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Mitsubishi Heavy Industries, Ltd.

Analysis of Rotorcraft Vibration Reduction Using a Center-of-Gravity Offset

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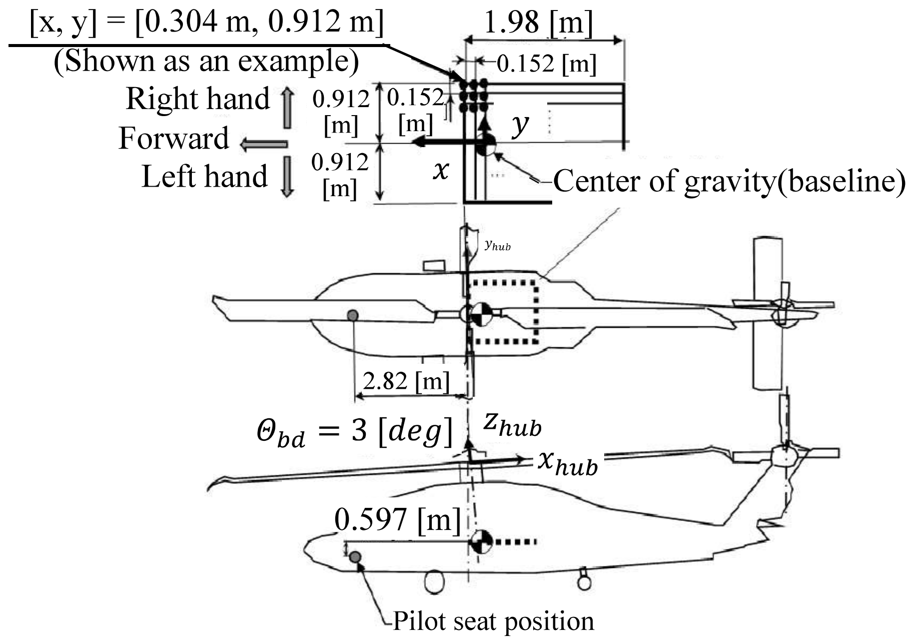
Introduction

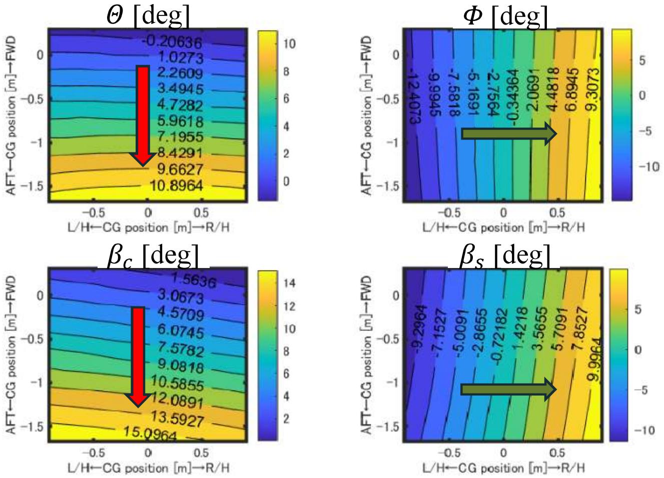
- Rotorcraft suffers from high level of vibration especially during high-speed cruise flight.
- So called “N/rev” vibration is dominant, various efforts have been made such as passive vibration absorbers, active vibration devices.
- The passive absorbers weighs a lot, the active devices are expensive.
- Intentional offset of CG from the right below a main rotor hub is introduced.
- CAMRAD II analysis was conducted to verify how vibration changes and why.

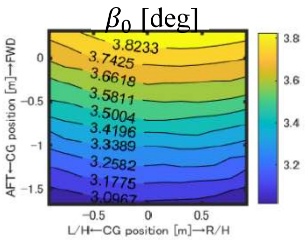
Baseline Helicopter

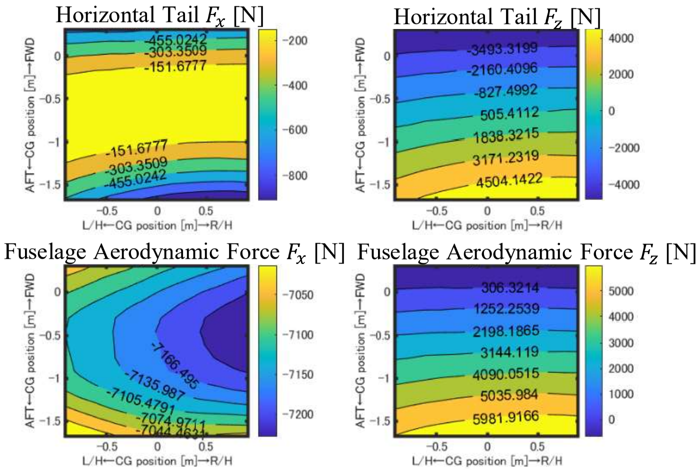
- The middle-sized rotorcraft , SH-60K, was chosen to conduct the analysis.
- CAMRAD II trim calculations were conducted at 182 CG locations including the baseline CG as [x, y]=[0,0] when the rotorcraft was cruising at 61.7 [m/s] (120[kt]).
- The fuselage was deemed as a rigid body.
- Free wake method was employed.



Trim analysis results(vehicle attitude, flapping angle fuselage forces)

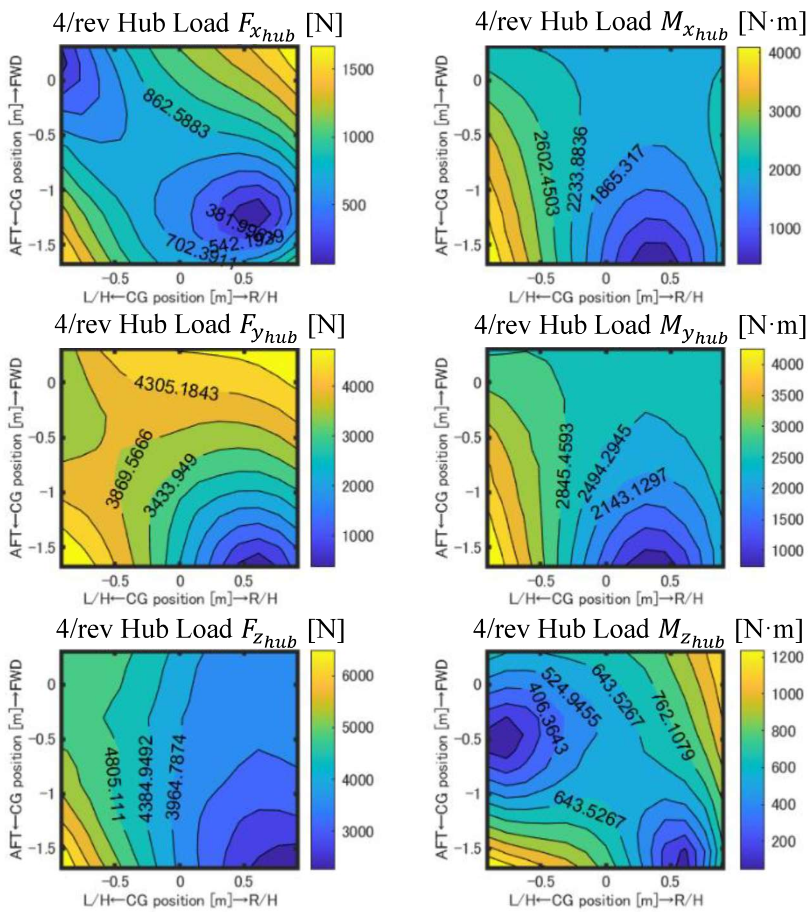






- Θ and Φ increase as CG moves aft and rightward, respectively. In contrast, β_c and β_s increase to maintain the main rotor thrust tilt forward and leftward and overcome the Θ and Φ increases, respectively.
- As Θ increases, the lift, which is close to F_z, acting on the horizontal tail and the fuselage also increases, and the main rotor thrust decreases. This thrust decrease results in a decrease in the coning angle β_0 as well.
- As the difference in Θ from 5 deg increases, the drag, which is close to $-F_x$, acting on the horizontal tail and the fuselage increases and decreases, respectively. Θ is expected to relate to the angle determined by the downwash of the main rotor and the cruise speed. Moreover, $-F_x$ acting on the fuselage is not strongly affected by the increase in Φ.

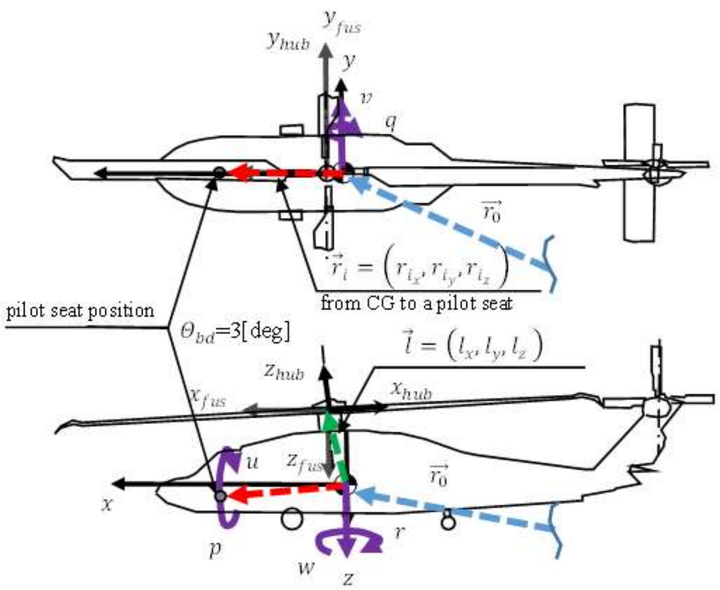
Trim analysis results(main rotor hub forces and moments)



- The 4/rev vibration is dominant relative to other harmonic vibrations, where a rotor with four blades is considered.
- The magnitude of the 4/rev vibration is shown, the phase is also obtained for each force and moment.
- The moments are expected to be small by considering the moment of inertia of this fuselage.
- Each load component at the MRH has its own minimum value at a different specific CG location.

Where should CG be positioned to obtain the minimum vibration?
"Maybe RHS AFT, But…"

Pilot seat acceleration



- Derived 4/rev vibratory forces and moments are substituted into the Euler EOM.
- u, v, w, p, q, r are numerically solved.
- The 4/rev pilot seat acceleration is also derived.

➢ Euler EOM

$$m(\dot{u} + qw - rv) = F_x$$

$$m(\dot{v} + ru - pw) = F_y$$

$$m(\dot{w} + pv - qu) = F_z$$

$$I_x\dot{p} - I_{yz}(q^2 - r^2) - I_{zx}(\dot{r} + pq) - I_{xy}(\dot{q} - rp) - (I_y - I_z)qr = M_x$$

$$I_y\dot{q} - I_{zx}(r^2 - p^2) - I_{xy}(\dot{p} + qr) - I_{yz}(\dot{r} - pq) - (I_z - I_x)rp = M_y$$

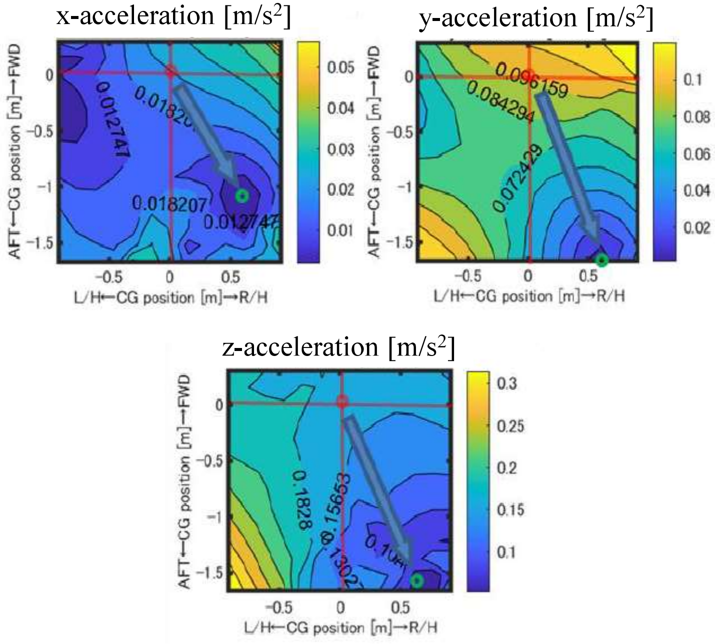
$$I_z\dot{r} - I_{xy}(p^2 - q^2) - I_{yz}(\dot{q} + rp) - I_{zx}(\dot{p} - qr) - (I_x - I_y)pq = M_z$$

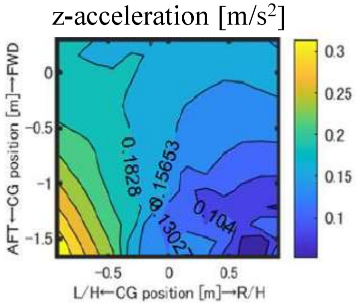
➢ Pilot seat acceleration

$$\vec{a} = \frac{d^2\vec{r_0}}{dt^2} + \frac{d^*\vec{\omega}}{dt} \times \vec{r_i} + (\vec{\omega} \cdot \vec{r_i})\vec{\omega} - (\vec{\omega} \cdot \vec{\omega})\vec{r_i}$$

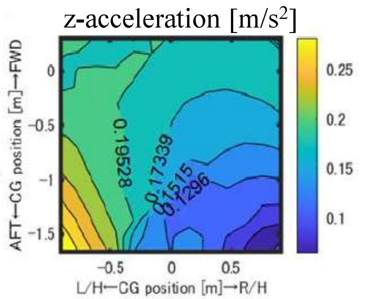
$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} \dot{u} + qw - rv + r_{i_y}(pq - \dot{r}) + r_{i_z}(pr + \dot{q}) - r_{i_x}(q^2 + r^2) \\ \dot{v} + ru - pw + r_{i_z}(qr - \dot{p}) + r_{i_x}(pq + \dot{r}) - r_{i_y}(p^2 + r^2) \\ \dot{w} + pv - qu + r_{i_x}(pr - \dot{q}) + r_{i_y}(qr + \dot{p}) - r_{i_z}(p^2 + q^2) \end{bmatrix}$$

Results(The 4/rev Pilot seat accelerations)

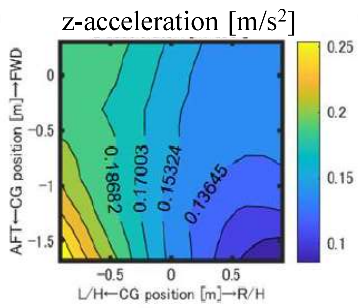




From six loads acting on an MRH



From three forces acting on an MRH

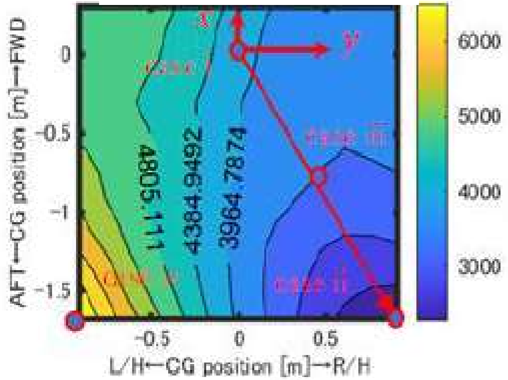


From $F_{z_{hub}}$ acting on an MRH

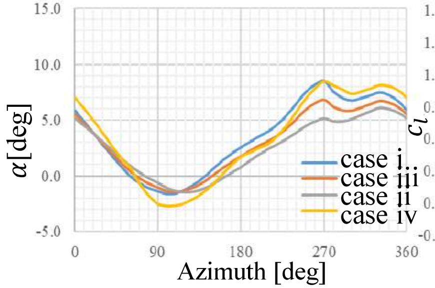
- Each x-, y-, and z-acceleration component reaches its own minimum value at each different CG position, but generally, every component decreases as the CG moves toward the right side and backward.
- A pilot inherently has physical characteristics to feel mainly the z-acceleration. In addition, the plots show that the z-acceleration at the pilot seat position is dominant in contrast to the x- and y-acceleration. The z-acceleration reaches no more than 40% of its baseline value.
- The pilot z-acceleration contour plots caused by six loads and by three forces are similar, which means that the 4/rev moments have small influences on pilot z-acceleration. In addition, the z-acceleration contour plot caused by the 4/rev $F_{z_{hub}}$ force is also similar to those caused by six loads and by three forces, which means that the $F_{x_{hub}}$ and the $F_{y_{hub}}$ have small influences on pilot z-acceleration. The 4/rev force $F_{z_{hub}}$ itself can become the simplest vibration index.

Insight into 4/rev F_{zhub} vibration force

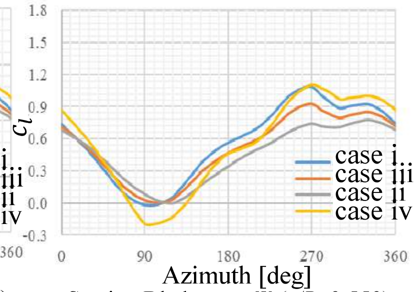
4/rev Hub Load F_{zhub} [N]



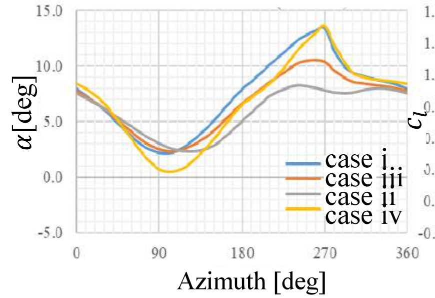
Section Blade α vs Ψ (r/R=0.825)



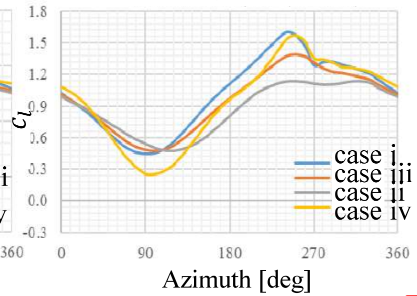
Section Blade c_l vs Ψ (r/R=0.825)



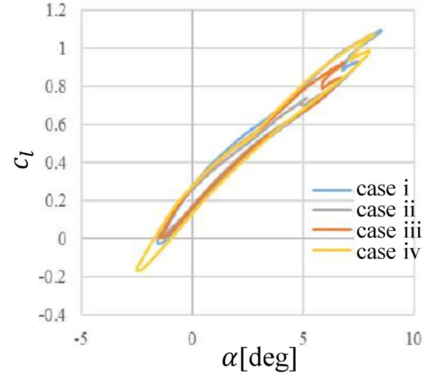
Section Blade α vs Ψ (r/R=0.550)



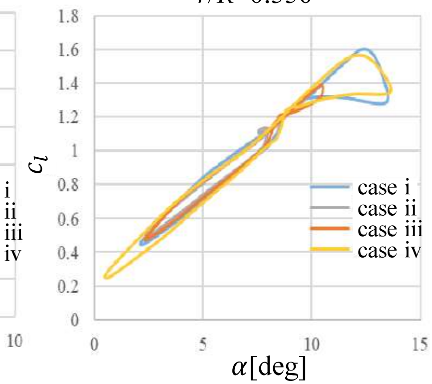
Section Blade c_l vs Ψ (r/R=0.550)



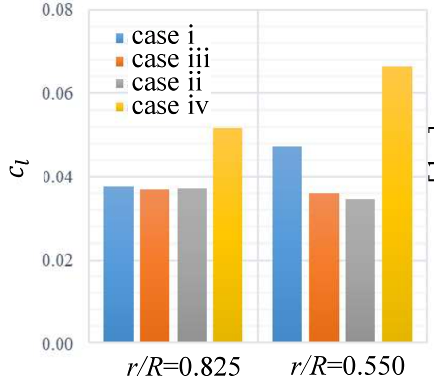
r/R=0.825



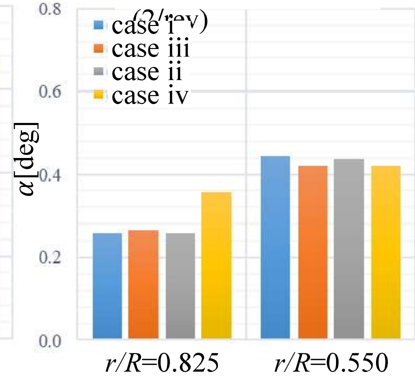
r/R=0.550



Blade Section c_l (2/rev)

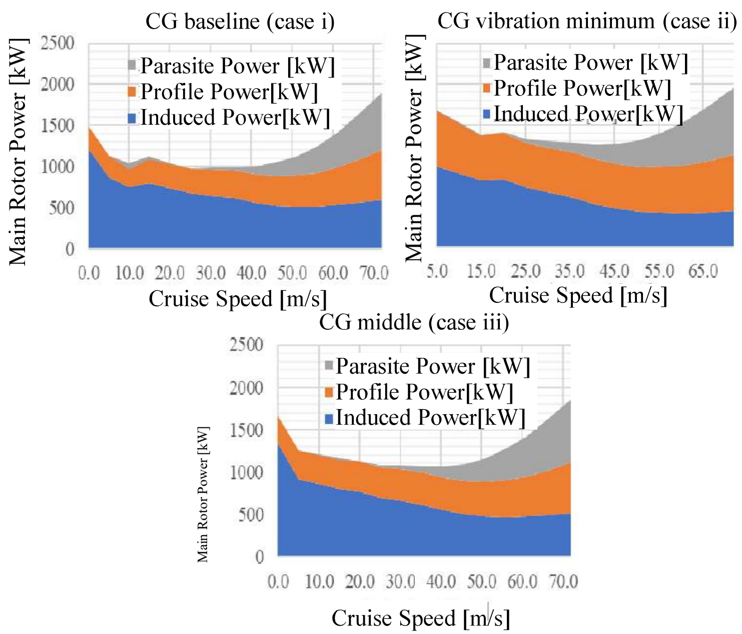


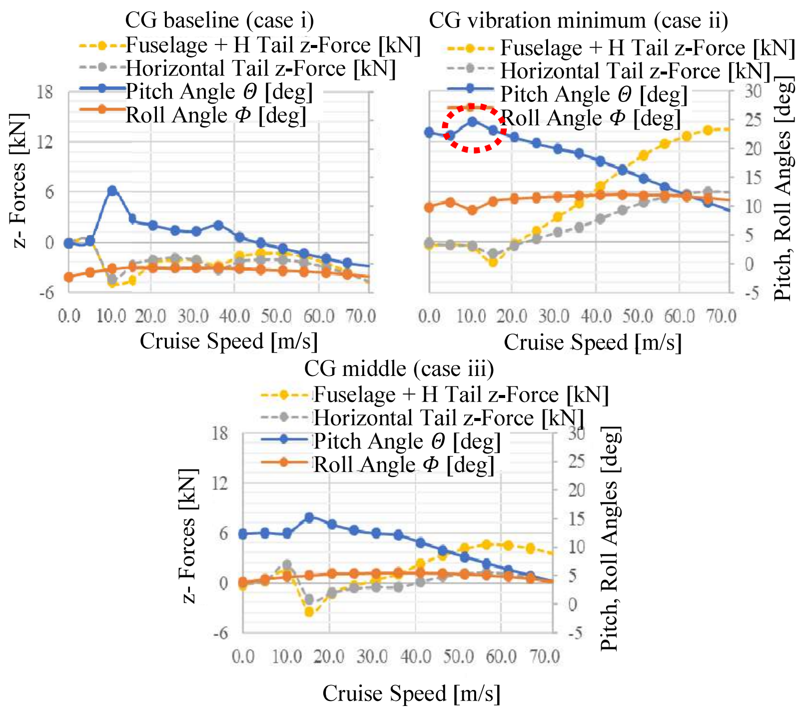
Blade Section α (2/rev)



- F_{zhub} Magnitude : case iv > case i > case iii > case ii
- The $c_l(\Psi)$ azimuthal plots are not proportional to the $\alpha(\Psi)$ plots.
- The hysteresis of $\alpha - c_l$ plot was observed due to dynamic stall.
- the order of the 4/rev F_{zhub} among the four cases agrees with that of the amplitudes of the 2/rev $c_l(\Psi)$.

Main rotor power and trim attitude





- Especially, in hover, the total powers in (cases ii, iii) are 30% and 10% larger than that in (case i), respectively.
- The differences in the total power among these cases in a high cruise speed flight are smaller than those at hover.
- The maximum pitch angle of 23 deg for (case ii) is not acceptable for a pilot.

Conclusions

- Main rotor hub 4/rev vibration forces and moments were calculated with CAMRAD II when CG is intentionally offset from the baseline position.
- The z-directional acceleration was dominant and reached at least 40% of the baseline value.
- The dynamic stall influences the order of the 2/rev $c_l(\Psi)$ and that the order is in accordance with that of the 4/rev F_{zhub}.
- By considering degradation of 30% increase in hovering power, CG should be positioned within case iii. At that point, we can still obtain 20% vibration reduction.
- It should be easier to accomplish CG offset for a light-weight single rotor eVTOL than to do it for heavy preexisting rotorcraft.

References

1) Yoshizaki.Y., and Sunada. S., “Analysis of Rotorcraft Vibration Reduction Using a Center-of-Gravity Offset,” Trans. Jpn. Soc. Aeronaut. Space Sci., 66, (2023) pp. 1-9.

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