HARMONIC RESONANCE AND BONE CONDUCTION
Mechanisms, Physiological Effects, Neural Entrainment, and Safety Thresholds

ABSTRACT
Harmonic resonance and bone conduction are often conflated in acoustics, vibration therapy, and perceptual research. This paper distinguishes harmonic resonance as a governing physical principle from bone conduction as a biological transmission pathway. A unified framework is presented covering frequency-dependent physiological effects, neural entrainment, transmission pathways, and safety considerations.

1. INTRODUCTION
Mechanical vibration interacts with biological systems through resonance. When an external oscillation approaches a system·s natural frequency, energy transfer increases non-linearly. In humans, this underlies both beneficial applications (hearing prosthetics, rehabilitation, neuromodulation) and adverse effects (fatigue, disorientation, tissue stress). Bone conduction is a specialized pathway that routes vibrational energy through skeletal structures directly to the auditory and vestibular systems.

2. HARMONIC RESONANCE
Harmonic resonance occurs when a periodic force excites a system at or near its natural frequency, producing amplified oscillation.

Key properties:
- Frequency-specific amplification
- Phase coherence is critical
- Applies to mechanical, acoustic, and biological systems

In biological systems, tissues and bones exhibit distributed resonant bands rather than single frequencies. Resonance is a physical condition that precedes perception.

3. BONE CONDUCTION
Bone conduction transmits vibrational energy through cranial bones directly to the cochlea, bypassing the eardrum.

Primary interfaces:
- Cochlea (auditory perception)
- Vestibular apparatus (balance and orientation)
- Cranial nerve coupling

Characteristics:
- Most effective below ~4 kHz
- Strong somatic component (·felt sound·)
- Localized primarily to skull and jaw structures

Bone conduction does not create resonance; it routes resonant energy into specific biological systems.

4. FREQUENCY BANDS AND EFFECTS
0.1·4 Hz: Autonomic regulation, parasympathetic dominance
4·12 Hz: Vestibular and limbic modulation
12·40 Hz: Skeletal and neural integration

40·90 Hz: Bone-dominant resonance
90·250 Hz: Auditory·somatic bridge
250 Hz·4 kHz: Auditory clarity
Above 4 kHz: Minimal transmission via bone

5. NEURAL ENTRAINMENT
Rhythmic vibration can synchronize neural firing patterns through somatosensory, vestibular, and auditory pathways. Bone conduction engages all three simultaneously, increasing entrainment efficiency. Observed effects include altered time perception, changes in focus or calm, and heightened body awareness.

6. TRANSMISSION PATHWAYS
Air conduction provides high-frequency clarity but little somatic engagement. Bone conduction provides embodied perception but is frequency-limited. Whole-body vibration provides systemic entrainment with reduced localization.

7. SAFETY CONSIDERATIONS
Amplitude and duration are stronger predictors of risk than frequency alone. Potential adverse effects include headache, vestibular disturbance, fatigue, and tissue stress under chronic exposure.

Design rule:
Resonance amplifies load. Systems must dissipate energy faster than it accumulates.

8. UNIFIED MODEL
Harmonic resonance determines amplification.
Transmission pathway determines anatomical routing.
Biological interface determines perception.
Emergent effects manifest as cognitive, sensory, or physiological change.

9. IMPLICATIONS
Applications include engineering of bone-conducted interfaces, medical hearing and vestibular therapies, neuromodulation research, and embodied human·computer interaction systems.

10. CONCLUSION
Harmonic resonance is the amplification condition; bone conduction is a delivery pathway. Their interaction explains why certain vibrational stimuli feel immersive, regulating, or destabilizing. Properly bounded, resonance-based systems can be designed for safety and clarity.

Key statement:
Resonance governs magnitude.
Conduction governs location.
Biology governs meaning.