

MBits: Multi-modality 3D-printed objects via resonance-tunable spring-mass units

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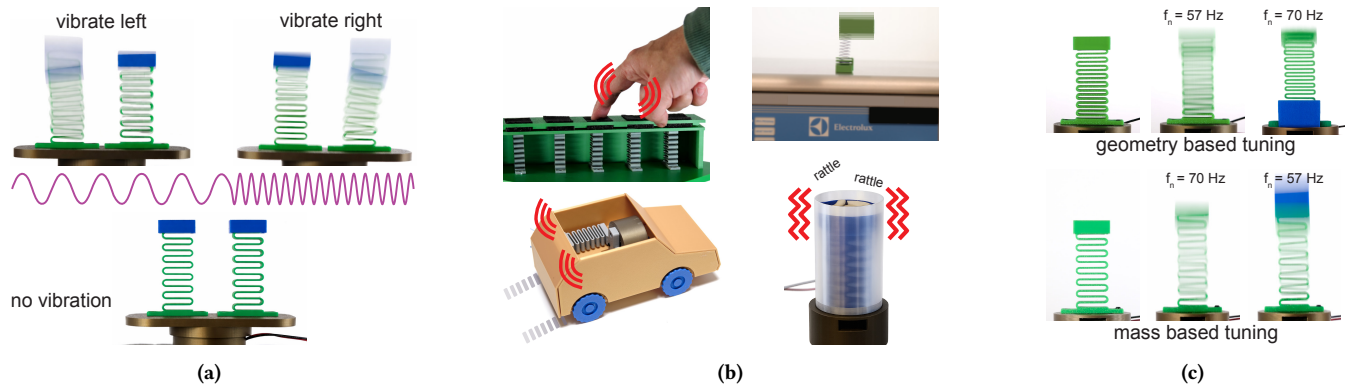


Figure 1: MBits are 3D-printable spring-mass units that are designed to resonate at specific frequencies. When driven by a single actuator, MBits can be targeted individually, relatively, or together by changing the input signal (a). MBit resonance can be used to create single-actuator objects that provide rich haptics, audio feedback, motion, or display (b), and MBits can be tuned post-fabrication by adjusting their geometry or mass (c).

Abstract

The geometric customization possible using digital fabrication has unlocked various explorations into objects' static properties: their shape, texture, materials, and embedded mechanisms. Less-explored is how geometry can enable new modes of interactivity through customizing object *dynamics*—how an object responds to forces and motions. We contribute MBits: programmable, simulatable, and reconfigurable spring-mass units which react to mechanical waves and enable controllable dynamical outputs in the form of haptics, motion, display, and audio. Objects with MBits can be printed from scratch using our toolkit or can include off-the-shelf springs, with geometry or mass modification pre- or post-manufacture to tune their responses. Each MBit responds strongly to a single vibrational

frequency, and collections of multiple MBits can, with a single actuator input, create mechanical filters, cascading sequences, or individually targetable vibration regions. We contribute a collection of characterization experiments, embedded in a CAD design tool, along with sample applications showing the possibilities of MBits.

CCS Concepts

• Applied computing → Computer-aided design; • Human-centered computing;

Keywords

fabrication, resonance, springs, vibration, passive, mechanical

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1 Introduction

Vibration is a familiar sensation in everyday life, resulting from natural sources such as a bush rustling in the wind and artificial sources like the shaking of a subway car. Most vibrations we experience, however, are incidental side-effects to some other process; the primary source of purposefully generated vibration is in the form of vibrotactile actuators located in mobile phones or smart-watches. While familiar, such vibrations are typically used only for haptics [5], with greater expressivity often gained by adding more actuators [15].

Outside of HCI, vibrations are often seen as a source of unwanted energy to be filtered out. Analogously to electrical filters for high-frequency electromagnetic signals, arrays of mechanical filters and resonators have long been used to isolate and route specific frequencies [21, 34], with recent work applying these principles to fabricate tunable band-pass filters [11, 43] and signal demultiplexers [4]. However, these frequency-dependent structures operate primarily at a microscopic scale, require precision manufacturing, and are typically used as internal signal processors to filter or isolate the input frequencies.

Inspired by these mechanical-engineering principles, our work shifts the burden of expressivity from active electronics to passive physical geometry. We introduce *MBits*: 3D-printable, tunable geometry that mechanically demultiplex the vibration from a single active actuator into multiple, individually controllable outputs, which can then be mapped to diverse interactive modalities. Each MBit is designed as a spring-mass unit with a defined natural frequency at which it responds strongly to an input vibration. By integrating multiple MBits with distinct natural frequencies in an object and exciting them using vibration signals composed of multiple frequencies, a single actuator can selectively drive different elements of a device individually or in groups (see Figure 1, left). Hence, MBits mechanically demultiplex actuation signals, enabling multiple controllable outputs from a single actuation source. By adjusting each MBit’s spring geometry or mass (either pre- or post-manufacture), its natural frequency can be modified (Figure 1c). By adjusting the multiplexed input signal, different MBits can be targeted with different intensities. Using this approach, designers can generate unique patterns of motion and vibration that manifest as multiple forms of interaction, including haptic feedback, acoustic signals, motion, and visual displays.

In this paper, we present the following contributions:

- a design space of frequency-dependent spring-mass geometries, demonstrating enabling multiple diverse, yet predictable, physical interactions using only a single actuator;
- design and characterization of 3D-printed MBits primitives across configurations and interaction modalities; and
- a software toolkit that enables designers to design and integrate MBits, validated through a set of application prototypes spanning haptics, motion, visual, and acoustics.

2 Related Work

Previous research has investigated how static mechanical properties can influence how forces propagate through an object, and what effects they enact; for example, haptic sensations can be created with texture [22, 47] or mediated via compliant material [36, 55].

Dynamic properties, such as a structure’s response to vibration by resonating with or suppressing the oscillatory energy, have also been explored. Dhiab et al. used a series of ribs bonded to a flat surface to inhibit the propagation of high-frequency waves emitted by an array of piezoelectric transducers [3]. TactPrint [39] applies a lattice structure around a vibrotactile actuator to confine the vibration sensations to an area local to each actuator, rather than vibrating the entire object. With MBits, in contrast, we view whole-object vibration as an *advantage*, enabling us to target specific MBits at arbitrary locations, with only a single actuator required.

Other research in HCI has investigated passively tuning object properties after fabrication. Several strategies have been developed to change an object’s haptics, including its texture [16] and its resistance to user-applied force [36, 53]. Passive acoustic properties can be manipulated by reconfiguring “voxels” [27] or via a user intentionally blocking sound holes [49], while visual appearance can be manipulated with color-changing inks [20] or via reconfigurable metamaterials [19]. With MBits, we also examine passively tuning (by adjusting attached mass or blocking part of the spring structure), but instead focus on achieving resonant properties which can then be used for multi-modality output.

Mechanical springs—the core of MBits—have been in use for thousands of years, and made of a wide variety of materials [6]. While springs are often used in different devices, they are less common in HCI as a fundamental focus of research. However, several examples do exist. Ondulé [13] investigated 3D-printed helical springs for deformable objects, while Kinerly [14] used both helical and spiral springs to enable self-propelled motion in 3D-printed objects. Park et al. designed a spring for energy absorption and return in a 3D-printed upper-limb prosthesis [37], and Digital Mechanical Metamaterials [17] and StayTuned [36] store energy via printed springs. Lamello’s springy tines resonate at different frequencies to indicate user interaction [40]. MBits uses, and manipulates, the natural resonance of springs to enable multiple points of vibration and motion based on a single actuator.

The core technique we use in MBits is *resonance*: when an object is subject to vibration at a given frequency, MBits with a closely matching natural resonant frequency react with a large-amplitude oscillation. Few works in HCI have dealt with mechanical oscillation. Skinput [12] used a concept similar to our own, with multiple spring-mass units implementing a mechanical Fourier-transform for on-body touch sensing, and Trusscillator [23] enabled human-scale fabrication of oscillating structures. Outside HCI, researchers utilized resonance for frequency selective electromagnetic actuation to independently stimulate spring-mass elements for high-resolution tactile displays [32, 33]. While their approach relies on specialized micro-scale electromagnetic hardware and local magnetic materials, MBits embeds resonance tuning within macroscale, passive 3D-printed geometries. This structural offloading allows a single actuator to drive not only localized haptic feedback, but also different interactive modalities including acoustics, motion, and visual displays.

Conceptually, using a single actuator to drive multiple outputs through geometric design is the converse of using a single sensor to sense multiple inputs through geometric manipulation. This type of work has been explored heavily in HCI, with designers using, among others, multi-sensor bricks [26], microphones [25, 40], and

microcontrollers [38, 42]. We are inspired by their general approach to design.

3 MBits: Working Principles and Design Space

At its core, an MBit is a spring-mass unit consisting of a single spring with a mass attached to its free end. How this structure responds to an input vibration is governed by the relationship between the frequency of the input signal (f_{in}) and the fundamental (or natural) frequency of the MBit (f_n)—the specific rhythm at which it naturally prefers to oscillate. By designing or adjusting the physical properties of these components, we can program how they react to different vibrations. MBits use the frequency-dependent properties of spring-mass units to amplify, preserve, damp, filter, split, or combine outputs from a single vibrational actuator. In contrast with previous work which leveraged multiple actuators (e.g., [39]), this is achieved using a single vibrational motor, while each MBit is tuned to respond to a selective frequency band. These controllable vibrational outputs can then be used for haptics, displacement or motion, and sound—and they can be tuned and controlled both before and after manufacture.

3.1 Natural Frequency and Frequency Response

The idea of natural frequency can be intuitively understood by imagining pushing a child on a playground swing. When the swing is pushed in perfect time with its natural rhythm, the system efficiently absorbs the energy and the swing goes much higher. Similarly, as the input frequency f_{in} approaches an MBit’s natural frequency f_n , its output amplitude increases, reaching its maximum at the resonant point ($f_{in} = f_n$; the peak in Figure 2b). Conversely, if the swing is pushed rapidly and completely out-of-sync with its natural frequency, the system becomes inefficient: as the input frequency increases past resonance, the output amplitude also steadily decreases. Amplitude eventually reaches a 1:1 transmission ratio at $f_{in} = \sqrt{2}f_n$; at this point, the spring provides zero amplification, simply passing the baseline input vibration through exactly as received (*unity* in Figure 2b). For all input frequencies beyond this point ($f_{in} > \sqrt{2}f_n$), the MBit actively dampens the input (*damping* in Figure 2b). The input frequency and energy are always preserved and passed through; it is the *amplitude* of the output that changes. This frequency-dependent behaviour—from amplified resonance to dampened isolation—forms the foundation of all interactions with MBits.

Natural frequency is not a static trait. In a spring-mass unit, the natural frequency depends upon both the spring and the mass: both can be designed upfront, measured, or tuned after a MBit is deployed (Figure 2a). Increasing or decreasing an MBit’s f_n are both possible, using different techniques. In the playground swing example, a larger child will make the swing oscillate more slowly, while shortening the swing’s rope will increase the frequency. We use similar strategies to manipulate the natural frequency of MBits Section 4. In the display application shown in Figure 1, a user can clip on different geometric adjusters to tune an MBit display flag to alert them to different washing machine cycles.

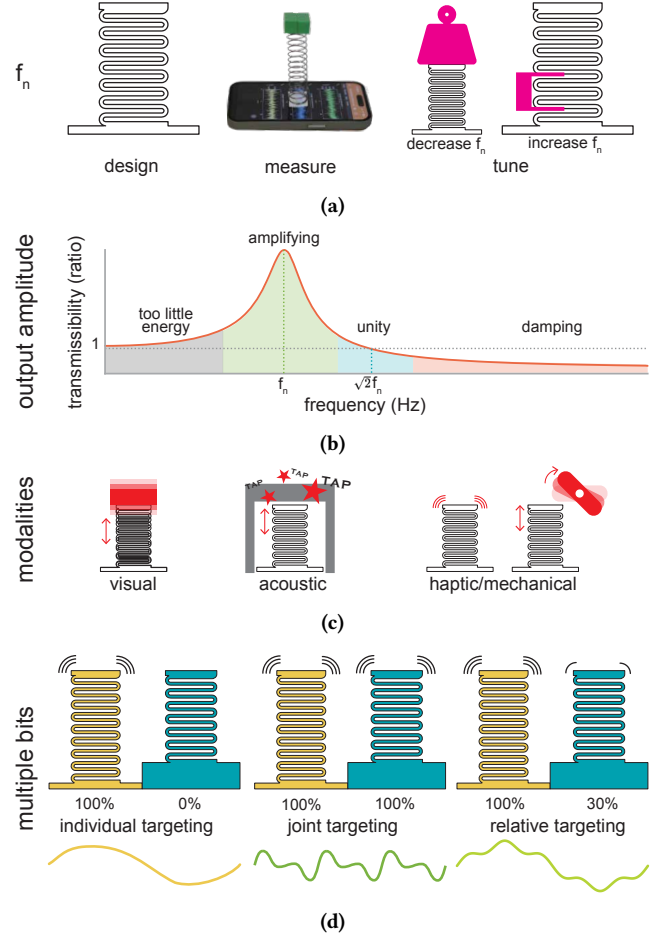


Figure 2: MBits are spring-mass units whose natural frequency can be designed, measured, and tuned (a). The amplitude of an MBit’s response to an input frequency is determined by the relationship of the input frequency to the MBit’s natural frequency (b). MBits’ oscillation can create various outputs: visual, acoustic, and haptic or mechanical (c). Including multiple MBits in a design enables individual, joint, or relative targeting (d).

3.2 Design Space for Interaction

MBits bounce at different amplitudes depending on the input frequency, and this bouncing can be used in various ways (Figure 2c). *Visually*, a vibrating MBit appears both extended and blurred compared to non-vibrating ones (Figure 1c); this effect can be used to display or highlight information as, for example, an oscillating MBit pops up above the edge of a box and becomes visible. *Acoustically*, the structure’s rapid oscillation displaces surrounding air to generate audible frequencies; furthermore, its amplified movement at resonance can strike adjacent surfaces, producing distinct mechanical taps or buzzing alerts, which is used in the pill reminder in Figure 1. *Mechanically*, an MBit creates a vibration that can be distinguished due to its frequency and amplitude. The button array in Figure 1 creates custom haptic sensations to guide users, while

the car uses vibration combined with barbed feet to create and direct locomotion.

By harnessing these modalities, a single MBit can be adapted for different forms of interaction. Consider the washing machine notification Bit: an MBit tuned to the frequency of its spin cycle can serve as a visual indicator of the machine’s state. However, by encasing that same MBit such that its resonating tip repeatedly strikes an adjacent wall during resonance, we transform visuals into into acoustic feedback.

3.3 Enabling Multiple MBits with Demultiplexing

As MBits actuate with larger amplitude at resonance ($f_{in} = f_n$) and remain relatively still away from the resonant point, this presents an opportunity for mechanical signal demultiplexing (Figure 2d). By attaching multiple MBits—each tuned to a unique natural frequency, e.g., 40 Hz and 60 Hz—to a single vibrating object, we can selectively drive one, some, or all of the MBits by manipulating the input signal. Vibrating the object with a pure 40 Hz signal will oscillate the 40 Hz MBit with high amplitude relative to the 60 Hz MBit. A composite signal containing both 40 Hz and 60 Hz will activate both MBits simultaneously at their highest heights. By adjusting the amplitude of each frequency component, we can independently control the bouncing of individual MBits. This is conceptually similar to an audio equalizer¹, where individual frequencies (MBits) can be set to different volumes (amplitudes). This approach is not limited to only two MBits; in theory, any number can be individually, jointly, or relatively targeted. Additionally, if multiple MBits are tuned to the same natural frequency, they will resonate together, allowing us to activate a group of MBits simultaneously with a single input frequency. We use two MBits in the car in Figure 1, which can be driven jointly (car goes forward), individually (car turns), or together but with different amplitudes (car turns while going forwards).

4 Parameters and Characterization of MBits

Translating these behaviours into reliable, predictable, and easily-makeable MBits requires understanding the underlying mechanical properties of their geometry. Much of the physics applies to any type of spring, however we 3D print our MBits. This allows us full control over all dimensions, CAD program simulation, and simpler integration and assembly into complex systems. In this section, we describe the governing physics of MBits, detail the characterization experiments we used to extract predictive models for 3D-printed PLA, and validate our model. Later, we report on using off-the-shelf springs for MBits.

The natural frequency f_n of a MBit’s spring-mass unit is governed by its spring material, spring geometry, and oscillating mass. The material and geometry dictate the spring’s stiffness k , while the total oscillating mass m_o is the sum of the mass that has been attached to the free end of the spring (m_a) and one-third the mass of the spring itself (m_s) [48]. For an ideal system, $f_n = 1/(2\pi)\sqrt{k/m_o}$ [48], but actual, physical springs also experience damping due to air

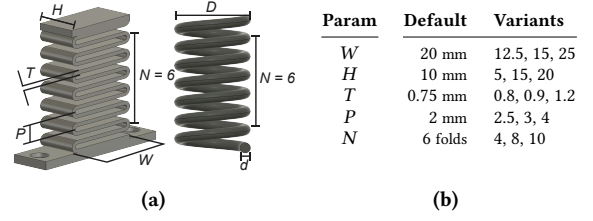


Figure 3: We model our stiffness equations for accordion springs (a), left on helical springs (a), right. We systematically modified spring parameters to extract stiffness and damping information (table).

resistance and material viscoelasticity, particularly if they are plastic. To ensure reliable interactions, we must design for the damped natural frequency, $f_d (< f_n)$:

$$f_d = \frac{1}{2\pi} \sqrt{\frac{k}{m_a + \frac{1}{3}m_s}} \cdot \sqrt{1 - \zeta^2} \quad (1)$$

where ζ , the damping ratio, accounts for the effects of air resistance and spring material. Note that, except when explicitly addressing damping, we use f_n and f_d interchangeably to refer to the fundamental frequency of a spring.

While m_a and m_s can be easily calculated using standard CAD volumes and material density (e.g., PLA density² $\approx 1240 \text{ kg/m}^3$), the stiffness (k) and damping ratio (ζ) are dependent on the physical geometry of the spring itself. Therefore, we conducted a series of empirical characterization experiments to extract reliable regression models that relate k and ζ to geometric dimensions.

4.1 Fabricating MBits for testing

To maximize repeatability, we designed an accordion-type spring (Figure 3a, left) which can be 3D-printed lying flat with no support material necessary. To systematically characterize spring stiffness k , damping ζ , and natural frequency f_n , we specified a baseline set of dimensions and created variants by changing one at a time, resulting in a test set of 16 unique MBits, summarized in Figure 3.

All samples in this work, unless otherwise noted, were printed on a Bambu Lab X1 Carbon (Bambu-brand PLA Basic, 0.2 mm layer height, 20% infill, nozzle 0.4 mm, and 2 wall loops). While the global infill density was set to 20%, the spring folds themselves were effectively printed as solid structures as their thickness was less than or equal to that of the printer’s wall perimeters. Further, except in the print orientation discussion (refer to Section 7.1.2), we printed all MBits lying flat on the bed.

4.2 Modeling stiffness, k

We model stiffness as a power-law relationship between geometric and material parameters, the specifics of which we derive from the theoretical mechanics of helical springs. Wire-based helical spring stiffness depends on the wire diameter d , the coil diameter D , number of turns N , and a material-dependent coefficient G , such that stiffness $k = G \cdot d^4 / (D^3 N)$. We adapt the helical spring formulation to our printed accordion springs. Wire diameter d corresponds to

¹https://en.wikipedia.org/wiki/Audio_equalization

²<https://store.bambulab.com/products/pla-basic-filament>

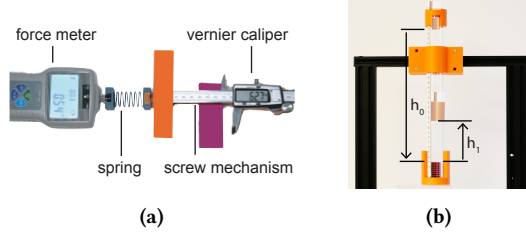


Figure 4: To measure stiffness, we used a custom rig for elongating printed springs (a). To measure damping, we use a transparent tube with ruler to guide a dropped mass from a fixed point (h_0), estimating bounce height (h_1) using video recording (b).

the cross-sectional area ($\pi/4d^2$) of the spring resisting deformation; in the accordion spring, the corresponding cross-sectional area is $T \cdot H$. The helical coil diameter D corresponds to width W of our springs, the non-cross-sectional dimension of resistance; the number of helical turns N corresponds to the number of accordion folds N ; and the material-dependent coefficient G is directly relevant for our springs.

We also noted from early tests that the pitch P of our springs had an inverse effect on stiffness (with stiffness reducing as neighbouring folds got further apart), analogous to the difference between open- and close-coiled helical springs. The adapted power-law model is therefore $k = G \cdot (H^a T^b) / (W^c N^d P^e)$ as a base.

We measured the stiffness of the 16 sample springs—summarized in Figure 3—using a 3D-printed test setup (Figure 4a). We elongated each spring 3 times to 1, 3, 6, 10, and 15 mm using a screw mechanism, measuring displacement x with a digital caliper mounted on the mechanism and the reaction force F at each displacement using a digital force meter³. Stiffness k was derived from the slope of the resulting force-displacement curve: $F = kx$. We fitted derived k s to the power-law model, resulting in

$$k = 8.14 \times 10^5 \cdot \frac{H^{1.03} \cdot T^{2.85}}{W^{2.78} \cdot N^{0.95} \cdot P^{0.14}} \quad (2)$$

This model achieves a high fit ($R^2 = 0.998$, and RMSE = 5.33 N/m), giving confidence in the possibility of generating spring geometries for a target stiffness.

4.3 Modeling damping, ζ

Damping reduces peak amplification and shifts spring resonance to a lower frequency, f_d . To design and fabricate objects with predictable vibration responses, we require the damping ratio ζ .

We calculated ζ for each of our 16 springs by performing drop tests following the procedure of Yang et al. [53]. We dropped masses of 10, 15, and 20 g from a fixed height $h_0 = 270$ mm and recorded the maximum bounce height h_1 at 240 fps using a FujiFilm X-H2 camera (Figure 4b). We extracted ζ using the logarithmic decrement method [29], i.e., $\zeta = \delta / \sqrt{(2\pi)^2 + \delta^2}$ where $\delta = \ln(h_0/h_1)$. For our 16 springs, ζ varied from 0.21–0.43, ($\mu = 0.31$, $\sigma = 0.06$). Using the spring geometries, we then fitted a regression model to predict ζ ,

following Eq. (2):

$$\zeta = 0.064 \cdot \frac{H^{-0.029} \cdot T^{-0.358}}{W^{-0.832} \cdot N^{0.04} \cdot P^{0.614}} \quad (3)$$

The regression model shows a good fit with $R^2 = 0.857$ and RMSE = 0.019. While the damping ratio ζ theoretically changes with added mass, its impact on the damped natural frequency is governed by the term $\sqrt{1 - \zeta^2}$ (see Equation 1). Within our toolkit, we do not consider the effect of mass variation on ζ because mass variations within our interaction space are relatively small, fluctuations in ζ yield negligible changes to ζ^2 . However, for applications requiring higher precision, designers can utilize the damping coefficient c . Because c is determined by structural geometry and remains independent of mass, it enables the exact calculation of the damping ratio for any mass using the relationship $\zeta = c / (2\sqrt{k \cdot m})$. Using our experimental drop-test data, we fitted a corresponding regression model to predict c :

$$c = 12.490 \cdot \frac{H^{0.492} \cdot T^{1.066}}{W^{0.534} \cdot N^{0.5} \cdot P^{0.689}} \quad (4)$$

This model also demonstrates a strong fit ($R^2 = 0.929$, RMSE = 0.068 Ns/m).

4.4 Validating the MBit model

To verify that our derived regressions accurately predict physical behavior, we experimentally measured the damped natural frequency $f_{d,exp}$ of all 16 sample MBits. We used a voice-coil actuator⁴ as the vibration source in our experiments to maintain exact control over vibrational frequency. The actuator was driven by a continuous sinusoidal waveform generated by a Teensy 4.1 microcontroller and audio module. The Teensy also recorded the dynamic response of the system via two Adafruit LIS3DH 3-axis accelerometers sampled at ≈ 582 Hz; one was attached at the base to monitor the input vibration, and the other at the free end of the spring to measure the output vibration (Figure 5).

We mounted each MBit on the voice coil and we swept the input frequency f_{in} from 20 Hz to 100 Hz in 1 Hz increments, holding each step for 5 seconds to allow the mechanical oscillation to stabilize. For low-stiffness models with a predicted $f_n < 20$ Hz, we extended the lower bound to 15 Hz to capture the resonant peak, restricting this extended range to only the necessary models to prevent overheating the voice coil at low frequencies.

Signal fidelity was confirmed via coherence analysis⁵, measuring how much power is transferred between the input and output at each frequency, which yielded values $> 0.97\%$. This test confirmed that the system response was highly linear and strongly driven by the actuator across the entire tested frequency range. We then computed the transmissibility⁶ T —the ratio of output acceleration to input acceleration—at each frequency step. The peak of the resulting T curve identifies the MBit’s actual experimental damped natural frequency $f_{d,exp}$. We compare this measured frequency with the theoretical f_d , taking into account the additional mass of the top-mounted accelerometer and its fixture ($m_a = 4.4$ g). Our comparison

³Baoshishan ZP-50N, 0.01 N resolution

⁴Acouve Laboratory VP216 http://www.acouve.com/pdfs/AcouveKorea_Transducer_2.pdf

⁵[https://en.wikipedia.org/wiki/Coherence_\(signal_processing\)](https://en.wikipedia.org/wiki/Coherence_(signal_processing))

⁶[https://en.wikipedia.org/wiki/Transmissibility_\(vibration\)](https://en.wikipedia.org/wiki/Transmissibility_(vibration))

revealed a high predictive accuracy, with error margins ranging from 0.6% to 5.03% ($\mu = 2.2\%$, $\sigma = 1.3\%$), as illustrated in Figure 5b. Given the average damping of our printed springs, delivering an input frequency that is off by this 2.2% margin results in a small drop in amplitude, retaining nearly all of the maximum resonant energy. Our model closely tracks physical behavior across the entire parameter space, accurately capturing how specific geometric changes shift the resonant point.

4.4.1 Validating Post-Fabrication Tunability. Because an MBit's damped natural frequency (f_d) is governed by its oscillating mass (m_o) and stiffness (k), its interactive behavior can be tuned after fabrication without requiring a reprint. To verify that post-fabrication modifications reliably follow our models, we tested two tuning methods: (a) added mass and (b) coil blocking.

Decreasing f_n via Adding Mass. Adding mass to the free end of an MBit increases m_o , lowering the resonant frequency. We experimentally validated this behavior by attaching known mass to baseline springs and measuring the new $f_{d,exp}$. The measured frequency shifts closely matched the theoretical predictions (Eq. (1)), with an average error of $\leq 3\%$ (see Appendix A).

Increasing f_n via Coil Blocking. Spring frequency can be increased by mechanically “short-circuiting” the turns of the spring (e.g., using a physical clip). This reduces the number of active turns (N), increasing the structural stiffness (k). Through experimental validation, we verified that mechanically blocking turns results in a natural frequency (f_n) identical to one printed with the reduced number of turns (e.g., an 8-turn spring with 2 blocked turns has f_n identical to a printed 6-turn spring), with a mean predictive error of $\leq 5.2\%$ (see Appendix A).

5 MBits Toolkit

While Section 4 provides a numerical model for designing MBits, manually calculating predictive regressions and mapping them to printable CAD geometries is tedious and might be inaccessible for some designers. To help designers create various applications integrating MBits, we developed a parametric design script using the Grasshopper environment for the Rhino 3D modeling tool. Our toolkit UI (Figure 6) allows designers to (1) define a geometric bounding box and generate MBits with specific f_n , including several at a time, (2) ensure amplitude thresholds are met for particular interactions, (3) create multiple MBits with either identical or uniquely addressable resonant behaviors, and (4) simulate post-fabrication MBit behaviour tuning.

5.1 Toolkit Implementation

Our toolkit generates printable MBit springs based on a bounding box constraint defined by the user and their target natural frequency f_n (Figure 6a).

In the background, the tool employs a two-step optimization sequence to find the optimal spring dimensions (W , T , H , P , N) that achieve the target f_n while fitting entirely within the defined bounding box. First, it iterates through possible coil turns and uses an SLSQP (Sequential Least Squares Programming) solver to calculate an optimum value that minimizes the frequency error while respecting maximum length and minimum coil gap constraints.

Second, to guarantee the geometry is printable, the solver performs a discrete local search around this continuous optimum, snapping the final variables to match our FFF printer resolutions (0.2 mm for W , H , and P ; 0.1 mm for T). To ensure successful fabrication and interaction, the tool enforces specific baseline constraints: it limits dimensions to accommodate standard 0.4 mm FFF nozzles, restricts generating high-frequency (> 90 Hz) springs to ensure adequate amplitude amplification under resonance (≥ 2.5 mm), and automatically enforces a 5 Hz separation threshold when generating multiple MBits to prevent interference. Using this custom script, we designed and fabricated several example applications demonstrating the multi-modal capability of MBits.

The toolkit automatically manages spatial offsets to accommodate the physical displacement of the spring across all applications. If the designed MBit is shorter than the user's bounding box length, the tool extrudes a rigid base to elevate it, positioning the free end 2.5 mm from the top constraint—matching the minimum resonant amplitude observed at our tested scale (Section 5.2.1). Finally, the tool exports a ready-to-print file in the STL format (Figure 6b). The toolkit also offers a simulation module for post-fabrication tuning. Users can evaluate how modifications—adding mass or short-circuiting coils—changes a printed MBit's behavior (Figure 6c). By recalculating the changed oscillating mass (m_o) and active turns (n_{active}), the tool predicts the new damped natural frequency (f_d).

5.2 Validating toolkit-designed MBits

To validate our system, we used the toolkit to generate seven MBits with target f_n s from 25–100 Hz out of PLA, each specified to fit within $20 \times 20 \times 35$ mm and with an attached mass equal to that of our measurement apparatus (4.4 g). After fabrication, we measured the true f_n s using the process described in Section 4.4 (Figure 7, crosses). We generated an additional two MBits for 35, 80, and 100 Hz using different bounding-box constraints for each, and measured their f_n s (Figure 7, circles). A linear regression fit gave $R^2 = 0.969$.

5.2.1 Understanding amplitude amplification. Beyond targeting a specific resonant frequency, physical applications based on MBits rely on the magnitude of their physical output; our tool was developed to ensure 2.5 mm spacing for this. To quantify how much MBits amplify input motion at resonance, we measured their physical displacement. We used the toolkit to design and fabricate 8 springs with natural frequencies 30–100 Hz in 10 Hz steps, vibrated each at its resonant frequency, and measured the maximum vertical displacement of the spring's free end relative to rest.

To quantify amplitude amplification at resonance, we developed a custom measurement apparatus (Figure 8a), consisting of an infrared counter sensor⁷ mounted on a stepper-driven linear slide (Figure 8a). We added a 0.5 g optical blocker to the free end of each MBit, such that it could pass between the arms of the sensor, blocking the IR beam. We accounted for this added mass in our f_d calculations (Eq. (1)).

We measured displacement using a two-stage probing sequence. First, to establish the baseline, the sensor was lowered at 3.0 mm/s until it detected the blocker, retracted 5.0 mm to eliminate mechanical backlash, and lowered again at a slower speed of 0.5 mm/s for

⁷Hailege LM393 Correlation Photoelectric Sensor

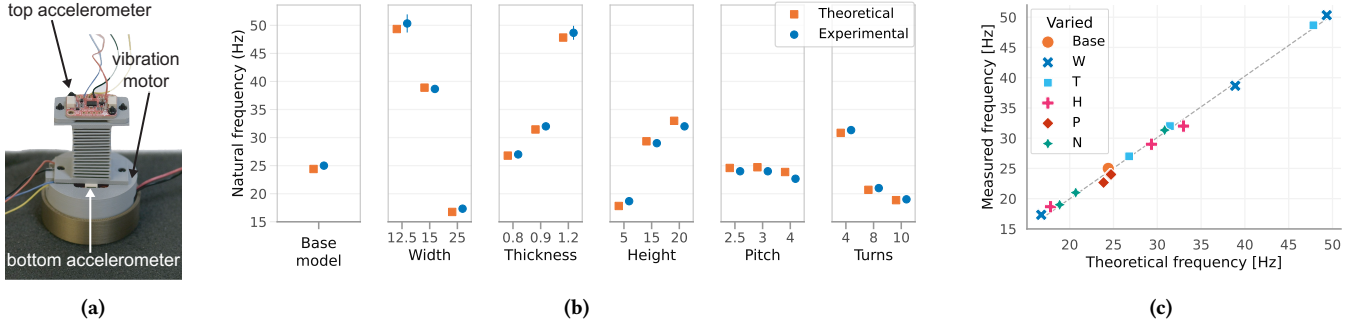


Figure 5: (a) Setup to record the acceleration response of spring-mass units during forced vibration. (b) Among our 16 test models, theoretical and experimental natural frequencies closely aligned, with average error 2.2%, $\sigma = 1.3\%$. (c) Theoretically predicted frequency vs. measured frequency for the 16 test models.

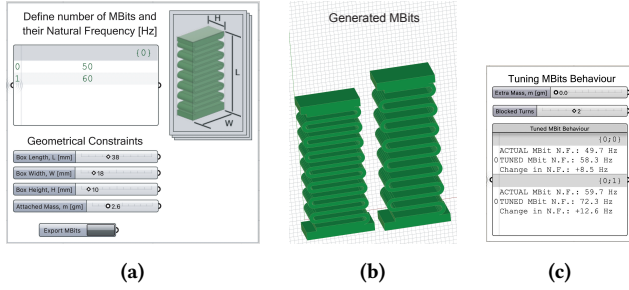


Figure 6: MBits generator for the Rhino 3D modeling environment. The designer defines frequencies, bounding boxes, mass constraints, and how many MBits are needed (a). The toolkit generates the MBits (b). Afterwards, the designer can tune f_n using mass- or geometry-based modifications (c).

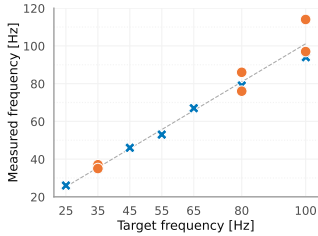


Figure 7: Target versus measured frequencies for 13 MBits generated with our toolkit. Models represented by crosses were generated under bounding-box constraints of 20 × 20 × 35 mm, while each circle represents a model generated with a different, unique bounding box.

exact zeroing. After recording the zero-position, the sensor was retracted 30 mm. We used our voice coil to vibrate the MBit at its resonant frequency. Once the oscillation stabilized after 2 s, we repeated the two-stage probing sequence to detect the peak height of the oscillating blocker, calculating the difference between the resting position and maximum position. To minimize measurement error, we averaged the results of three trials per model.

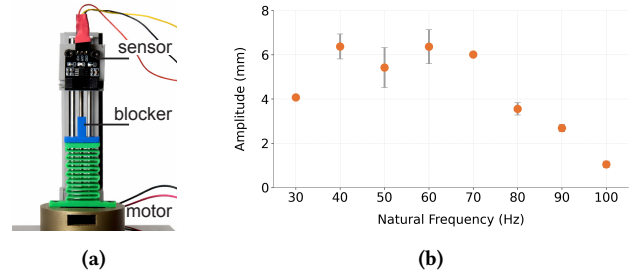


Figure 8: To estimate the amplitude of MBits during resonance, we created a custom rig using a stepper-driven linear slide and an infrared interrupt sensor (a). We measured the resonant amplitude of 8 MBits with f_n 30–100 Hz, finding a decrease after 80 Hz (b).

MBits show high amplitude (≈ 6 mm) for models with f_n 40–70 Hz. For higher-frequency models (> 90 Hz), increased stiffness restricts amplitude amplification above 2.5 mm (Figure 8). We therefore adjusted our tool to use 2.5 mm as a practical minimum gap for creating haptic and acoustic feedback; this also allows for some imprecision in manual assembly. We note that this threshold may need re-assessment with other actuators or fabrication processes.

6 Applications

We developed a series of applications highlighting the potential of using a single actuator to control varied outputs, including haptics, motion, acoustics, and display.

6.1 Spatial Haptics

Vibrotactile feedback targeting specific perceptual features can render textures, convey motion cues, and guide gestures [24]. Conventional methods require an array of actuators managed by complex electronic control systems; below we highlight MBit-based devices which use a single actuator for the same tasks.

6.1.1 Tactile Illusion: A Continuous-position 2D Tabletop. Phantom sensations arise when two vibration stimuli are perceptually “averaged” into a single sensation [1]. Shifting the amplitude balance

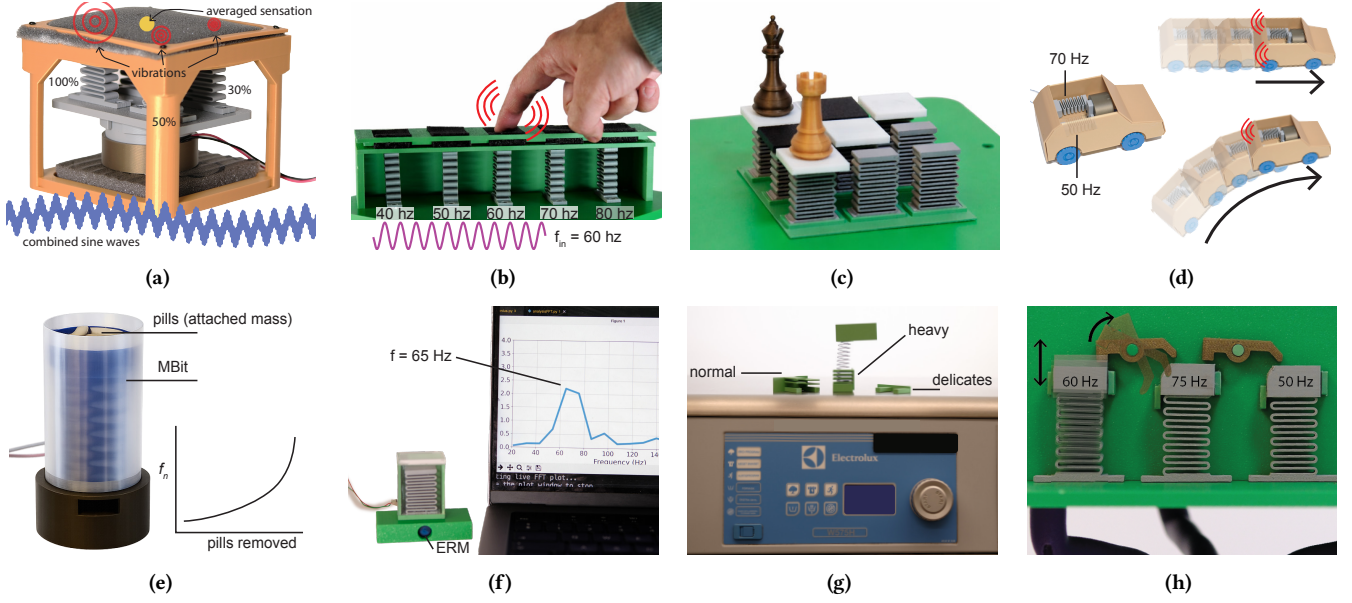


Figure 9: A “phantom haptics” tabletop uses relative vibration in an MBit grid to move the perceived haptic location (a). A haptic control panel gives users eyes-free guidance (b). A chessboard can sense when pieces are moved by the change in f_n due to their unique masses (c). A vibrolocomotive car can turn or drive straight, depending on input (d). Pills in a pill bottle with an MBit can be used as a distinctive mass for vibroacoustic notifications (e). Acoustic identification enables over-the-air sensing for mechanical user ID (f). An MBit on a washing machine harvests its vibrations to display the end of a specific cycle, set using geometric clips (g). A sequential display trips latches as MBits vibrate to track if a sequence was detected in order (h).

between the two stimuli can further create an illusion of motion [18]. We fabricated a hand-sized platform with four MBits (40, 50, 60, and 70 Hz) arranged in a grid underneath, driven by a voice coil (Figure 9a). On top of the haptic grid is a piece of foam to make the sensation more comfortable. By playing a continuous frequency sweep between pairs or groups of MBits, the sensation moves smoothly between them and creates a feeling of movement. A reverse sweep reverses the perceived motion. Changing the frequency separation between the MBits could change the characteristics of the illusion; this separation allows for some overlap in sensation due to their damping curves, but post-fabrication tuning could enable end-user customization.

6.1.2 Targeted Haptic Guidance: Haptic-Assisted Control Panel. Localized vibrotactile cues create eyes-free guidance for locating controls [46]. With MBits, we printed a set of five MBit buttons (40, 50, 60, 70, 80 Hz), driven by a single voice coil, that can be vibrated individually or in groups. Each button has a 2.5 mm separation between the user-facing surface and the top of the MBit, which allows it to vibrate the surface under resonance. Through overlaying frequencies in the input signal, the device can direct users to press one, two, or three buttons at once (Figure 9b).

This is a mechanical analog to Frequency-Division Multiplexing in telecommunications [50]: the f_n serves as a hardwired “address” for extracting specific signals from an unaddressed global broadcast.

6.1.3 Reconfigurable Haptics: Chess Training Board. Our chess training board can teach users about illegal and strategic chess moves. It features nine individually addressable MBits in a grid,

and two playing pieces with known masses. By vibrating at the f_n of a square with the added mass m_a of an illegally placed piece taken into account (Eq. (1)), the board can shake off that piece while leaving the other untouched (Figure 9c).

6.2 Vibration-driven Motion

Vibration-driven motion using stick-slip friction or vibro-impact mechanics [35, 54] allows objects to move across surfaces without traditional wheels or complex steering and transmission mechanisms. However, conventional multi-directional vibration robots typically require multiple localized actuators to control steering and direction. Using the principle of vibro-impact mechanics [54], we built a toy car propelled by the vibration of two MBits (50 and 70 Hz). A vibration signal of only one frequency turns the car, while a vibration mixing both drives it forwards. Changing the relative amplitudes of the two frequencies adjusts turning radius (Figure 9d).

6.3 Acoustic Interfaces

Sound can be used for sensing or feedback, but traditionally requires dedicated buzzers or speakers. By coupling our MBits with physical striking surfaces, we can generate sound from passive objects or detect the change in sound during user interaction.

6.3.1 Targeted Acoustic Alert: Smart Medicine Tray. We built a smart medicine container where the pills themselves act as added mass m_a (Figure 9e). As pills are consumed, the decreasing mass increases the container’s f_n . To convey a reminder, the base vibrates the container at an f_n corresponding to the expected pill count. If

the pills are not taken, the container resonates and rattles loudly; otherwise, f_n is shifted and the container falls silent. This frequency shifting also enables automated refill reminders.

6.3.2 Acoustic Authentication: Mechanical User ID. We built a mechanical user-ID system that can identify a laptop user and automatically load their preferences. We printed four visually identical MBits with f_n s of 30, 45, 65, and 80 Hz, with a 2.5 mm gap between the top of each resonator and a cap. Next to the laptop is a tray running constant frequency sweeps from 20–100 Hz; the laptop runs an FFT on the stream from its microphone. When an MBit corresponding to a given user is placed on the tray, it resonates and emits a sharp, audible acoustic spike at its characteristic frequency, allowing the laptop to detect its presence and load the corresponding preferences (Figure 9f).

6.4 Vibro-Visual Displays

6.4.1 Battery-Free Appliance Monitoring. Homes and industrial workspaces are rich sources of state-dependent vibrations. Household washing machines cycle through distinct rotational speeds, and industrial CNC machines operate at specific RPMs depending on the type of machining being performed. Instead of equipping these devices with active, battery-powered IoT monitoring systems, we can harness these existing vibrations as direct inputs to MBits to passively indicate machine states. We fabricated passive visual indicators that physically attach to these vibration sources (Figure 9g). For a household washing machine, we use a single MBit tuned to its high-RPM vibration during the spin cycle (1600 RPM $\approx$ 27 Hz). It remains hidden during the initial wash but resonates and comes into view during the spin cycle. This MBit can be adjusted to different cycles using clips: blocking 2 turns tunes it to the eco cycle, while blocking 3 turns tunes it to the delicates cycle.

6.4.2 MBit Visual State Machine. To demonstrate how MBits can display multi-stage processes (such as a CNC machine progressing from a rough cut to a fine cut), we developed a mechanical sequential state machine. We deployed an array of three MBits (60, 75, and 50 Hz) on a vibration testbed to simulate multi-state machinery. Between the MBits are latches, which can only be opened when the MBits are triggered in a specified order (i.e., the 2nd MBit cannot resonate until after the 1st MBit has resonated and unlatched it, Figure 9h). This application demonstrates how MBits can be combined with mechanical logic to visually verify that operations are performed in a proper order and no step is skipped.

7 Discussion, Limitations, and Future Work

7.1 Beyond Flat-Printed PLA Accordions

In this work, we primarily investigated 3D-printed flat accordion springs, as they are easy to fabricate without support structures and simple to integrate into customized bounding boxes. However, the fundamental technique of relying on a particular spring's natural frequency is neither material- nor geometry-dependent.

7.1.1 Expanding the Material Palette. Using the methodology from Section 4, we extracted f_d , k , m_s , and ζ of MBits for three additional

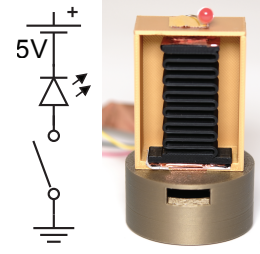


Figure 10: We printed an MBit in conductive PLA that serves as a basic mechanical switch: it connects an LED circuit while the spring is resonating. Due to cPLA's high contact resistance, we use conductive tape at the top.

Material	k [N/m]	ζ	m [g]	f_d [Hz]	$f_{d,exp}(\sigma)$ [Hz]	ϵ [%]
PLA Basic	141.01	0.36	5.21	24.40	25.00 (0.00)	2.44
PLA Support	81.56	0.44	5.21	17.83	21.67 (0.58)	21.49
PETG	83.73	0.39	5.21	18.54	19.00 (0.00)	2.47
PLA Conductive	149.15	0.40	5.21	24.69	27.00 (0.00)	9.35

Table 1: We printed 3 copies each of 4 identically dimensioned springs to validate our model (Eq. (1)) for several 3D-printable materials, PLA Support, PETG, and PLA Conductive, then followed the methodology described in Section 4 to extract the remaining parameters.

printable materials: PETG⁸, PLA support⁹, and conductive PLA¹⁰ (Table 1). We printed three copies of our base model (i.e., model with default values, see Figure 3, table) in each material and report the average results. We found that the errors between predicted and experimental f_n were low for PETG (2.47%) and PLA Conductive (9.35%), and much higher for PLA Support (21.49%)—likely due to its brittleness. While multi-material prediction is not currently implemented in our toolkit, these results confirm that the core method is broadly applicable to other printable thermoplastics. We measured the f_n of a spring printed in PLA Conductive and used it to make a basic mechanical switch for an LED: the LED is on when the spring resonates (Figure 10).

7.1.2 Printing non-flat MBits. We further explored non-flat printing, as fully print-in-place interactive objects has long been a goal of HCI research [28, 45, 52]. To explore how the layered structure of FFF printing affects our models [40, 41], we printed three copies each of three models at four orientations (Figure 11a) and measured variations in extracted stiffness using the method in Section 4.2. Stiffness dropped by up to 71% from our baseline for springs printed at 60° due to reduced layer adhesion and shear forces acting against the layer lines; the changes in stiffness were non-linear with angle. However, within-orientation variability was low and similar across the print orientations (Figure 11b), suggesting that future work

⁸<https://eu.store.bambulab.com/products/petg-translucent>

⁹<https://eu.store.bambulab.com/products/support-for-pla-new>

¹⁰<https://3deksperien.dk/products/3de-premium-conductive-filament-1-75mm>

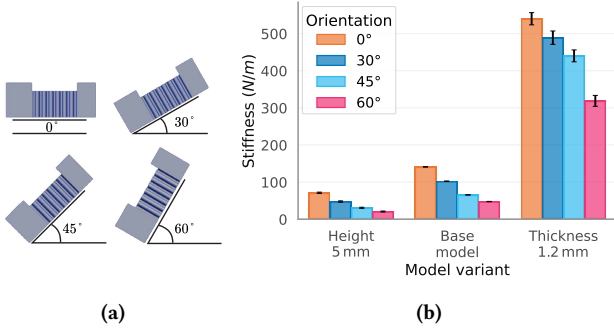


Figure 11: We printed spring models at 4 orientations (0°, 30°, 45°, 60°) (a), and measured variation in stiffness (b).

could potentially fit new regression models or material parameters to each printing orientation.

7.1.3 Using off-the-shelf springs. While our regression model (Section 4.2) is robust for printed geometries, designers may wish to use off-the-shelf, custom, or modified springs in designs. We developed a rapid smartphone-based characterization method based on free-vibration theory. When a spring-mass system is excited by a single tap and left to freely oscillate, it naturally vibrates at its natural frequency. To capture these vibrations, we adhere the spring directly to a smartphone¹¹ using double-sided tape and excite it via a sharp downward tap on its top (Figure 12a). As the spring freely oscillates, we use the phone’s built-in accelerometer¹² to record these vibrations over time. We then apply FFT to this acceleration data to identify the dominant peak, which corresponds to the spring’s natural frequency f_n (Figure 12b). We then weigh the spring (m_s) and solve Eq. (1) for k (using $\zeta = .3$, the mean damping value measured for our PLA springs).

We compared the results of this approach to the method of Figure 4a for four of our 16 3D-printed springs, with $f_n = 19\text{--}39\text{ Hz}$. We found $< 8\%$ error in stiffness measurement for springs vibrating below 50 Hz, a cap imposed by the $\approx 100\text{ Hz}$ sampling rate of the phone’s accelerometer. To verify its applicability to non-printed geometries, we also used this technique to extract f_n and k for the off-the-shelf metal spring used in our washing machine application; the smartphone-extracted stiffness (42.14 N/m) closely matched the baseline captured with our custom rig (45.0 N/m), assuming that metal springs has negligible damping ratio, i.e., $\zeta = 0$.

7.1.4 Other spring geometries. While we focused on accordion springs that are easy to print at a variety of f_n s, future work may explore helical- [13], cantilever- [40], or leaf-type [8] springs. Given their different geometries, such springs afford different types of interactions: helical springs can be twisted to adjust geometry (instead of requiring clips), while cantilever springs oscillate across an arc instead of linearly such that they could strike 2 endstops per oscillation. Leaf-type springs anchor in multiple places, and might be used for transmitting vibration inputs from one area to another. These all suggest unique opportunities for the types of

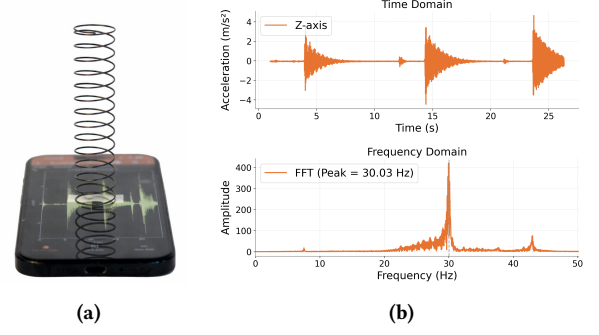


Figure 12: Smartphone setup recording the acceleration of the “off-the-shelf” spring (a). The system vibrates at its natural frequency (f_n) which can be estimated using a Fourier transform of the acceleration data (b). Using Equation 1 and the spring’s mass, we can get a rough estimation of the spring stiffness.

passive geometries or materials in which MBits could be embedded, but the theory and application areas explored here likely still apply.

7.1.5 Non linear springs. MBits utilize the linear springs, whose stiffness— and hence resonant frequency—remain constant regardless of the input amplitude. Exploration of non-linear springs—such as hardening or softening spring [30] remain unexplored—will enable the resonant frequency to shift dynamically depending on vibration amplitude. This will enable amplitude-dependent filtering or actuation. This will enable amplitude-dependent filtering and actuation. For example, a non-linear MBit can act as a dynamic haptic switch that resonates to provide feedback during a low-amplitude input, but dampens the output if a vibration at the same frequency becomes too aggressive. This occurs because the higher amplitude shifts the spring’s resonant frequency, meaning a different, shifted input frequency is now required to resonate the MBit.

7.1.6 Other sources of oscillation. Spring-mass units are classic media for oscillation, but this phenomenon can be found in various other contexts: for example, Helmholtz resonators¹³ feature oscillating air in a system analogous to spring-mass units [44], and future work could explore using air oscillations along with air-based computation [31, 41] to create passive, mechanically predictable outputs similar to those we demonstrate here. Ripples in liquid also obey equivalent physical laws, and suggest that designing printable liquid containers for use with liquid-powered sensing [2, 7, 9] might be able to make use of MBits-like interactions.

7.2 Limitations

Most of our applications rely on the same voice-coil actuator used in our experiments (Section 4.4). While ERMs are inexpensive and easy to work with, it can be difficult to drive them at an exact frequency; in contrast, the voice coil offered excellent reproduction of an input audio signal as vibration. However, this actuator is not appropriate in all circumstances: it does not vibrate silently; at 49 g it is rather heavy; and if it is not grounded and isolated from interface

¹¹Apple iPhone 15 Pro

¹²Using Phyphox, <https://phyphox.org/>

¹³https://en.wikipedia.org/wiki/Helmholtz_resonance

components, the user will feel vibrations directly from the actuator rather than from the MBits. The other sources of vibration we explored (the washing machine (Figure 9g) and the ERM (Figure 9f)) show promise in harvesting environmental vibrations and using smaller, lighter actuators for particular applications.

A primary limitation of 3D-printed plastics is their susceptibility to material fatigue and viscoelastic creep [10]. As noticed in our experiments, achieving high-frequency MBits requires stiffer springs ($f_n \propto k$), and this higher stiffness can cause localized internal stress during cyclic loading. Over time, continuous high-amplitude vibration or prolonged static loading can induce micro-yielding in PLA, permanently altering its stiffness and causing the natural frequency to drift. Future computational toolkits could systematically compensate for this anticipated fatigue by integrating modular tuning elements directly into the design: the software could generate a slightly over-stiffened spring coupled with discrete, removable mass units. As continuous cyclic loading degrades the spring's stiffness, the user could sequentially detach these segments—perhaps snapping off one piece after a specified number of actuation cycles or time. By proportionally reducing the resonating mass as the stiffness drops, the original target frequency is perfectly restored. This type of software-enhanced, live, post-fabrication correction technique is outside our current scope, but suggests ways in which post-fabrication tunability can be employed for ensuring continued predicted function.

7.3 Scalability of MBits

We implemented and validated MBit-enabled devices at the “tab” and “pad” scales [51], targeting hand-scale and tabletop tangible interfaces (roughly 3–20 cm). While we have not explicitly fabricated objects outside of this size range, the underlying physical principles of mechanical resonance are inherently scalable, suggesting that MBits could be adapted for both microscopic and architectural structures. At the micro-scale, mechanical resonance is already used in Micro-Electromechanical Systems (MEMS) for both sensing and actuation. Currently, these micro-structures require expensive lithographic cleanroom processes. However, as μm photocure techniques¹⁴ and similar high-resolution fabrication technologies become more accessible, MBits could embed interactivity and logic into 3D-printed micro-robots. Such scaling will require adjusting our models to shifting physical constants, as viscous damping (air resistance) will likely dominate mass at these sizes and frequencies.

Conversely, scaling up from handheld objects to room-scale or shared workspace environments presents a possible next step for multi-user tangible interaction. Large-scale spring- and oscillation-based interactions have been explored for playground equipment [23], and could be expanded to give human-powered output using energy from other large, periodic interactions, like jumping on trampolines, rocking in a rocking chair, or climbing up stairs. Creating passive, multi-modal output from these interactions might create compelling designs, like the piano-decorated staircase that plays music as users step on it¹⁵. One challenge that will be faced in

scaling up and using human-frequency input is the need for ultra-low-stiffness springs ($f_n \propto k$): this might be mitigated through supports or added mass.

8 Conclusion

We introduced MBits, passive, printable mass-spring units that can create complex, frequency-dependent outputs in multiple modalities from a single vibrational actuator. We discussed different ways to identify, design, and tune the natural frequency of MBits; how to achieve visual, acoustic, and haptic or mechanical interaction; and how multiple MBits can be used in a single object to mechanically demultiplex signals. We embedded a series of characterization experiments for printed MBits in a design tool, which embodies expert geometric and material knowledge. We also highlighted various example applications that are enabled by MBits, from mechanical user identification to smart chess boards to driveable toy cars and machining sequence trackers. Finally, we discussed how passive response to specific frequencies can be extended to other spring materials and geometries, other media than springs, as well as to other scales. By exploring what outputs are possible with mechanical and geometric manipulation of single actuator signals, we unlock the converse of single-sensor systems previously pioneered in HCI, steering ever closer to a print-in-place future for interactive devices.

Acknowledgments

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¹⁴<https://bmf3d.com/2%ce%bcm-series-3d-printers/>

¹⁵<https://www.youtube.com/watch?v=2LXh2n0aPyw>

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A Experimental Descriptions

The parameters for the characterization experiments of MBits (detailed in Section 4) are summarized in Table 4.

A summary of these validation results is discussed in Section 4.4.1. The complete data sets are available in Table 2 (plotted in Figure 13a) for stiffness variations, and Table 3 (plotted in Figure 13b) for mass variations.

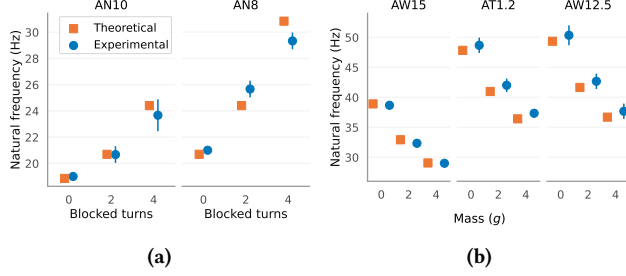


Figure 13: Effect on natural frequency of changing spring stiffness (a) or adding additional mass (b).

model	n_b	n_{eff}	k_{eff}	f_d [Hz]	$f_{d,exp}$ [Hz]	ϵ [%]
N10	0	10	89	18.85	19.00 (0.00)	0.78
	2	8	101	20.69	20.67 (0.58)	0.11
	4	6	141	24.40	23.67 (1.15)	3.02
N8	0	8	101	20.69	21.00 (0.00)	1.50
	2	6	141	24.40	25.67 (0.58)	5.17
	4	4	205	30.84	29.33 (0.58)	4.89

Table 2: The effect of the change in stiffness by blocking the number of spring turns, n_b , on natural frequency

model	m_{add} [g]	f_d [Hz]	$f_{d,exp}$ [Hz]	ϵ [%]
W15	0	38.90	38.67 (0.58)	0.59
	2	32.92	32.33 (0.58)	1.77
	4	29.05	29.00 (0.00)	0.18
T1.2	0	47.82	48.67 (1.15)	1.77
	2	40.96	42.00 (1.00)	2.53
	4	36.40	37.33 (0.58)	2.55
W12.5	0	49.34	50.33 (1.53)	2.01
	2	41.64	42.67 (1.15)	2.48
	4	36.69	37.67 (1.15)	2.67

Table 3: The effect of the additional mass, m_{add} , attached to the spring-mass unit top.

Variant			Theoretical	Measured mean (σ) value					
Variable	Name	Value		f_d [Hz]	$f_{d,exp}$ [Hz]	ϵ [%]	k [N/m]	ζ	c [Ns/m]
Base model	A	—	24.4	25.00 (0.00)	2.44	141 (0.74)	0.36 (0.04)	1.03 (0.07)	5.21
Width (base = 20 mm)	W12.5	12.5 mm	49.34	50.33 (1.53)	2.01	503 (11.50)	0.23 (0.05)	1.25 (0.05)	4.95
	W15	15 mm	38.90	38.67 (0.58)	0.59	320 (2.67)	0.24 (0.04)	1.03 (0.03)	5.05
	W25	25 mm	16.75	17.33 (0.58)	3.47	74 (0.40)	0.43 (0.02)	0.90 (0.11)	5.41
Thickness (base = 0.75 mm)	T0.8	0.8 mm	26.79	27.00 (0.00)	0.79	164 (2.38)	0.32 (0.05)	0.98 (0.02)	5.21
	T0.9	0.9 mm	31.45	32.00 (0.00)	1.76	231 (3.62)	0.31 (0.04)	1.14 (0.07)	5.35
	T1.2	1.2 mm	47.82	48.67 (1.15)	1.77	540 (16.45)	0.28 (0.03)	1.56 (0.11)	5.51
Height (base = 10 mm)	H5	5 mm	17.81	18.67 (0.58)	4.78	71 (0.68)	0.38 (0.05)	0.77 (0.03)	4.85
	H15	15 mm	29.34	29.00 (0.00)	1.15	217 (0.32)	0.35 (0.01)	1.25 (0.17)	5.61
	H20	20 mm	32.99	32.00 (0.00)	3.00	292 (9.61)	0.35 (0.03)	1.45 (0.17)	5.95
Pitch (base = 4 mm)	P5	5 mm	24.59	24.00 (0.00)	2.39	136 (0.92)	0.29 (0.02)	0.82 (0.09)	5.21
	P6	6 mm	24.72	24.00 (0.00)	2.90	136 (0.74)	0.26 (0.02)	0.74 (0.11)	5.25
	P8	8 mm	23.87	22.67 (0.58)	5.03	125 (1.29)	0.21 (0.05)	0.55 (0.03)	5.31
Turns (base = 6 turns)	N4	4 turns	30.84	31.33 (0.58)	1.59	205 (1.52)	0.29 (0.09)	0.98 (0.12)	4.98
	N8	8 turns	20.69	21.00 (0.00)	1.50	101 (0.96)	0.30 (0.03)	0.71 (0.06)	5.45
	N10	10 turns	18.85	19.00 (0.00)	0.78	89 (0.44)	0.31 (0.04)	0.69 (0.04)	5.71

Table 4: Summary of model variants. Each variant changes one variable from the base model’s defaults. We show theoretical (f_d) and measured ($f_{d,exp}$) natural frequency and the error ϵ between them, and measured stiffness k , damping ratio ζ , damping coefficient c , and oscillating mass m_o (attached mass m_a plus 1/3 spring mass m_s ; see Eq. (1)).