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TOWARDS SAFE & SUSTAINABLE STRUCTURES: CAN HUMAN JUMP TIMING RELATIVE TO VIBRATION IMPACT SERVICEABILITY?

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1. Introduction

Structures + **Rhythmic jumping** → **Human-structure interaction**

Old: x Bulky; x High carbon footprint

Contemporary: ✓Slender, lightweight; ✓Greener; x Prone to human-induced vibrations

- Common during sports/civic/religious events
- Imparts loads up to 4x a person's body weight (W)
- x Causes large vibrations when in resonance

- x Unexpected structural response
- x Affects structural safety and serviceability (Figure 1)

Footbridge in Cuernavaca, Mexico, 2022 | Grandstand of Goffert Stadium, Nijmegen, Netherlands, 2021 | Temporary grandstand in Lincoln, UK, 2004

Figure 1: Examples of structural damage due to rhythmic jumping

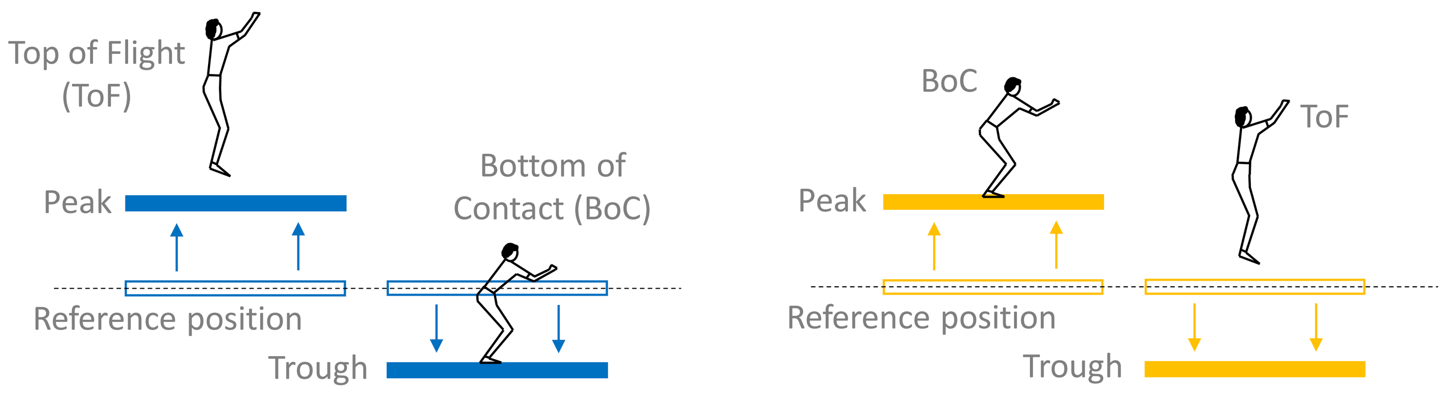
2. Knowledge gap and aim of the study

Gap: Existing models for predicting jumping-generated forces:
- Are inaccurate as based on limited data
- Overlook jump timing relative to structural vibration [1]

Aim: To investigate the effect of the timing of rhythmic jumps relative to platform vibration

Purpose: To improve models and structural designs and ensure safety, comfort and sustainability

3. Jump timing relative to vibration



Timing A: ToF coincides with the platform's peak position; BoC coincides with the trough

Timing C: BoC coincides with the platform's peak position; ToF coincides with the trough

Figure 2: Illustration of jump timing relative to platform vibration

- Rhythmic jumping on vibrating platforms needs to be described by not only the frequency of jumping (FoJ) but also the timing relative to vibration (Figure 2)

4. Tests involving rhythmic jumping

Variables

- f_a — FoJ (target): 2.0, 2.4, 2.8 Hz (On both vibrating & stationary platforms)
- f_p — Platform vibration frequency: 2.0, 2.4, 2.8 Hz (Harmonic, 2 m/s² amplitude)
- Φ — Jump timing (target): A, B, C, D (Figures 2 & 3) – Studied for the first time

Set-up (Figure 4)

- Platform vibrations; Metronome beats to control FoJ & timing
- AMTI Force plate to measure generated force
- OptiTrack Motion capture system to track kinematics for extraction of achieved timing
- 10 test subjects with MoCap suit & body markers

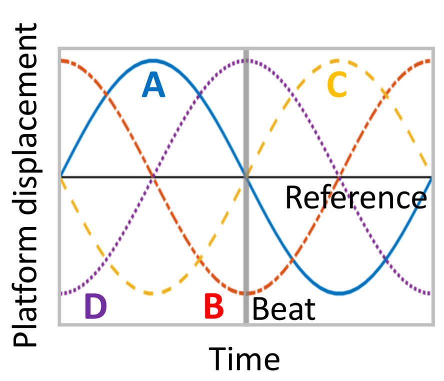
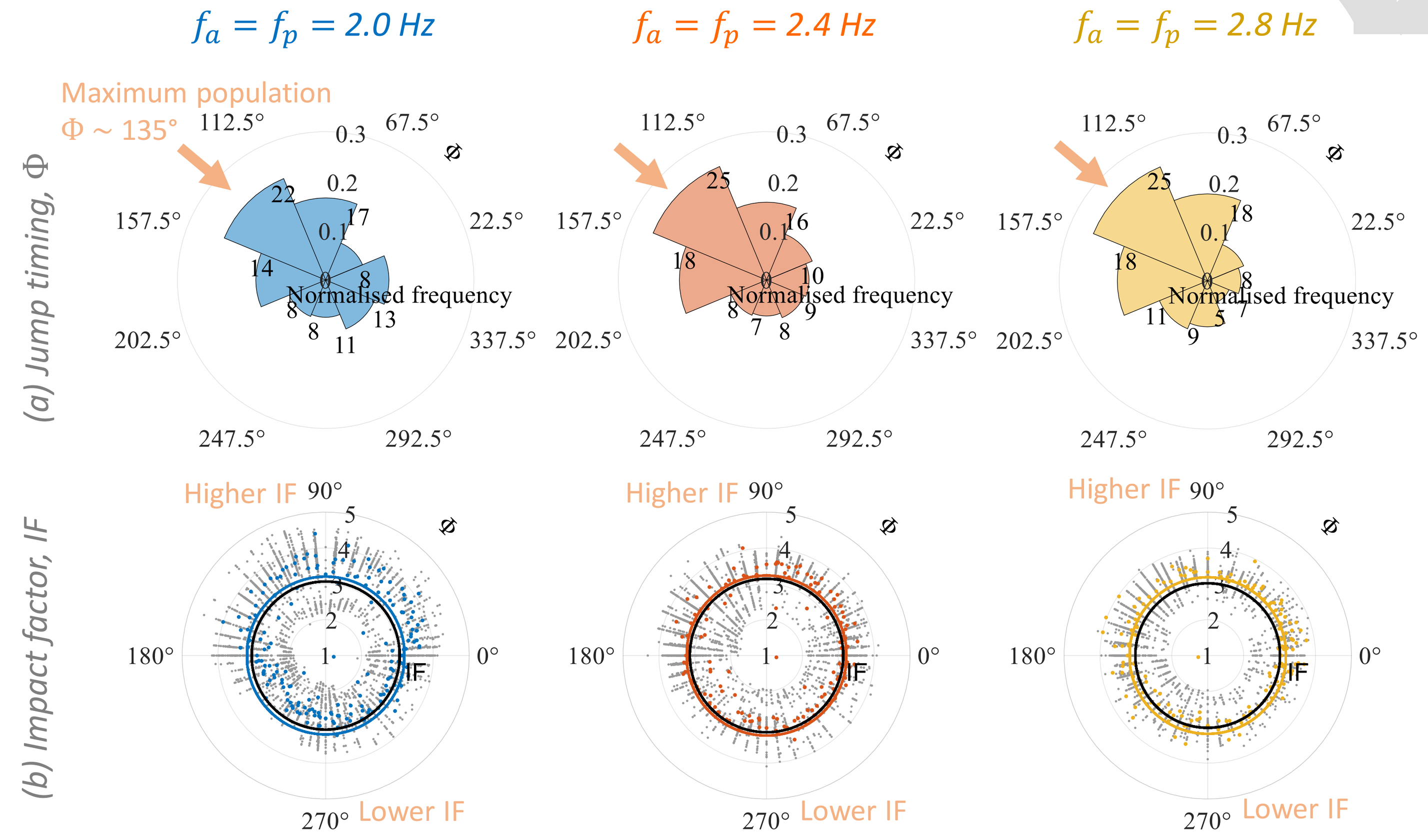


Figure 3: Metronome beat timing relative to platform displacement: A, B, C, D; Target relative phase [2, 3] between jumper and platform, Φ = 0, 90, 180, 270°, respectively

Figure 4: A fully instrumented test subject jumping on the platform

5. Results



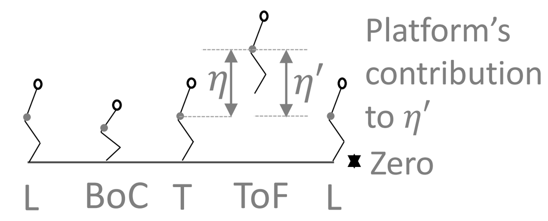
Grey dots: Cycle-by-cycle (c-b-c); Dots in colour: Mean at each Φ value; Circle in colour: Overall mean on vibrating platform; Black circle: Overall mean on stationary platform

Figure 5: Distribution of (a) Jump timing and (b) Impact factor achieved at three FoJs

- Expected 25% population each in bins encompassing Φ of 0, 90, 180 and 270°, but achieved maximum population at Φ ~ 135° (Figure 5a) → Jumpers adjusted timing to take off from a higher position and during the downward platform motion
- Higher impact factor (IF = peak force/W) corresponded to Φ between 0 and 180° and lower between 180 and 360° on the vibrating platform, compared to the stationary platform (Figure 5b) → Timing adjustment results in greater force
- Overall mean IFs at each frequency on both platforms are similar but c-b-c values are timing-dependent (Figure 5b) → Use of c-b-c values appropriate over mean values

6. Physical interpretation

Stationary platform



η = Jump height; η′ = Landing height; L: Landing; T: Take-off

Figure 6: Illustration of $\eta = \eta'$ on the stationary platform

Vibrating platform

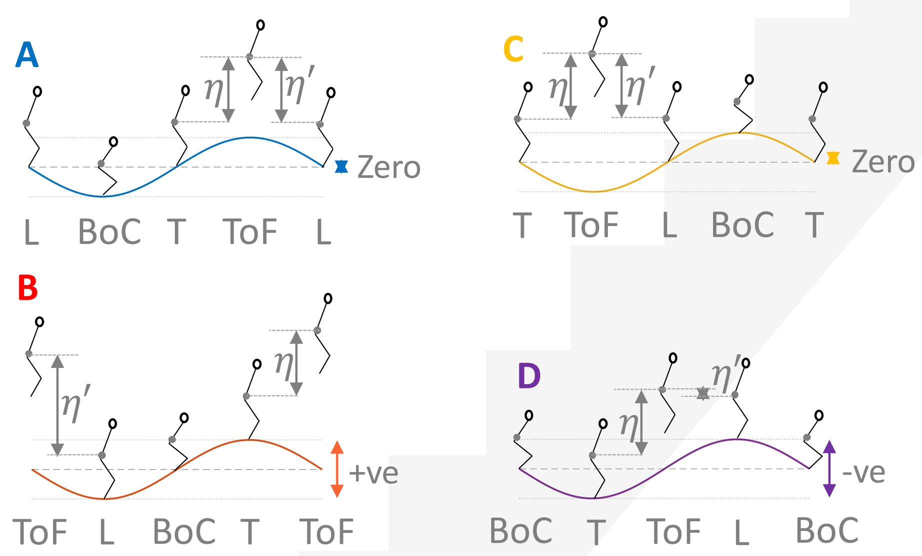


Figure 7: Physical interpretation of four target timings for low-amplitude vibrations

Jumping on vibrating vs stationary platforms (Figures 5, 6 & 7)

A and C: η' and force are similar to stationary platform

B: Greater η' and force → Injury risk, Longer flight → Late landing → Φ tends to 135°

D: Lower η' and force, Muscular effort → Premature landing → Φ tends to 135°

7. Conclusions

- Jump timing adjustment and the timing-dependent impact factor necessitate a timing-dependent model of jumping-generated force
- Neglecting the effect of timing may result in load underestimation

Application: ✓It is proposed to incorporate a timing-dependent load calculation into vibration serviceability guidelines to ensure both human comfort and structural safety without compromising sustainability

References

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2. Abraham N.M., Williams G., & Zivanovic S. 2023. Impact of vertical vibrations on human rhythmic jumping. Structures 57.
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