TOWARDS HYBRID TESTING FOR HELICOPTER COMFORT

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ABSTRACT

Helicopters are notorious for their high vibration levels, and occupant comfort remains one of the key challenges of vertical flight. Occupant comfort can be evaluated through numerical analysis or flight testing. While numerical models are very useful in early design, they may fail to address uncertainty and non-linearity in seat and human biodynamics. On the other hand, the tests can only be performed after flying prototypes are ready, which is a very late stage to make significant improvements. A hybrid solution could reduce the drawbacks of both approaches by combining the flexibility of modern simulation tools with a physical set-up of seat and occupant; therefore, allowing realistic, safe and repeatable comfort evaluations at early design phases. A hybrid testing framework offers evaluation of helicopter ride comfort through real-time coupling of a numerical model representing the loads and structural dynamics of the airframe and a physical model of the occupant. The numerical helicopter model simulates the transmission of vibratory loads to the cabin floor, while a physical system consisting of a seat, cushion, and mannequin is placed on a multi-axis shaker table. In this study, before implementing the full hybrid simulation, the physical shaker table is temporarily replaced by validated simulation model of MASTto allow tuning of the control parameters and detailed investigation of coupled dynamics before testing.

INTRODUCTION

Helicopter passengers and crew, also referred to as occupants, are subject to significant levels of whole-body vibration (WBV) due to the complex loading environment generated by the main and tail rotors, engine and gearbox operation (Ref. 1). The loads are transferred to the occupants by the airframe and could be identified by its structural dynamics. While vibration control is well studied from the perspective of structural loads and fatigue, less attention is typically given to the local vibratory environment experienced by occupants.

High levels of vibration, especially in the frequency range of 4–30 Hz typical of rotor blade passing frequencies, can result in discomfort and long-term health impacts such as lower back pain or spinal disorders (Refs. 2,3). WBV standards are developed to guide comfort analysis, including BS-6841 (Ref. 4), ISO-2631 (Ref. 5), NASA Ride Quality (RQ) (Ref. 6), and Intrusion Index (II) (Ref. 7). Among these, ISO 2631 is more general, and better reflects the helicopter crew ratings (Refs. 8, 9), which also addresses frequency weightings that emphasize the human body's greater sensitivity to low frequency vertical oscillations.

While standards like ISO-2631-1 are widely used for assessing whole-body vibration, several studies have shown discrepancies between the predicted comfort based on ISO 2631-1 and self-reported experience (Ref. 10). This highlights that while the standard remains an essential baseline that offers a consistent and objective quantification of it, the comfort perception is multi-factorial and may be influenced by factors like posture, fatigue, and seat design. For example, a study on helicopter pilots found that even when vibration exposure estimates were within the lower threshold of the ISO daily exposure limits ($0.32-0.51\ m/s^2$), a high incidence of lower back pain was reported (Ref. 11). This suggests that posture and seat dynamics may interact with the structural vibration in a way that the comfort is not fully captured by these metrics, showing the importance of physical testing and biomechanics coupling into the comfort evaluation. Nevertheless, ISO 2631-1 is a valuable reference framework and is useful in any form of comfort assessment

Considerable research has delved into modelling the structural dynamics of rotorcraft and integrating occupant biodynamic response (Ref. 12). A recent work has explored lumped-parameter, finite element, and multibody human body models for comfort evaluation, differing in complexity and fidelity (Ref. 13). It demonstrated that lumped-parameter analysis models can be used for their ease of setup without posing significant differences to that of more detailed models. These models have been integrated into high-fidelity simulation environments allowing modular state-space assembly of rotorcraft and the feedback of biodynamic forces into the model (Ref. 12). These studies emphasize the modelling approach and related trade-offs. On the other hand, these analyses are fully virtual and accuracy can be improved is a physical rig is set up with human or mannequin to better capture the seat and biodynamic loads.

Traditional methods for analysing dynamic systems rely on numerical models or physical testing. While the numerical models offer flexibility and speed, they require simplifications. On the other hand, despite offering valuable research outcome, the physical testing is resource intensive, and may not capture full system interactions in as flexible.

Hybrid testing, or pseudo-dynamic testing, bridges these approaches by coupling the numerical and experimental subsystems. This improves the power for complex dynamic systems. It allows a part of the system which is difficult to model due to non-linearities, uncertainties or the complexity of the subsystem to be tested, while the remainder is simulated. This method has been successfully applied civil engineering (Refs. 14, 15), some showed the methods to incorporate the dynamic loads in the experimental subsystems (Ref. 16) and is gaining more attraction in aerospace applications, particularly for vibration and control system testing (Ref. 17). Building on these principles, hybrid testing is now being explored in many disciplines to combine numerical models with rig-based subsystems (Ref. 18).

Hybrid testing can help to better investigate the comfort related problems during the design phase as it can accelerate comfort assessment and improve accuracy. The faster assessment is achieved by quickly simulating loads and airframe response using already existing models. The improved accuracy is accomplished by using physical human-seat or mannequin-seat instead of relying on their heavily simplified models. Based on these benefits and with an aim to understand and help mitigate the discomfort related effects in a design phase, this study explores a hybrid framework that combines a computational model of the helicopter airframe with a physical occupant system mounted on a Multi-Axis Simulation Table (MAST). The objective is to replicate representative floor vibrations in real-time, measure the dynamic seat–occupant response, and feed this reaction force back into the structural model, closing the loop between numerical and experimental subsystems.

METHOD

Hybrid Simulation Framework

The proposed hybrid framework consists of a finite element model of the helicopter airframe dynamics and a physical test rig with a seat, cushion, and mannequin placed on the MAST. The airframe model predicts the floor motion at selected cabin locations under rotor-induced loads. This predicted floor motion is applied to the MAST, exciting the physical seat and occupant system. An example to the experimental subsystem for this hybrid test framework is shown in Fig. 1. The physical setup consists of the MAST motion platform with hydraulic actuators to generate the desired motion, seat, mannequin, and sensors such as load cell and accelerometers to obtain the relevant data for comfort analysis. This set-up is being improved for coupled analysis.

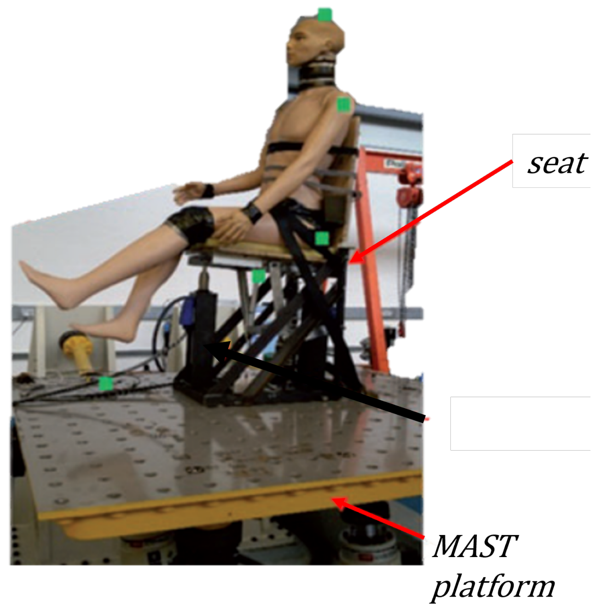

Figure 1: Experimental subsystem of the physical subsystem consisting of the MAST, seat, and mannequin.

When a real occupant or mannequin is mounted on the seat, the human body and seat cushion interact dynamically with the vibration input. This interaction generates a reaction force at the seat–floor interface which acts back on the helicopter cabin structure. Neglecting this feedback can lead to substantial errors in simulated or measured responses, as the occupant–seat system effectively adds mass and damping that modifies the local response.

To better illustrate the influence of feedback, an analogous system of 2 degrees of freedom can be considered with such components: a larger mass representing the helicopter, M, a smaller mass representing the occupant, m, and a stiffness representing the occupant and connecting the two masses, as shown in Fig. 2. This system represent the conventional way of comfort assessment, where the structure is simulated and the response is applied to seat-human without considering the effect of seat-human dynamic on the system.

For the case of an uncoupled system, first the motion of the larger mass is obtained for sinusoidal input,

$$M\ddot{X} = F(t) \implies \bar{X} = \frac{F}{-\omega^2 M} \tag{1}$$

Then, if this motion is applied to the smaller mass without any feedback from the small mass as typically implemented in comfort testing, the response of the smaller mass is:

$$m\ddot{x} + kx = kX \implies \frac{x}{F} = \frac{k}{-\omega^2 M(k-\omega^2 m)} \tag{2}$$

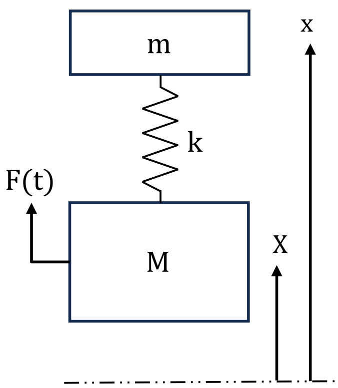

Figure 2: Schematic of a 2-dof analogous system

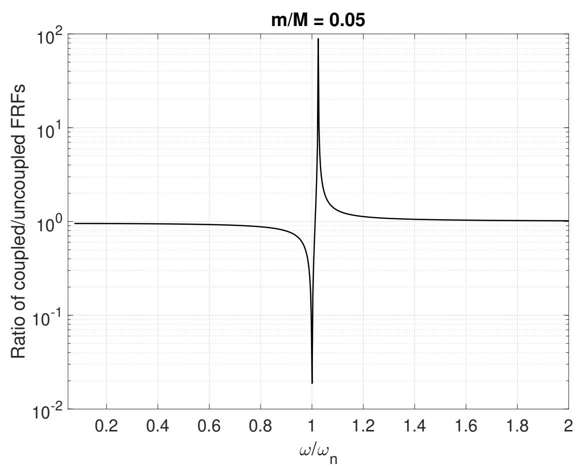

Figure 3: 2-dof system response to uncoupled and coupled framework with varying mass ratios

However, the coupled system brings about the real solution for the displacement of masses, since it helps couple the force coming from the smaller mass onto the larger mass. Depending on the size of the big mass, the effect of the seat and occupant could change the local vibration levels, therefore the comfort level. The equations of motion of the real system is:

$$M\ddot{X} + k(X - x) = F(t) \tag{3}$$

$$m\ddot{x} + kx = kX \tag{4}$$

which leads to:

$$\frac{x}{F} = \frac{k}{-\omega^2 kM + \omega^4 mM - \omega^2 mk} \tag{5}$$

These transfer functions are constructed using representative larger mass of $M = 2500kg$, stiffness of $k = 22600N/m$ and a seat-human combined mass of $m = 125kg$. It is shown in Fig 3 that the feedback changes the outcome significantly near the resonance frequency (ω_n), while away from it both systems give similar response. This could lead to significant errors in comfort assessment especially if the excitation is near resonance, which could extend to a bandwidth of $0.8\omega_n$ and $1.2\omega_n$. While this system is an simplification, it could given an idea about excitation of a particular airframe mode, as in the helicopter airframe with many resonance frequencies. Therefore, ignoring the feedback in such tests could lead to larger errors in the evaluation of human vibration exposure.

This conceptual understanding motivates the adoption of a real-time hybrid simulation approach for helicopter occupant (crew/passenger) comfort analysis. There are two options for a hardware-in-the-loop testing, as discussed on the simple system. The first one is the uncoupled system, shown Fig. 4-a, which assumes the floor vibration is predetermined and directly applied to the system, which is typically done in practice by directly applying a prescribed data-set to experimental set-up. The second one is coupled system, as shown in Fig. 4-b, which modifies the floor excitation based on the seat-human feedback. According to that, the forces due to human-seat dynamics at the interface are measured using a load cell. Then, the feedback loop is formed by adding the measured seat–occupant force to the forcing vector that also includes the rotor hub loads. The floor vibration prediction is then updated in real-time, creating a coupled loop between the physical and digital subsystems.

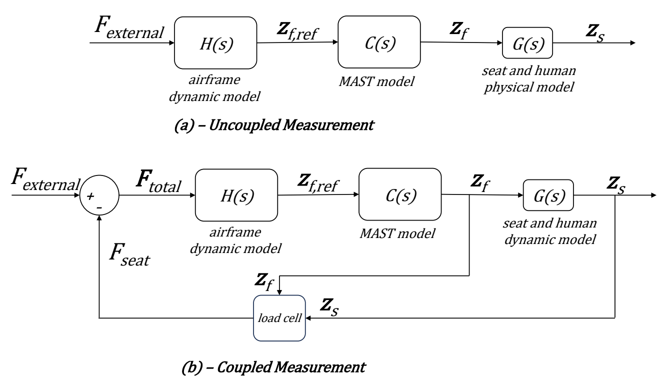

Figure 4: Schematic of the (a) uncoupled and (b) coupled (hybrid) simulation framework incorporating a digital helicopter model and physical seat–occupant system mounted on the MAST rig.

However, before working on the full hybrid system where the physical system is in play, a validated simulation model of the MAST rig will be used as shown in Fig. 5, which includes elements of the real system (valves, feedback) and their limitations. This way, the optimal controller parameters can be decided; justification is made before building the rig; and a through investigation is made to ensure safety. For this purpose, a set of simulations and experiments at different frequencies were performed to evaluate the representativeness of the simulation model as shown in Fig. 6. The displacements from the rig and from the simulation model are in good agreement. Therefore, the approach to replace the physical system with its replicated simulation model is a reasonable decision allowing for detailed investigation and rapid tuning of controller parameters before setting up the real system.

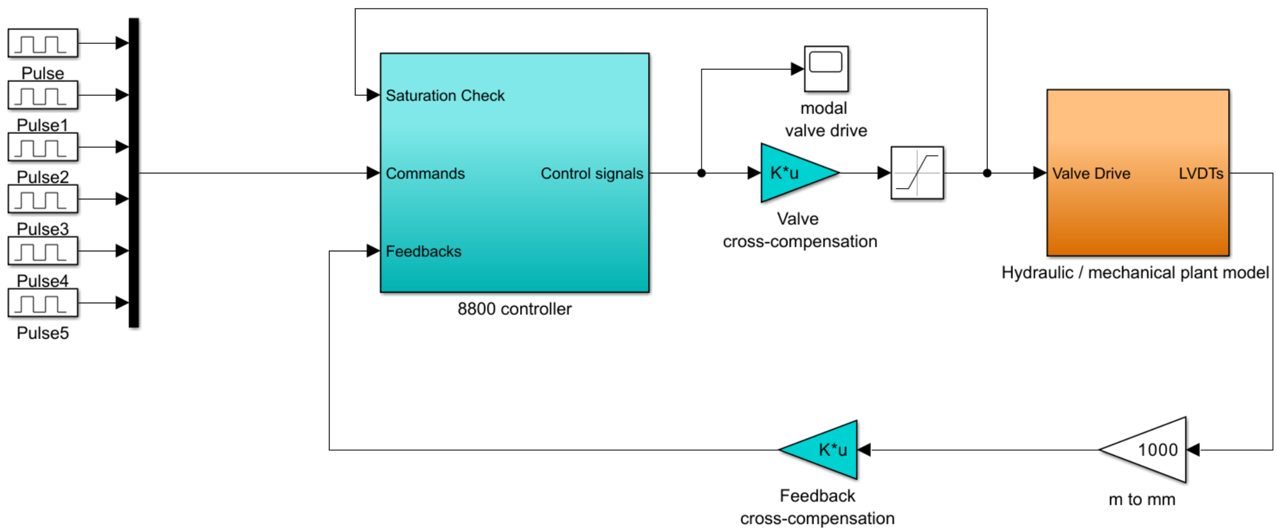

Figure 5: MAST simulation model

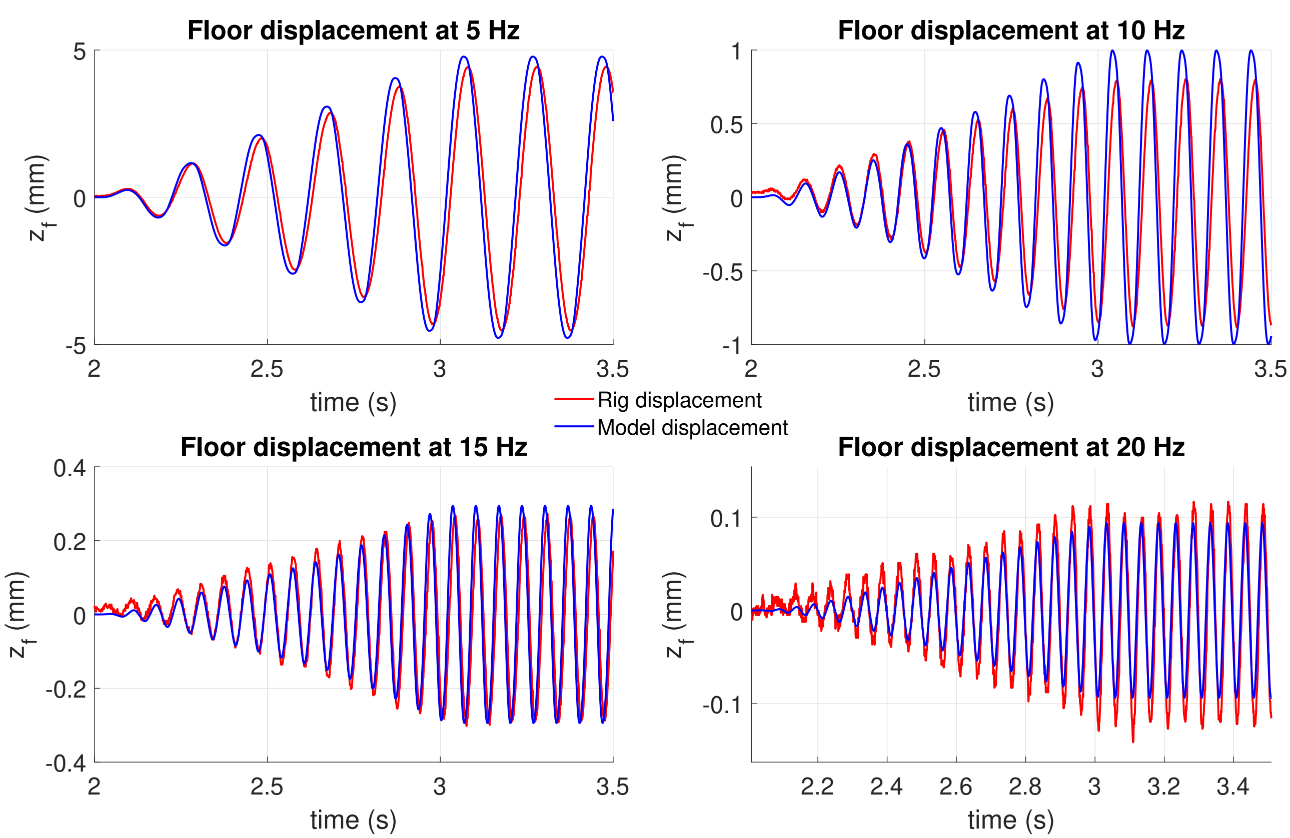

Figure 6: MAST rig and simulation model motions at frequencies of 5, 10, 15, 20 Hz.

Airframe Modelling

The airframe structure is an important aspect of comfort analysis as it can amplify the vibrations close to its natural frequencies. Both global and local floor modes can contribute, therefore a detailed finite element model (FEM) is essential. The airframe considered for the numerical subsystem of this work is based on Bo-105 helicopter airframe. Bo-105 is a light, twin-engine, multi-purpose helicopter with an empty weight of 1276 kg and a gross weight of 2500 kg. It has four blades in its main rotor, with the nominal blade passing frequency of around 7 Hz (Ref. 19).

Based on the limited data in (Ref. 20), a simplified finite element model of the Bo-105 helicopter airframe was developed in ANSYS Mechanical using beam elements and lumped masses to represent the distributed structure and key rigid-body components. The airframe was divided into four main subsystems—cabin floor, cabin frame, power transmission, and tailboom—defined from publicly available technical blueprints to preserve approximate geometry and realistic weight distribution. An exploded view of the model is shown in Fig. 7, highlighting the four structural sections.

Each subsystem was assigned specific mechanical properties, including cross-sectional dimensions, Young's modulus, and material density, while the material density was around that of aluminum alloys. This modular arrangement allowed for localized tuning of dynamic stiffness ($k = EA/L$) to better align the computed modal properties with published reference values for similar helicopters. Table 1 summarizes the associated beam masses, lumped rigid-body masses, and the resulting total airframe mass. The rigid masses capture the contribution of major components such as the rotor, gearbox, engines, and tail rotor. Although the total captured mass in Table 1 is slightly lower than the empty weight of Bo-105, the difference is primarily because the seat masses are excluded. This decision is made to represent the seat-related dynamics in the experimental subsystem.

Table 1: Structural mass breakdown of the helicopter airframe model

Component	Mass [kg]	Remarks
Cabin Floor	54.31	Beam elements
Cabin Frame	379.09	Beam elements
Power Transmission	146.93	Beam elements
Tailboom	169.50	Beam elements
Rotor + Gearbox	255.20	Lumped mass at A
Engine 1	63.00	Lumped mass at B
Engine 2	63.00	Lumped mass at C
Tail Rotor	50.00	Lumped mass at D
Total	**1181.04**	Combined mass

After tuning the beam subsystems, a modal analysis was conducted in ANSYS to extract the full mass (**M**) and stiffness (**K**) matrices. These were exported in sparse format and processed in MATLAB to construct the state-space matrices for

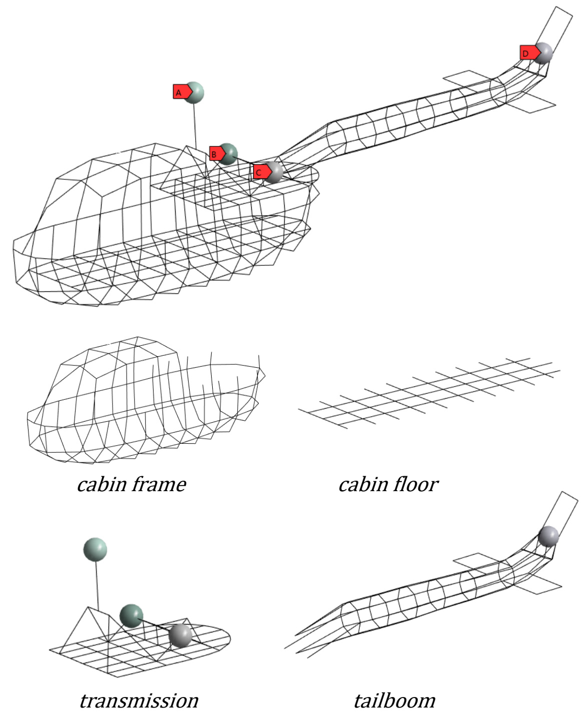

Figure 7: Exploded view of the helicopter structural model, showing cabin floor, cabin frame, power transmission, and tailboom subsystems.

reduced-order modelling. The governing structural dynamics in physical coordinates are given by:

$$\mathbf{M}\ddot{\mathbf{x}}(t) + \mathbf{K}\mathbf{x}(t) = \mathbf{f}(t), \tag{6}$$

where $\mathbf{x}(t)$ is the displacement vector and $\mathbf{f}(t)$ is the external forcing vector. A modal transformation is performed using eigenvectors ϕ:

$$\mathbf{x}(t) = \phi\mathbf{q}(t), \tag{7}$$

yielding the modal equations:

$$\ddot{\mathbf{q}}(t) + \mathbf{C}_r\dot{\mathbf{q}}(t) + \mathbf{K}_r\mathbf{q}(t) = \phi^T\mathbf{f}(t), \tag{8}$$

where $\mathbf{K}_r = \phi^T\mathbf{K}\phi$ and modal damping is assigned by:

$$[\mathbf{C}_r]_{ii} = 2\zeta_i\omega_i, \tag{9}$$

with $\zeta_i = 2\%$ for all retained flexible modes.

The reduced modal system is converted to a first-order state-space form for implementation in Simulink:

$$\dot{\mathbf{z}}(t) = \mathbf{A}\mathbf{z}(t) + \mathbf{B}\mathbf{u}(t), \quad \mathbf{y}(t) = \mathbf{C}\mathbf{z}(t) + \mathbf{D}\mathbf{u}(t), \tag{10}$$

where $\mathbf{z}(t) = [\mathbf{q}(t)\ \dot{\mathbf{q}}(t)]^T$.

Two inputs are defined for the coupled system: i: rotor-induced excitation at the main rotor node; ii) Seat–human feedback force where the seats are attached at to close the hybrid loop. The output is defined as the displacement and acceleration over nodes where the seats are attached at Fig. 8 shows four positions from the cabin floor, which represent approximate positions for pilot, co-pilot and two passengers.

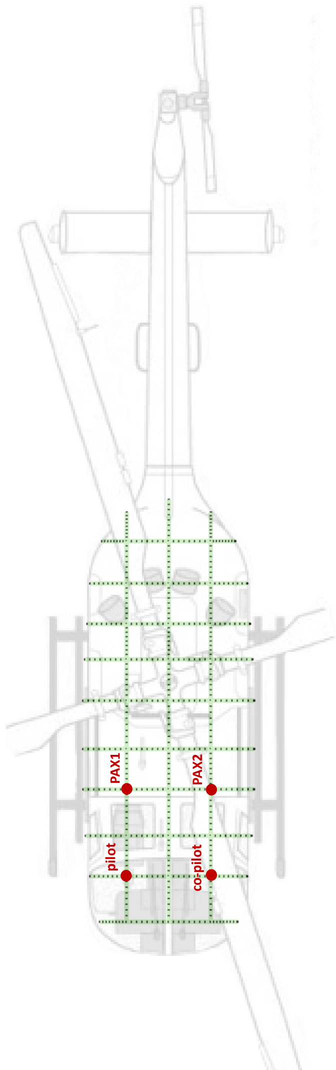

Figure 8: Locations of seat nodes considered for vibration analysis

To assess the representativeness of the developed structural dynamic model, the natural frequencies from the modal analysis were compared to literature values reported for the Bo-105 helicopter. The reference study in Ref. (Ref. 20) served as a benchmark for this comparison. Table 2 lists the first few natural frequencies obtained from the tuned model and those from the literature. While exact validation was not the objective of this study, this comparison demonstrates that the model reproduces a realistic modal distribution and bandwidth relevant for passenger vibration perception and hybrid testing.

Figure 9 shows the mode shapes that contribute to the cockpit vibrations, obtained from the structural model. The modal frequency of the first cockpit mode is quite close to the 4^{th} harmonics of the blade passing frequency ($4/rev$ - 28 Hz). Therefore, the excitation around this mode will likely cause such deformation.

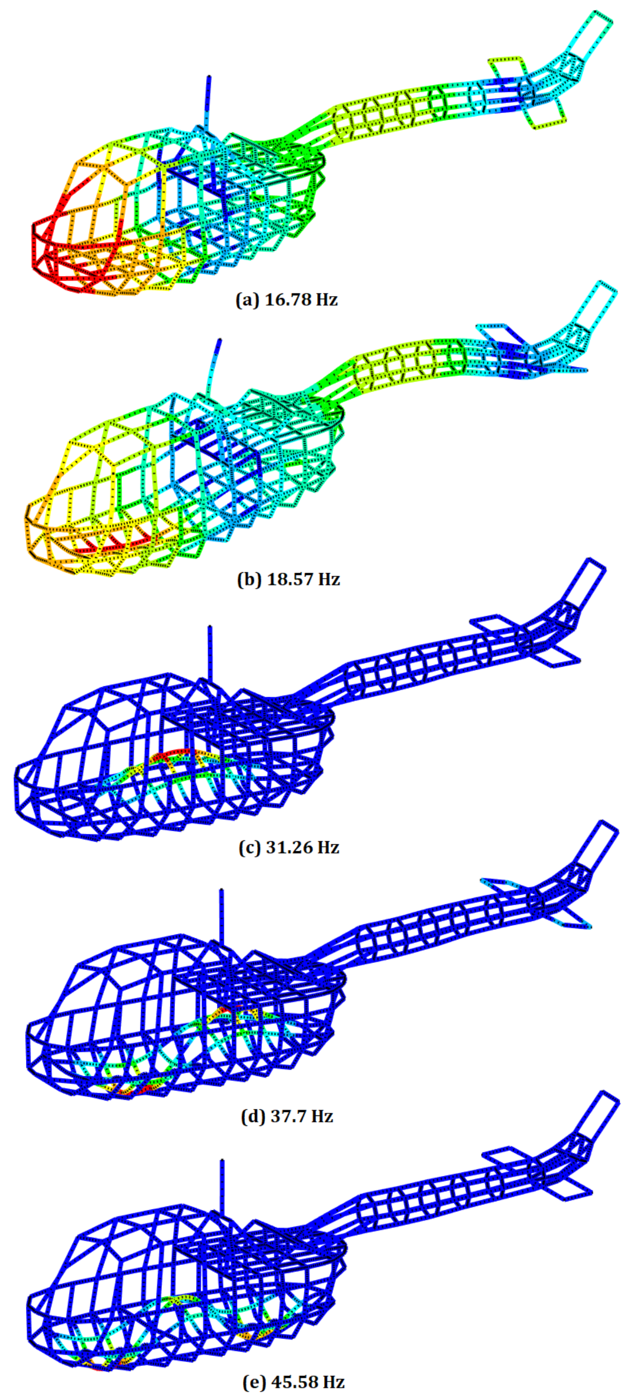

Figure 9: Representative mode shapes of the helicopter frame affecting floor vibration identified from modal analysis. (a) Pitching mode (16.78 Hz), (b) Lateral mode (18.57 Hz), (c) First cockpit mode (31.26 Hz), (d) Second cockpit mode (37.7 Hz), (e) Third cockpit mode (45.48 Hz).

Table 2: Comparison of representative natural frequencies affecting the cockpit floor vibrations with literature

Mode	This Study [Hz]	(Ref. 20) [Hz]
lateral	16.78	16.48
pitching	18.57	16.44
1st cockpit	31.26	32.34
2nd cockpit	37.7	39.04
3rd cockpit	45.48	43.1

Vibration Loads and Analysis

The vibration input applied to the airframe model is representative of dominant excitations in flight, primarily arising from the main rotor dynamics. In conventional helicopters like the Bo-105, blade passage over the fuselage produces periodic loads at integer multiples of the rotor rotational speed, also referred to as Nb/rev, where N being the number of rotor blades and b are integer multiples. Among these, the $4/rev$ harmonic typically results in the strongest structural response in the cockpit region due to the higher amplitude of lower modes.

In this study, a sinusoidal excitation is applied at $N/rev = 28$ Hz, corresponding to the 4th harmonic of a rotor with approximately 7 Hz rotor angular speed. The amplitude of the input load is scaled to approximately 10% of the MTOW, resulting in a peak force magnitude of 2452 N.

The simulation of other high-load scenarios during aggressive manoeuvres or blade–wake interactions is not taken into account with this load assumption but other loading scenarios can easily be applied. This load is applied vertically at the main gearbox mount, consistent with rotor-induced vibratory transmission pathways. Future work may include time histories extracted from real flight data or more complex broadband inputs to represent turbulence and gusts.

ISO-2631 Comfort Evaluation

The ISO 2631-1 standard (Ref. 5) provides guidelines for evaluating human exposure to whole-body vibration (WBV), particularly in seated and standing postures. It is widely used in assessing comfort and potential health effects in transport vehicles, including helicopters. The standard defines frequency-weighted acceleration metrics based on human sensitivity to vibration across various axes.

The frequency-weighted root-mean-square (RMS) acceleration is defined as:

$$a_w = \sqrt{\frac{1}{T}\int_0^T [w(t)\cdot a(t)]^2\,dt} \tag{11}$$

where $a(t)$ is the time-domain acceleration, $w(t)$ is the ISO-defined frequency weighting function (e.g., W_k for vertical axis), and T is the evaluation period.

In this study, the simulated vertical acceleration of the mannequin (obtained from the state-space model output) is post-processed using the ISO 2631-1 methodology. The signal is first passed through a digital implementation of the W_k filter corresponding to vertical axis vibration. Then, the weighted RMS acceleration a_w is computed over a 2-second simulation window.

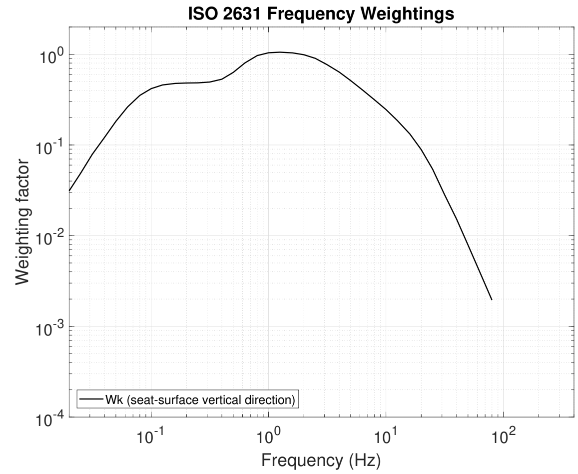

Figure 10: ISO-2631 frequency weighting factor in vertical direction.

This value is compared against the threshold bands recommended in ISO 2631-1 to infer passenger comfort levels. For short-term exposure, the standard suggests the following interpretation based on the frequency weighted acceleration a_w:

- $a_w < 0.315$ m/s^2: Not uncomfortable;
- $0.315 < a_w < 0.63$: A little uncomfortable;
- $0.5 < a_w < 1.0$: Fairly uncomfortable;
- $0.8 < a_w < 1.6$: Uncomfortable;
- $1.25 < a_w < 2.5$: Very uncomfortable;
- $2.5 < a_w$: Extremely uncomfortable.

RESULTS

Comfort Analysis Using Virtual Platform

To assess the vibration levels transmitted to the seat under realistic airframe dynamics, a set of closed-loop simulations was performed using the hybrid test framework introduced in Fig. 4-b. In this framework, the helicopter airframe model is digitally simulated and dynamically coupled with the numerical model of the physical seat–occupant system mounted on MAST. The rotor-induced vertical hub forces described in Sec. were used as excitation inputs.

Simulations were conducted for two excitation frequencies — 7 Hz and 28 Hz — representative of 1/rev, N/rev harmonics of the rotor. For both frequencies, the seat acceleration was evaluated at multiple cabin locations: pilot, co-pilot, and two passenger (PAX) seats as shown in Fig. 8. The responses were obtained for both the uncoupled and the coupled system, in

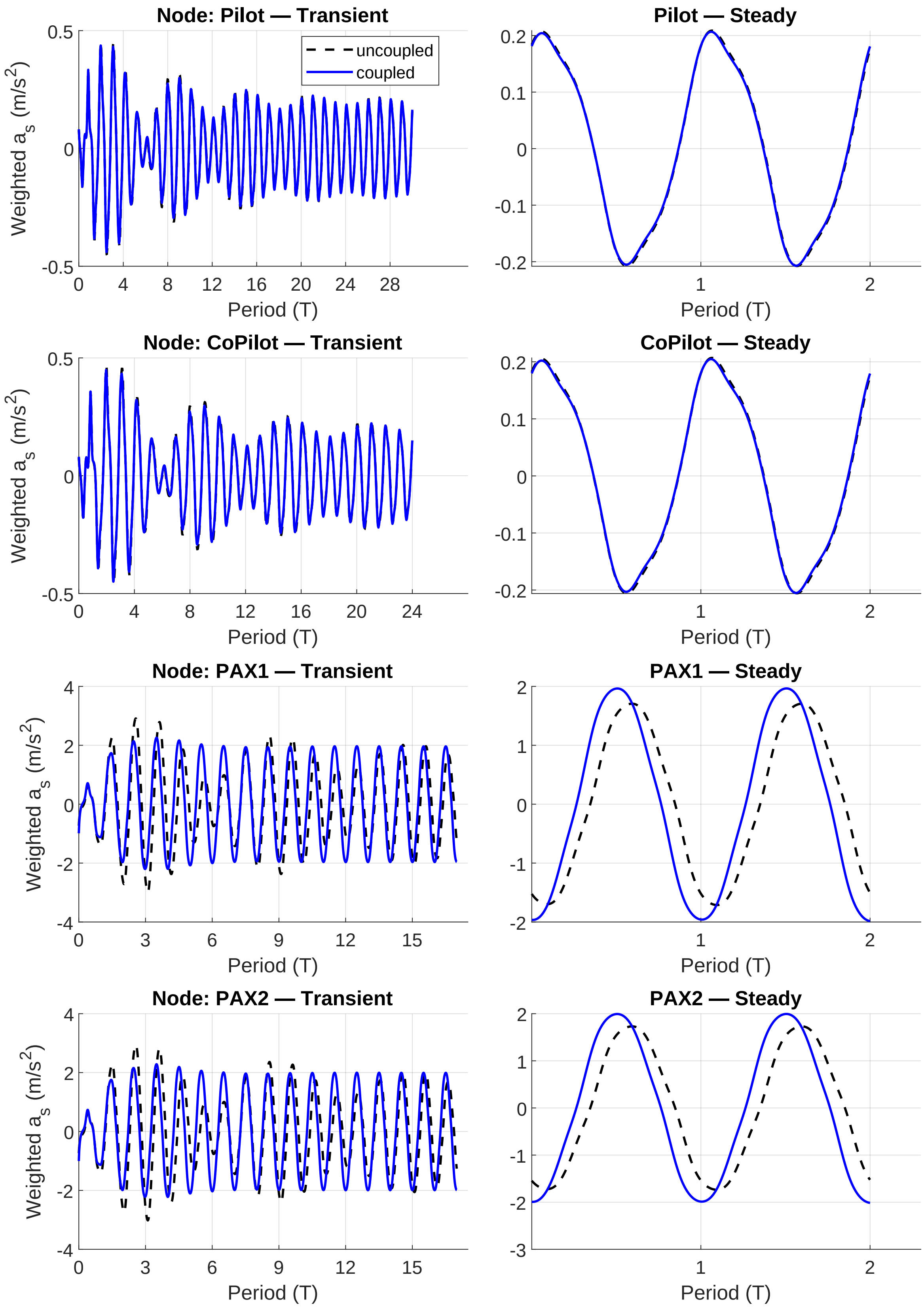

Figure 11: Time solution of comfort analysis across 4 selected nodes at 10% MTOW load and $1/\text{rev} = 7\,\text{Hz}$ at hub.

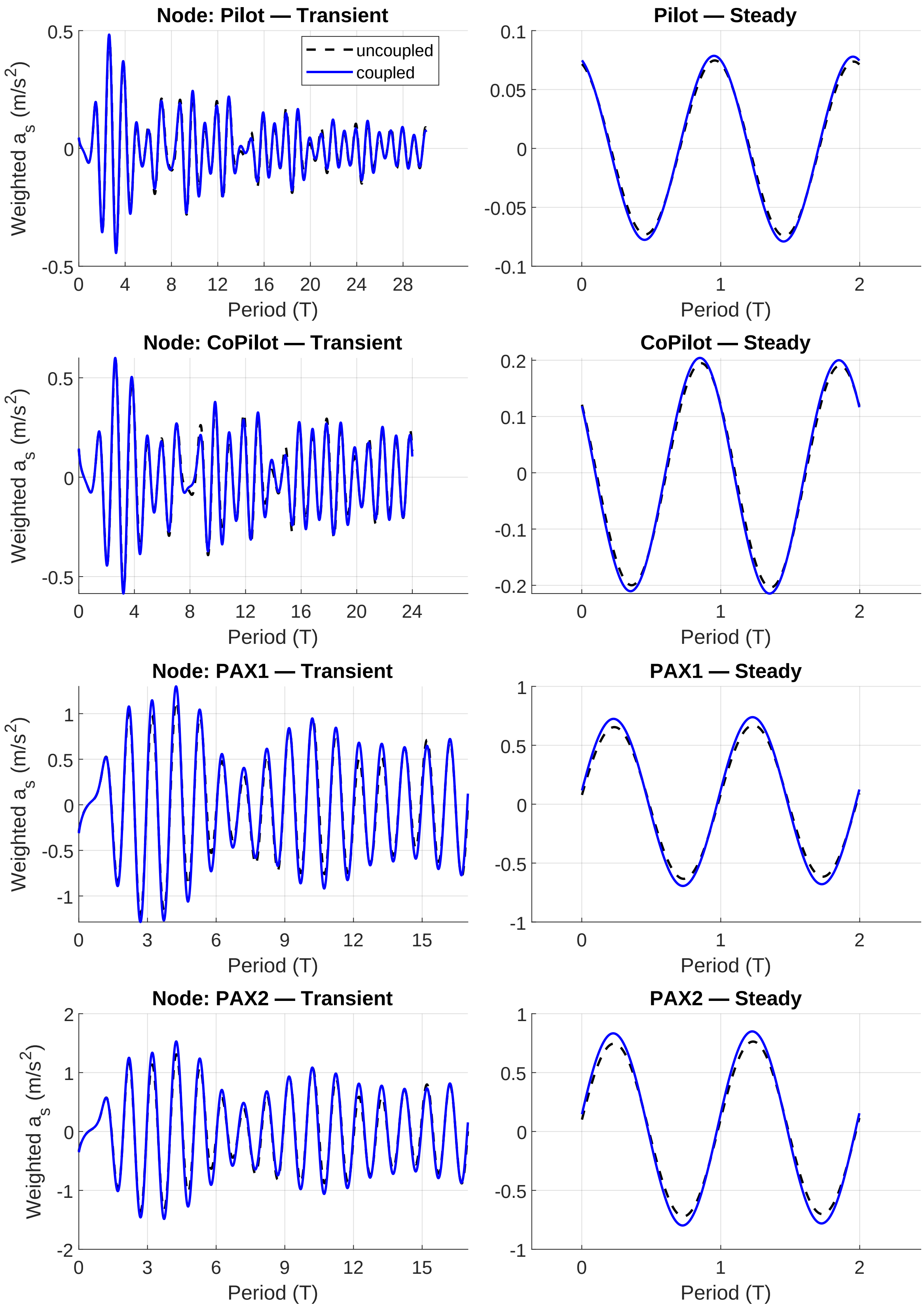

Figure 12: Time solution of comfort analysis across 4 selected nodes at 10% MTOW load and $N/\text{rev} = 28\,\text{Hz}$ at hub.

Table 3: ISO 2631 Weighted RMS acceleration (a_{RMS}) at seat locations under 10% MTOW excitation

	7 Hz		
Location	Uncoupled	Coupled	Δ (%)
Pilot	0.163	0.161	1.49
Co-pilot	0.163	0.160	1.81
PAX1	1.291	1.411	8.50
PAX2	1.308	1.430	8.53
	28 Hz		
Location	Uncoupled	Coupled	Δ (%)
Pilot	0.074	0.077	2.89
Co-pilot	0.153	0.159	4.14
PAX1	0.473	0.521	9.10
PAX2	0.539	0.600	10.12

which the seat–floor interface force is fed back into the structural model in real time.

The time simulations of seat acceleration outputs are presented in Figs. 11 and 12. The frequency-weighted (per ISO 2631) root-mean-square (RMS) acceleration levels are reported in Table 3. The results clearly indicate that the feedback loop influences the predicted seat vibration, especially near system resonance frequencies. For instance, at 7 Hz, which lies close to the seat–occupant natural frequency ($\omega_{n,\text{seat}} \approx 2.8$ Hz), coupling effects led up to 8.5% increase in weighted RMS acceleration at the PAX seats.

At 28 Hz, the relative difference in the uncoupled and coupled system response is increased since the excitation frequency gets closer to the first floor mode. Therefore, the coupling can have significant effect when local modes are excited.

In addition to steady-state vibration levels, the transient evolution of seat acceleration was also analysed. Across all frequencies, the system exhibited a settling time of approximately 15–30 cycles before reaching steady-state. This transient period is particularly relevant in short-duration manoeuvres or transitions, where comfort perception may be affected even if the steady-state vibration is within acceptable levels.

These findings confirm that excluding feedback from the seat–occupant system can lead to underestimation or overestimation of cabin vibration levels, depending on the frequency and location. The hybrid simulation platform thus enables more accurate comfort assessment and highlights the importance of including biomechanical feedback in cabin design and certification processes.

Effect of Seat Feedback Coupling on the System Response

Having illustrated the differences between the coupled and uncoupled transient and steady-state simulations, it would be useful to conduct frequency based analysis across a frequency range of excitation on the system. The fundamental difference in the two systems is having the seat dynamics included in the overall systems dynamics; therefore, the greatest influence is expected to be around the natural frequency of the subsystem.

To quantify the importance of including the seat–occupant dynamics in the loop, a comparison was made between the uncoupled and coupled frequency response functions that define the dynamics between the hub location and seat in terms of vertical motion. Figure 13 shows the frequency response of the floor displacement with and without the seat reaction force. Moreover, in determining these FRFs the MAST dynamics is taken as ideal, meaning the actual displacement is assumed to be perfectly aligned with the reference displacement, where the whole system is shown in Fig. 4. The plot qualitatively demonstrates that near the seat's natural frequency, the local floor vibration can be significantly modified, justifying the need for hybrid coupling for more precise analysis.

CONCLUSION AND FUTURE WORK

This work demonstrated the development of a digital–physical hybrid testing framework for helicopter passenger comfort analysis. A representative Bo-105 airframe model was constructed and reduced for real-time testing with a Multi-Axis Shaker Table (MAST). The most important results of the paper should are summarised as follows:

1. Preliminary validation showed the feasibility of replicating floor vibration input using a replicated simulation model of MAST and the actual MAST rig at different frequencies.
2. The hybrid testing framework demonstrated integration of a lumped seat–mannequin model with realistic stiffness and damping parameters to estimate the seat–occupant force feedback and the effect of this force on the coupled system.
3. Coupled and uncoupled simulations using rotor-induced hub forces showed that the feedback and the perception from the occupant are predicted differently from one another. The predicted difference is up to 8.5% at 7 Hz, and up to 10% at 28 Hz. These differences could be much higher based on the excitation frequency and seat-human dynamics, which confirm that excluding the feedback from seat-floor feedback force can lead to under- or overestimation of cabin vibration levels.
4. The magnitude of the quantified difference varied across cabin locations, and the frequency of excitation since it causes certain modes of the structure to be excited. In all cases, transients persisted for 15-30 periods before reaching steady-state.

Future work will address the implementation of a control algorithm to get the desired vibration on the motion platform, will integrate the seat and mannequin setup on the MAST, and will include comfort analysis across a mission profile. Then, authors aim to develop and commence the experimentations using the framework to different types of rotorcraft..

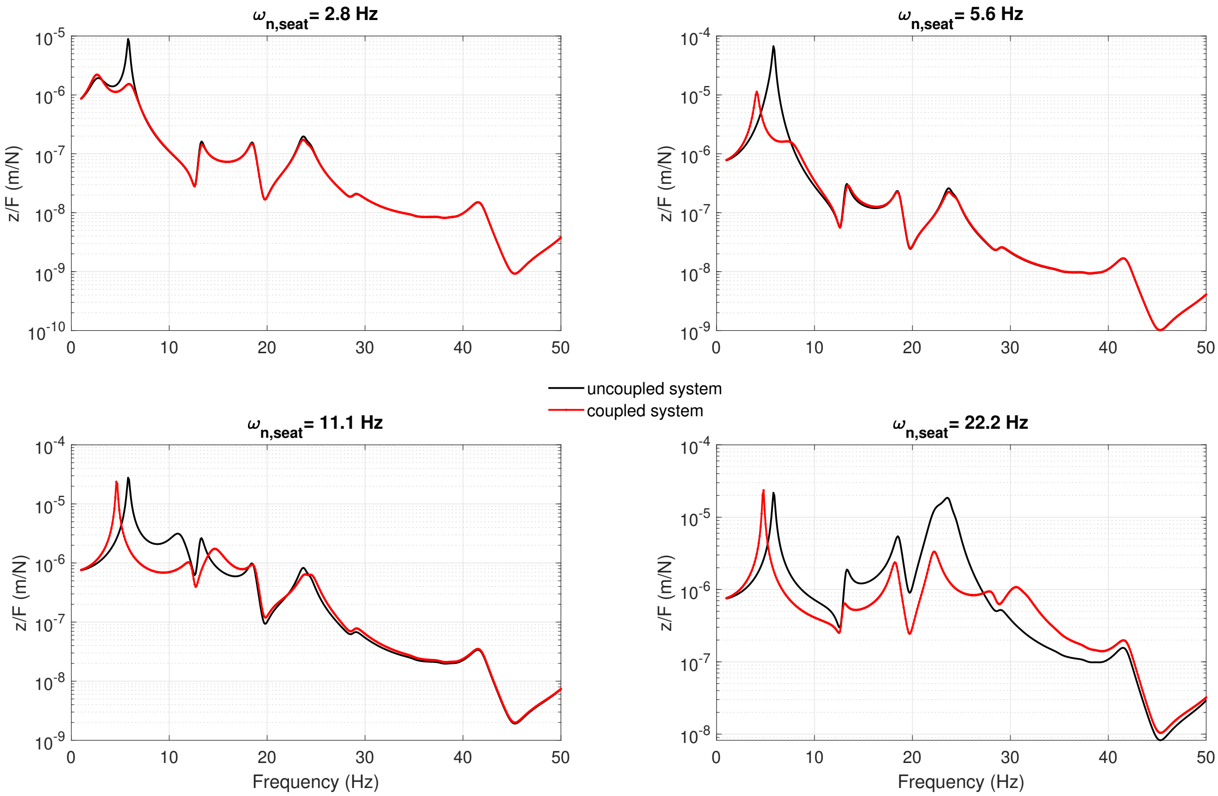

Figure 13: Uncoupled and coupled system response at multiples of nominal seat natural frequency from (Ref. 12).

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