Figure 1. Comparison between six participants' numerical and experimental stability curves rendering combination of mass and damping at two different position controller bandwidths (10 Hz – red and 30 Hz – blue). Stability curves were fit using the adjusted human impedance model parameters found in Table II.
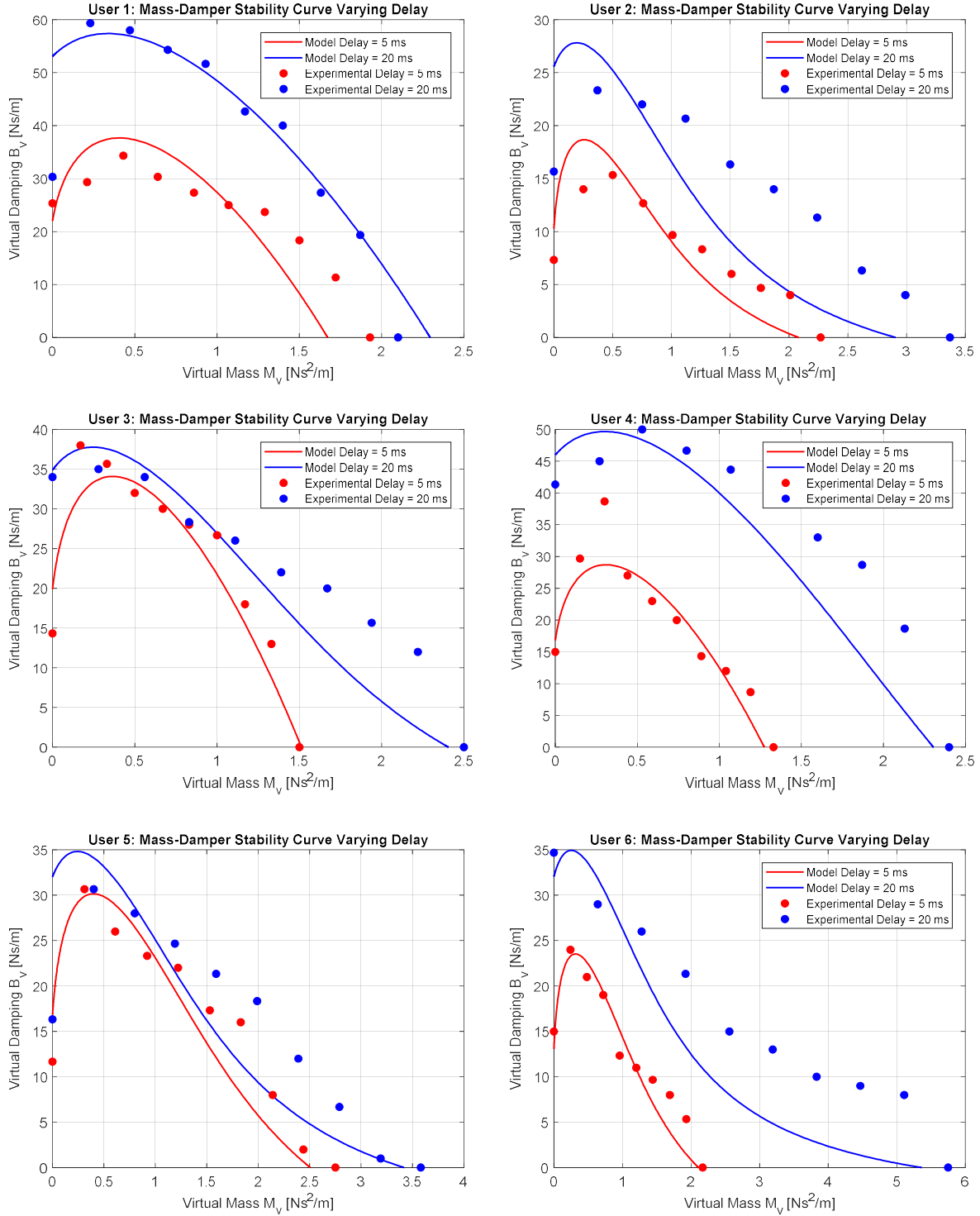
Figure 2. Comparison between six participants' numerical and experimental stability curves rendering a combination of mass and damping at two different additional loop delays (5 ms – red and 20 ms – blue). Stability curves were fit using the adjusted human impedance model parameters found in Table II.
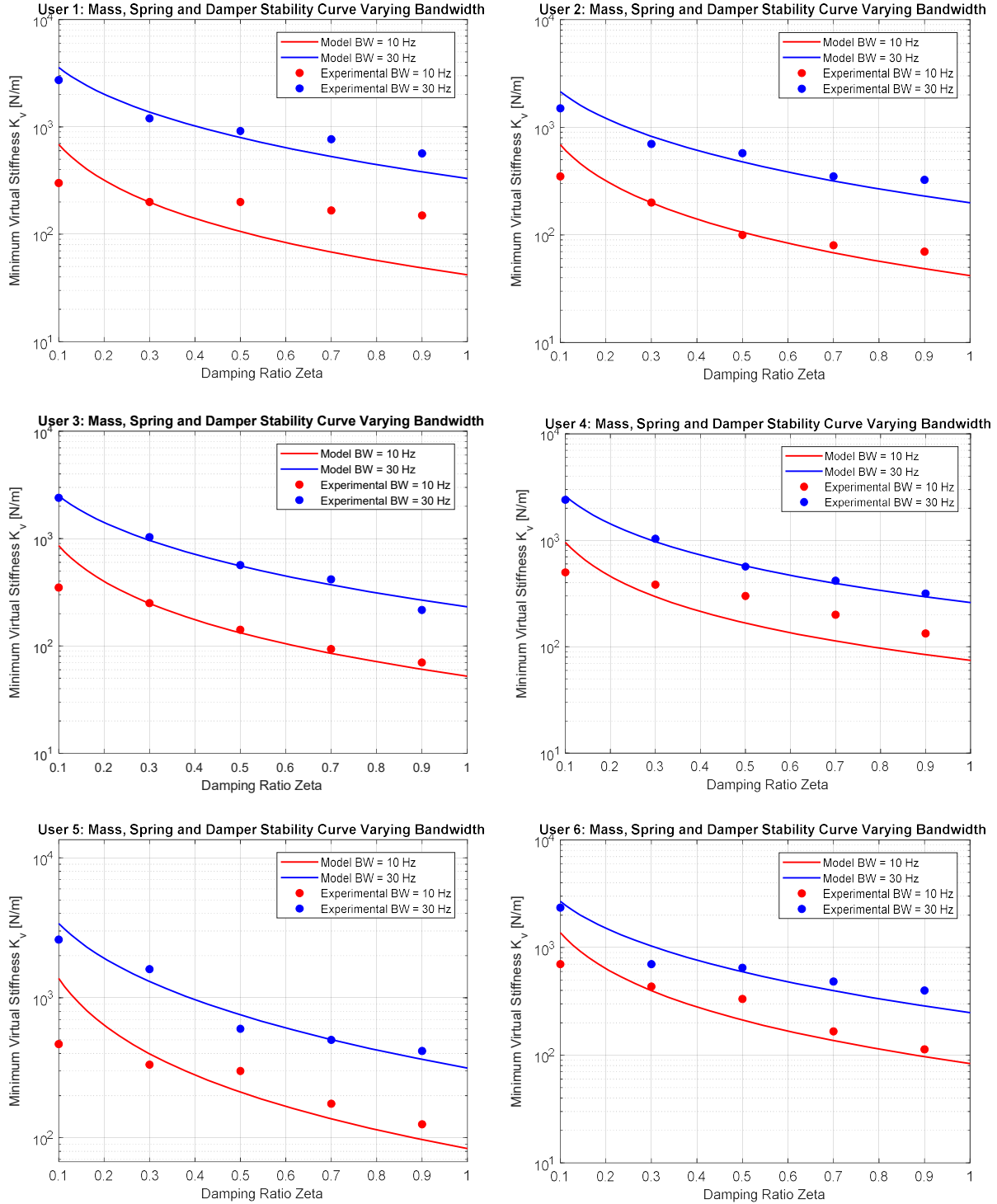
Figure 3. Comparison between six participants' numerical and experimental stability curves rendering a combination of mass, stiffness and damping simultaneously at two different position controller bandwidths (10 Hz – red and 30 Hz – blue). Stability curves were fit using the following damping parameters found in Table III.
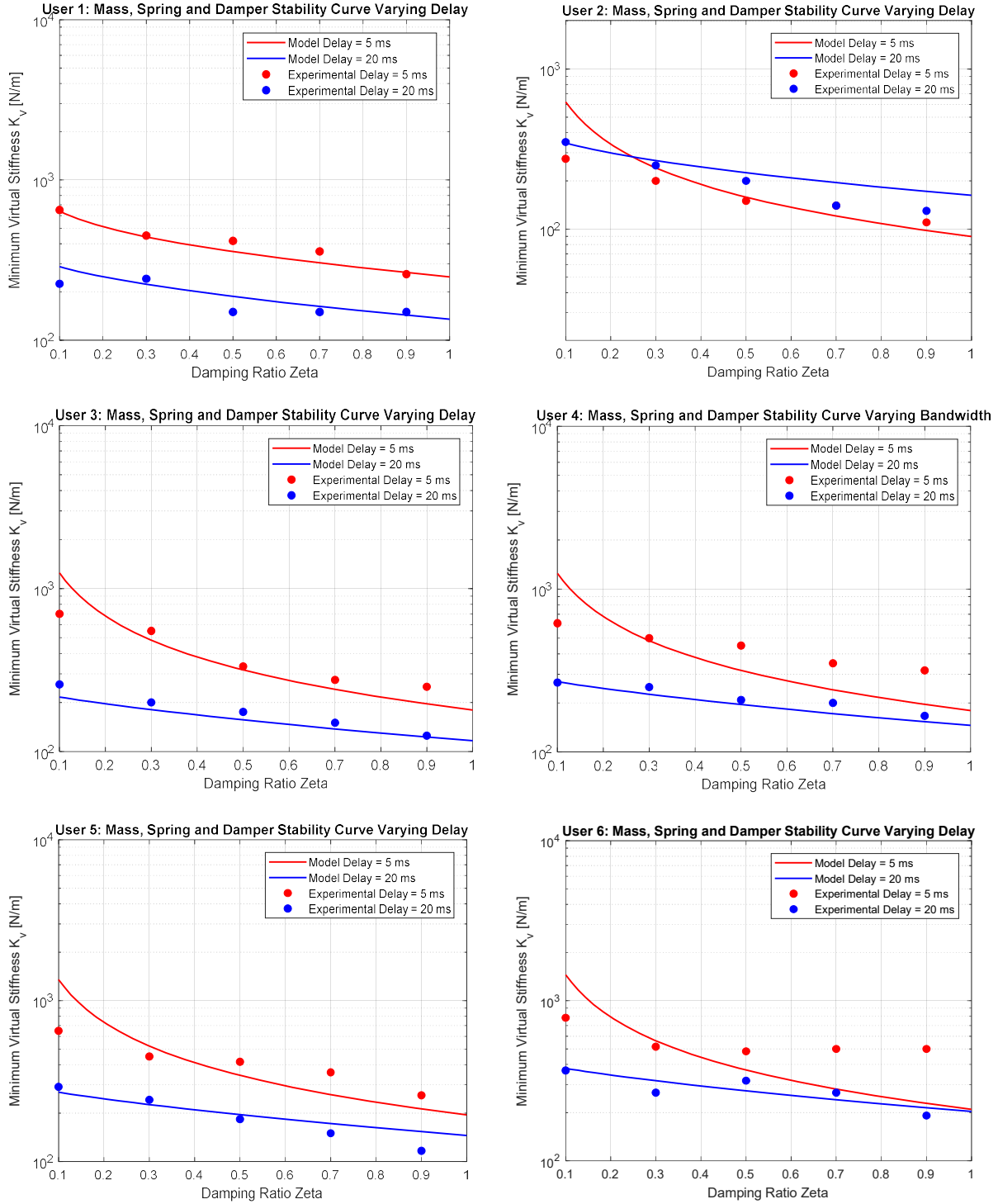
Figure 4. Comparison between six participants' numerical and experimental stability curves rendering combination of mass, stiffness and damping simultaneously with additional loop delay (5 ms – red and 20 ms – blue). Stability curves were fit using the following damping parameters found in Table III.

Table I. Experimental human impedance damping parameters of six participants. During the human impedance model estimation, each participant was asked to grasp the input of the device and maintain a consistent grip as a range of sinusoidal frequencies between 1 and 30 Hz were commanded, and device position and force were measured. This process was repeated for a total of three different grips: light, regular and firm.

User	Experimental Model Parameters: Damping (b_h)		
	Light Grip [Ns/m]	Regular Grip [Ns/m]	Firm Grip [Ns/m]
User 1	6	143	229
User 2	6	135	196
User 3	7	106	139
User 4	25	134	219
User 5	15	94	164
User 6	12	194	335

Table II. Adjusted human impedance damping parameters of six participants. During the experimental stability analysis rendering a combination of mass and damping (Fig. 1 and Fig. 2), the following adjusted damping parameters were used to best fit the experimental stability curves.

User	Adjusted Mass and Damper High Frequency Human Impedance Damping (b_h) or Two Parameter Human Impedance Model ($b_h + k_h$)			
	10 Hz Bandwidth	30 Hz Bandwidth	5 ms Delay	20 ms Delay
User 1	103 [Ns/m]	143 [Ns/m]	103 [Ns/m]	93 [Ns/m]
User 2	55 [Ns/m], 1600 [N/s]	35 [Ns/m], 3000 [N/m]	35 [Ns/m], 1000 [N/m]	35 [Ns/m], 650 [N/m]
User 3	139 [Ns/m]	139 [Ns/m]	95 [Ns/m]	50 [Ns/m]
User 4	94 [Ns/m]	134 [Ns/m]	80 [Ns/m]	80 [Ns/m]
User 5	45 [Ns/m], 1550 [N/m]	75 [Ns/m], 1550 [N/m]	60 [Ns/m], 1500 [N/m]	45 [Ns/m], 800 [N/m]
User 6	68 [Ns/m], 1900 [N/m]	55 [Ns/m], 2800 [N/m]	44 [Ns/m], 1200 [N/m]	45 [Ns/m], 920 [N/m]

Table III. Adjusted human impedance damping parameters of six participants. During the experimental stability analysis rendering a combination of mass, spring and damping (Fig. 3 and Fig. 4), the following adjusted damping parameters and high frequency human impedance approximation was used to best fit the experimental stability curves.

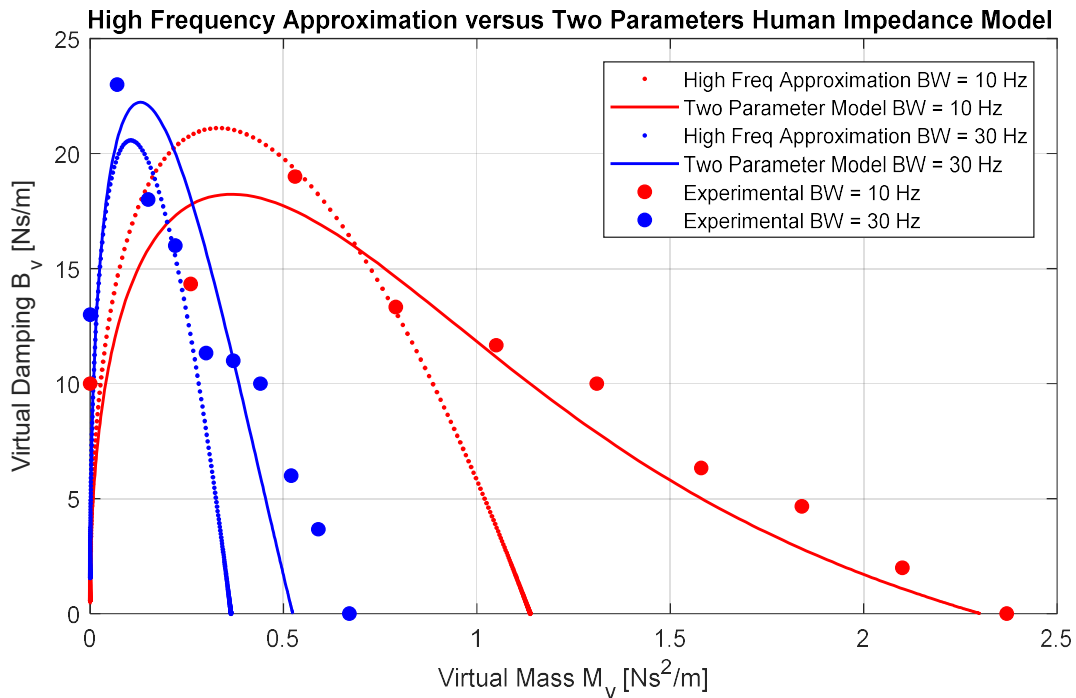| User	Adjusted Mass, Spring and Damper High Frequency Approximation Human Impedance Damping (b_h)			
	10 Hz Bandwidth	30 Hz Bandwidth	5 ms Delay	20 ms Delay
User 1	8	20	12	7
User 2	8	12	6	6
User 3	10	14	12	6
User 4	10	10	12	5
User 5	16	19	13	7
User 6	16	15	14	7

Figure 5. Comparison between the high frequency approximation human impedance model (dotted line) and two parameter human impedance model (solid line). For some users, the two-parameter human impedance model resulted in a better numerical fit of the stability region curves while rendering combination of mass and damping at two different position controller bandwidths (10 Hz – red and 30 Hz – blue).