady amplitude response **(b) Axis orbit**

Figure. Vibration response of disk2 at 500 rad/s

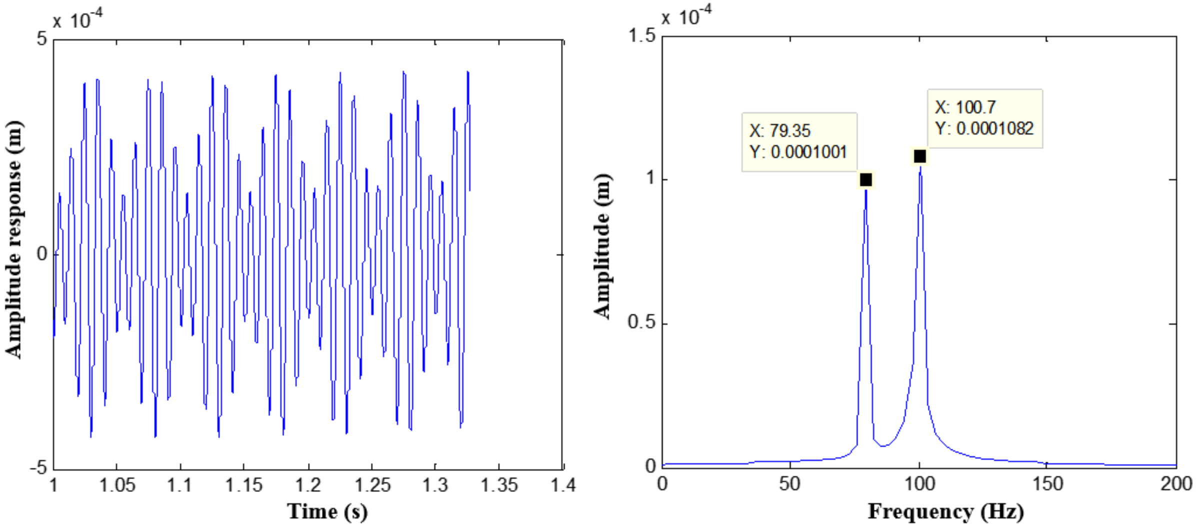
3. 1 Acceleration or deceleration maneuver



(a) Steady amplitude response (b) FFT spectrum (c) Axis orbit

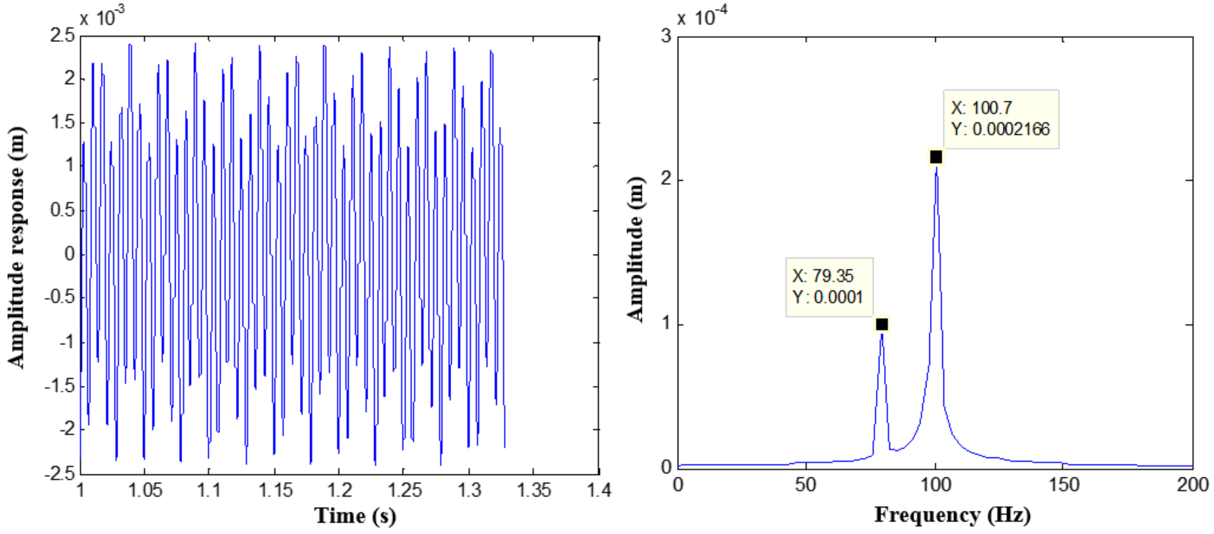
Figure. Vibration response with the sinusoidal excitation amplitude of 0.1 mm

3. 1 Acceleration or deceleration maneuver



(a) Steady amplitude response (b) FFT spectrum

Figure. Sinusoidal excitation amplitude of 0.2 mm



(a) Steady amplitude response (b) FFT spectrum

Figure. Sinusoidal excitation amplitude of 0.4 mm

3. 2 Dive or hovering maneuver

Table. Effect of dive or hovering angular velocity on the rotor system forward angular speed

Ω(rad/s)	Forward angular speed without maneuver （rad/s）				Forward angular speed with maneuver（rad/s）			
	1st order	2nd order	3rd order	4th order	1st order	2nd order	3rd order	4th order
0	227.06	853.31	2191.1	3213.6	227.05	853.31	2191.1	3213.6
1000	243.81	884.68	3387.7	4351.7	234.78	884.67	3387.7	4351.7
2000	258.26	905.06	4943.9	5766.9	258.24	905.05	4943.9	5766.9
3000	270.50	919.27	6695.0	7378.0	270.47	919.27	6695.0	7378.0
4000	280.80	929.73	8543.9	9114.2	280.78	929.72	8543.9	9114.2
5000	289.49	937.74	1044.5	1092.9	289.47	937.73	1044.5	1092.9

3. 2 Dive or hovering maneuver

(a) Steady response in *x* direction (b) Steady response in y direction (c) Axial orbit

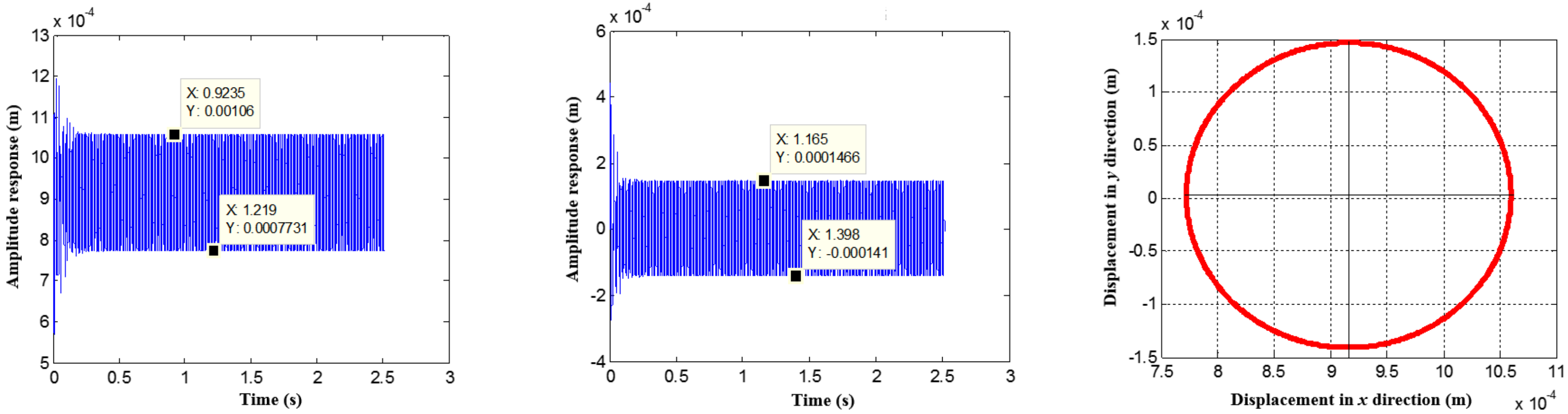


Figure. Vibration response in dive or hovering with the trajectory radius of 700 m and angular velocity of 0.26 rad/s

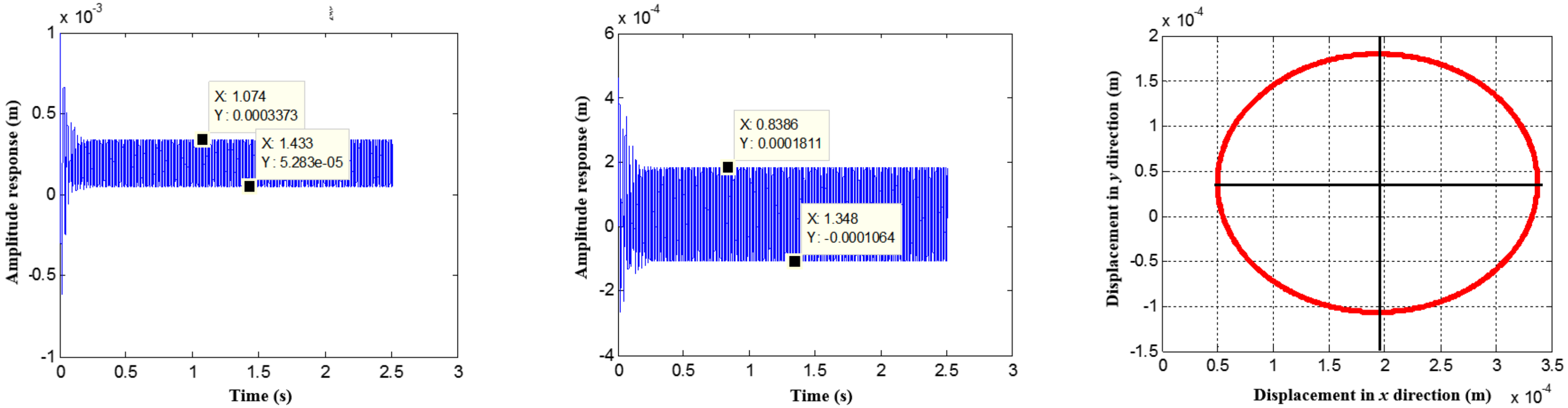


Figure. Vibration response in dive or hovering with overload coefficient of $\pm 1g$ and angular velocity of 3.5 rad/s

3.3 Rolling maneuver

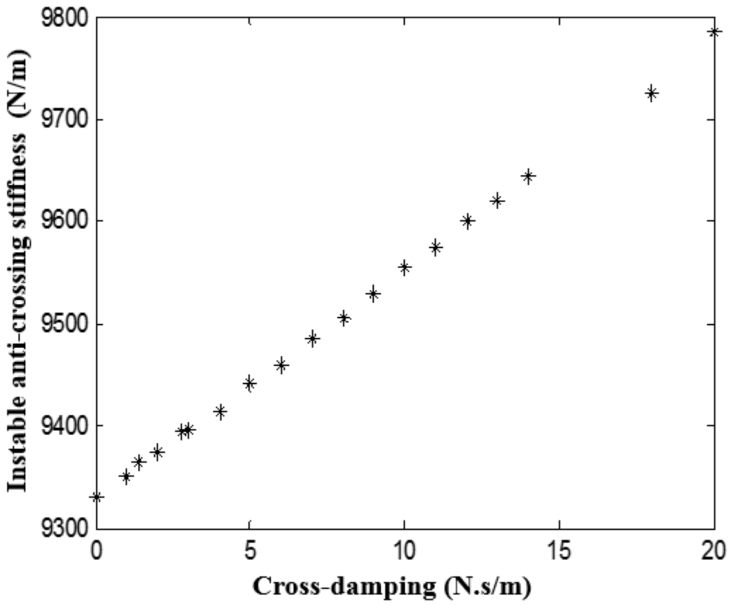


Fig. Influence of cross damping on system stability

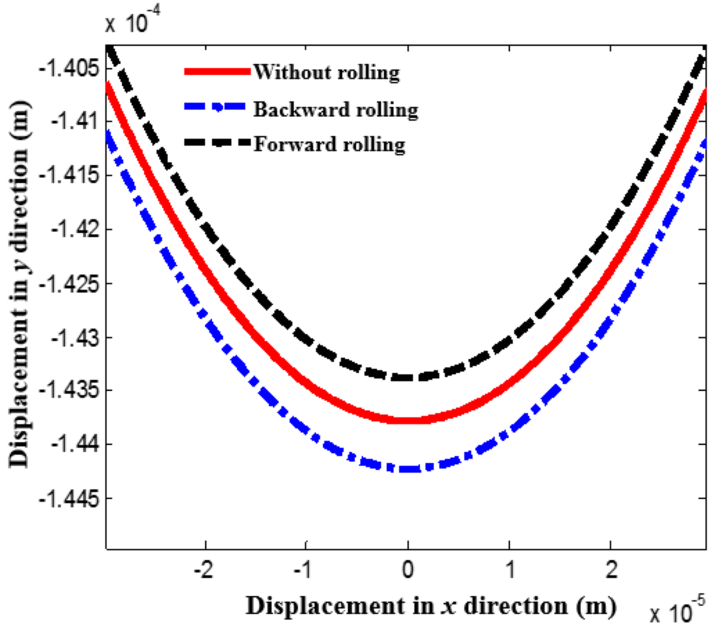


Fig. Effect of the inertia force in rolling

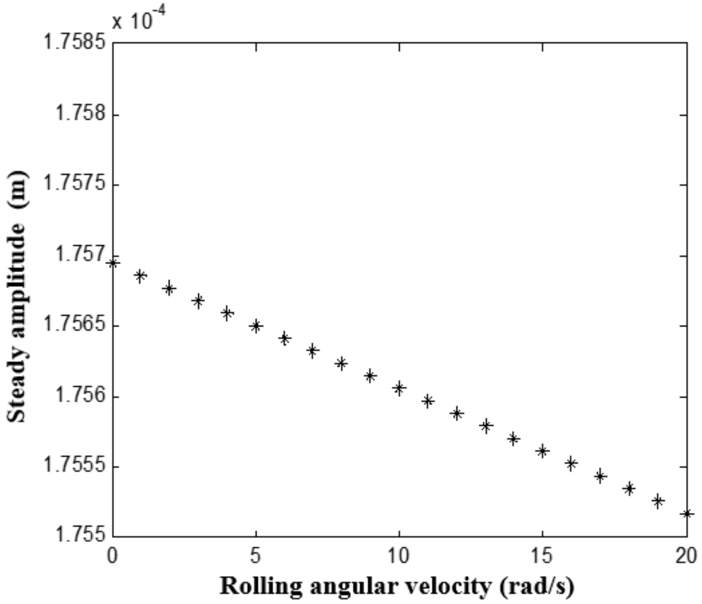


Fig. Effect of cross damping in rolling

4. Conclusions

(1) Lateral acceleration or deceleration leads to inertial force. The centre of the rotor trajectory oscillates along the direction of the exciting force when the acceleration is a sinusoidal signal.

(2) Hovering or dive causes centrifugal force, gyroscopic moment, inertia moment and additional stiffness. The additional stiffness has little effect on the critical speed of the rotor system, but centrifugal force and gyroscopic moment lead the centre of the axis trajectory shifting in different directions, which increases the possibility of rubbing between the stator and the rotor.

(3) Rolling leads to additional stiffness and damping. Backward rolling increases the amplitude of the rotor, while forward rolling decreases the amplitude. Anti-symmetric cross stiffness does not cause rotor instability because of the natural damping in the system. The cross-damping effect can inhibit the instability.

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Thanks

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