Mini-trampoline vibration exciter- Force measurements

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ABSTRACT

A mini-trampoline has been previously used as a vibration exciter by Koss, et al for the structural excitation of a foot- bridge. The jumper on the mini-trampoline is “bobbing”, just not lifting off the membrane to provide dynamic force to excite a foot- bridge into vibration in order to determine the stiffness and natural frequency of the bridge. The stiffness and natural frequency were identified as being 10.4 MN/m and 10.6 Hz respectively.

Results of bobbing tests are presented to determine the accuracy of using a jumper’s inertial force, mass of person multiplied by the body acceleration at the hip position, as being the transmitted force to the structure on which the mini- trampoline is stationed. The tests consisted of using two people with body masses of 55 kg and 100 kg and only employing three supporting legs that were instrumented to measure force transmitted to the ground. The three measured force signals were summed and analyzed using Matlab® software. A fourth channel was used to measure hip body acceleration for the case of the accelerometer strapped to the hip using a kidney belt.

Analyzed data from the tests demonstrate that the first two inertial force harmonic amplitudes, fundamental and first overtone, compare well with the measured transmitted force amplitudes through the three legs for the 50 kg jumper. Comparisons for the 100 kg person were poor. Also, normalized force-frequency spectra will be presented to estimate what hip body acceleration is required for the jumper to just lift off from the trampoline membrane.

Keywords: Mini- trampoline, Force- vibration exciter, Structural vibration I-INCE Classification of Subjects Number(s): 48

1. INTRODUCTION

Mini-trampolines are an exercise device used by people that helps build stamina and muscles. A by product of a person exercising on a mini- trampoline is a set of harmonic forces that are generated that have frequencies which are about integral multiplies of the fundamental transmitted natural reciprocating frequency (NRF). The second by product is a high amplitude fundamental frequency force of about one kN for a 100 kg jumper that is bobbing without just lifting off the mini-trampoline membrane. The fundamental frequency can be made to vary between 1.8 Hz to 2.46 Hz by using rigid discs of different diameters on top of the membrane. Thus, a mini-trampoline can be considered as a low frequency vibration shaker that delivers a high amplitude fundamental frequency force and harmonics thereof and that can be used for testing of floors and bridges. As a result of project by Rhodes (1), transmitted and inertia force data were obtained that can be used to determine under what conditions measured inertia can be used as a substitute for measured transmitted force for the purpose of calculating frequency response functions of floor or bridge vibration. Koss et al (2) used a mini–trampoline to measure the stiffness of a foot-bridge that is located at Victoria University in Melbourne Australia that employed measured inertia force as the transmitted force to the bridge. The bridge stiffness was also measured firstly, by using dead weight of students to load the bridge at near mid-span with the bridge displacement measured using a dial gage attached to the bridge and to an adjacent structure, and secondly, by using a large custom-made impact hammer and accelerometer to

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measure a frequency response function. A comparison of the results of measured stiffness for the foot-bridge will be given by Koss and Rouillard in a later publication (3). The emphasis in this paper is on comparing measured inertia forces to measured transmitted forces to the ground to determine under what conditions the inertia force can be used accurately to calculate frequency response functions for the structure under test. Measuring inertia force requires much less instrumentation than by using force transducers under three legs of the mini- trampoline. An example of a mini- trampoline bridge test is shown in Figure 1.

Figure 1. Jumper on top of mini- trampoline membrane at centre of Victoria university foot-bridge.

2. MEASUREMENT PROCEDURE

2.1 Experimental Measurements

Experimental data presented in this paper were taken from three force transducers placed under the three legs of the min-trampoline and one accelerometer attached to the mid-section of the jumpers by a kidney belt. These four transducers, via appropriate signal amplifying equipment, were coupled to a PC fitted with a 12-bit data capture system controlled using Matlab®. Data were sampled at 2000 Hz per channel. The three channels of measured transmitted force were summed to obtain the total transmitted force to the structure. Both the total transmitted force and mid-body acceleration were subjected to Fourier analysis using the Matlab® ***abs(fft(time history))*** command with a square time window applied. A signal time duration of thirty seconds of jumping was employed for all tests. The DC body accelerometer was calibrated by turning it upside down against gravity, while the manufacturer’s sensitivity values were employed for the force transducers for force calculations.

A 55 kg mass and a 100kg mass jumper took part in the measurements with the mini-trampoline located on a very stiff laboratory floor. The jumpers were asked to bob up and down and just not lift off the disk that was located on the mini-trampoline membrane so that the force time signal was continuous. Time history signals for the measured transmitted force and the inertia force are very similar in appearance. As an example of time histories, typical inertial force and measured bridge deck vibration are shown in Figure 2; the top trace is the inertia force while in the bottom trace of Figure 2 a higher force harmonic of the transmitted force excites the natural frequency of the foot-bridge.

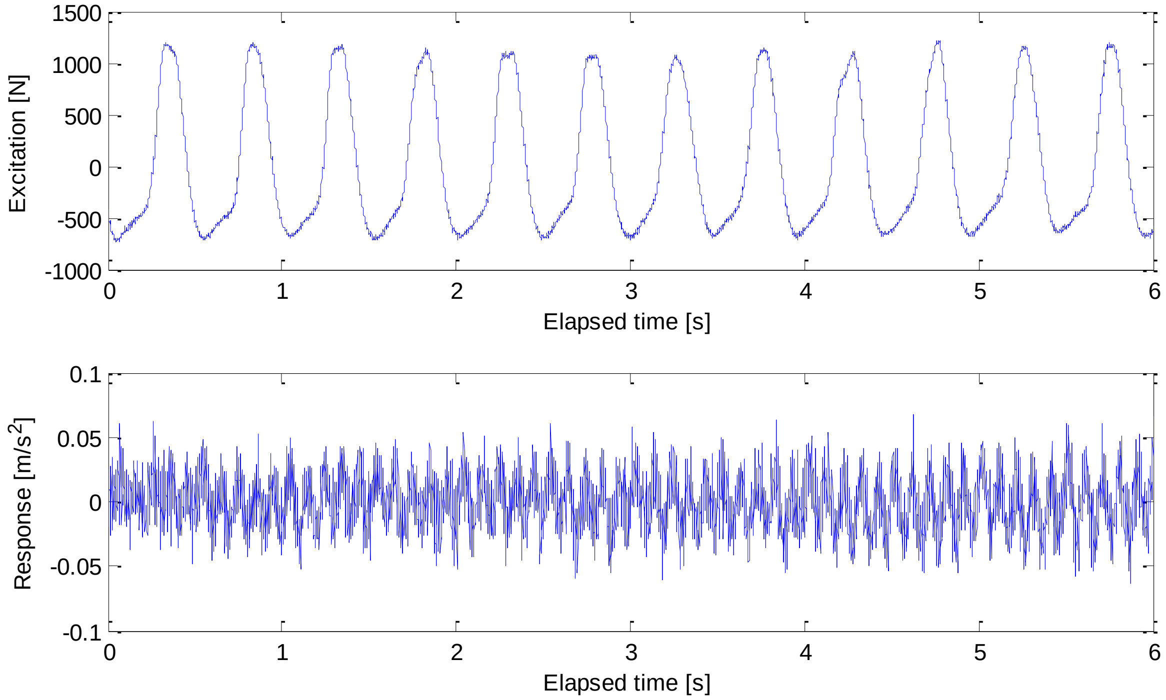

Figure 2. - Extracts of measured time histories from the Victoria University footbridge. Top: Inertial excitation force calculated by the product of acceleration measurements at the hip position and jumper mass; and bottom: measured bridge deck acceleration. The top trace displays the fundamental reciprocating frequency of 2 Hz and the bottom trace displays the structural natural frequency of 10.6 Hz

3. Results of in- laboratory measurements

3.1 Calculated results

The following data were calculated for the analysis:

- Frequency spectra of measured transmitted force
- Frequency spectra of hip acceleration to calculate inertia force
- Mean values and standard deviations of fundamental frequency force and fundamental frequency hip accelerations
- Mean values and standard deviation of fundamental frequency

3.2 Results

The purpose of this paper is to compare the frequency spectral amplitude of the measured transmitted force to the measured inertial force as calculated by the multiplication of the acceleration frequency spectrum measured at hip position by mass of a jumper. A full set of data will be given for the 100 kg jumper, and a final set of data will be given for the 55 kg jumper. Transmitted force frequency spectra for the 100 kg jumper for four disk sizes on the membrane are given in Figure 3; the spectra show that the fundamental frequency increases with increase of disk diameter and the peak fundamental frequency amplitude is less than 1000 N.

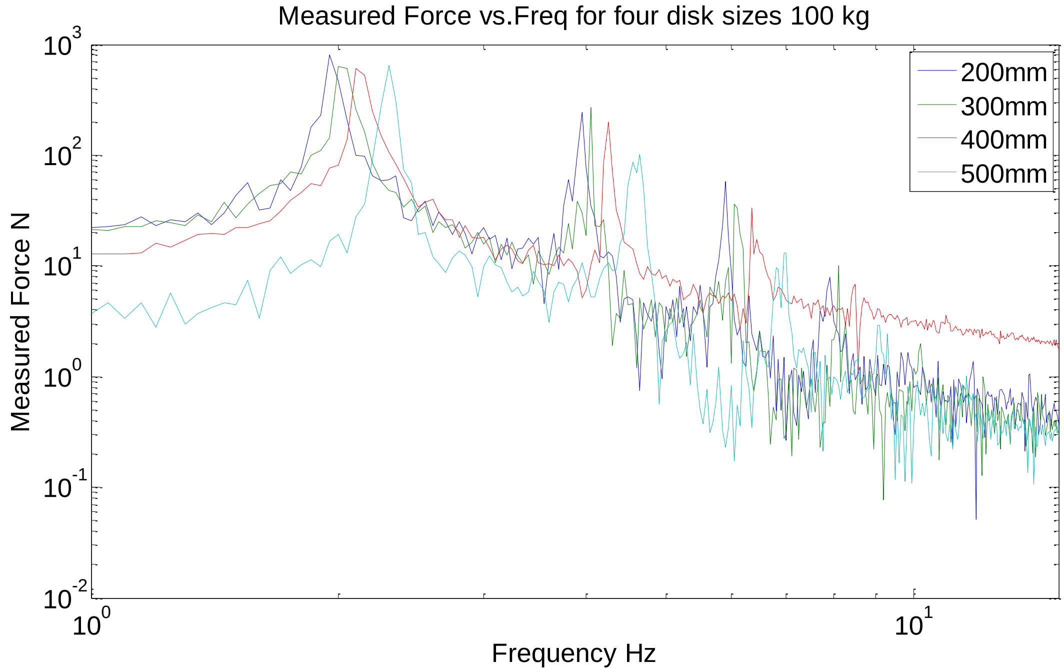

Figure 3. Measured transmitted jumper force frequency spectra for the 100 kg jumper for four disk sizes on the mini- trampoline membrane. Only a single spectrum is shown for each disk size

Statistical data for five jumping tests for each disk size and for the 100 kg jumper the data are given in Table 1. Although the jumper was asked not to just lift off the trampoline, the data in column 3 of Table 1 demonstrates that approximately average 1000 N peak fundamental frequency force only occurred for one of the five disk sizes, i.e. 600 mm. The lowest average fundamental frequency force amplitude is 603 N for the 500 mm disk. Data in column 5 of Table 1 demonstrate that the tests were consistent.

Table 1 – Statistical results for measured transmitted force to ground with a 100 kg jumper bobbing (and just not lifting off) on mini- trampoline with 200 mm to 600 mm disks on membrane. Five tests were undertaken for each disk size

	Spectral peak amplitude				Fundamental Frequency	
Disk diameter	**Greatest of five samples**	**μ (Mean)**	**σ (Std. Dev.)**	**σ / μ**	**μ (Mean)**	**σ (Std. Dev.)**
[mm]	**[N]**	**[N]**	**[N]**		**[Hz]**	**[Hz]**
200	1016	888	92	0.10	1.89	0.02
300	966	888	139	0.19	1.94	0.02
400	881	731	106	0.14	2.12	0.03
500	715	603	110	0.18	2.26	0.02
600	1023	946	107	0.11	2.46	0.04
Average:	920	783	112	0.14	----	0.03

Data in Table 1 demonstrates that the force fundamental frequency increases with disk size and that the mini-trampoline that was used has a fundamental frequency range that can vary between 1.89 Hz and 2.46 Hz (VR: there is no 2.61 Hz in the table) when a 100 kg jumper is on board the mini-trampoline.

Statistical results of measured hip acceleration are given in Table 2 for the 100 kg jumper and to obtain inertia force values multiply acceleration amplitudes by 100 kg. The mean value of 5 spectral peaks for three out of five disk sizes disk sizes are less than 1 g (9.81 ms^{-2}), while the mean value for the 200 mm disk size is 1 g and for the 600 mm disk size is much greater than 1 g. However, for a total of 25 tests the jumper never lifted off the wooden disk on the membrane.

Table 2 – Statistical results for measured hip position acceleration spectra with a 100 kg jumper bobbing (and not lifting off) on mini-trampoline with 200 mm to 600 mm disks on membrane. Five tests were undertaken for each disk size. To obtain inertial force multiply accelerations by 100 kg.

	Spectral peak amplitude				Fundamental Frequency	
Disk diameter	**Greatest of five samples**	**μ (Mean)**	**σ (Std. Dev.)**	**σ / μ**	**μ (Mean)**	**σ (Std. Dev.)**
[mm]	**[m/s^2]**	**[m/s^2]**	**[m/s^2]**		**[Hz]**	**[Hz]**
200	10.8	9.8	1.1	0.11	1.89	0.06
300	11.3	9.0	1.5	0.17	1.94	0.02
400	10.3	8.7	1.2	0.14	2.12	0.02
500	8.4	7.4	1.2	0.16	2.26	0.03
600	13.6	13.0	1.1	0.08	2.46	0.04
Average:	10.9	9.6	1.2	0.13	---	0.03

Data given in Table 3 gives the percentage difference between the measured hip acceleration and that calculated by dividing the transmitted force by the body mass of the 100 kg jumper. The results given in Table 3 indicate that only for the 200 mm disk for the fundamental frequency and for the first overtone is the percentage difference less than ten percent. All, the other results are unacceptable. Thus for this 100 kg jumper transmitted force should be measured by using force transducers under the min- trampoline legs.

Table 3 - Percentage difference between measured hip accelerations and that computed from (measured transmitted force)/(body mass) are presented in this table. Results are for 100 kg jumper and calculated from peak value from five tests. (otone is overtone).

	Difference [%]			
Disk diameter	**Fundamental**	**1st otone**	**2nd otone**	**3rd otone**
[mm]				
200	6.49	-7.42	61.72	140
300	17.39	10	132	381.81
400	16.79	15.17	140.47	140
500	16.92	4.09	144.44	162.50
600	33.33	16.84	155.10	1857.14
Mean difference [%]:	18.18	7.73	126.75	536.29

Data presented in Table 4 are for the same ratio *(measured transmitted force)/(body mass)* as that given in Table 3 except the data are for the 55 kg jumper bobbing on the mini- trampoline. Percentage differences are acceptable for the fundamental frequency and first overtone frequency amplitudes for the four disk sizes so that a hip accelerometer is acceptable for this size jumper. It would seem that all degrees of freedom or body parts are moving in phase. With out further detailed analysis, the heavier individual, 100 kg jumper, may have body parts that are not moving in phase with the hip accelerometer or all human degrees of freedom of the body are not moving in phase. This may explain the difference in results for both jumpers. Thus, a hip accelerometer can replace the force transducers for the 55 kg jumper but not for the 100 kg jumper.

Table 4 - Percentage difference between measured hip accelerations and that computed from (measured transmitted force)/(body mass) are presented in this table. Results are for 55 kg jumper and calculated from peak value from five tests. (otone is overtone).

	Difference [%]			
Disk diameter [mm]	**Fundamental**	**1st otone**	**2nd otone**	**3rd otone**
200	3.72	6.07	-5.55	51.11
300	1.99	4.04	-6.12	233.33
400	8.36	6.35	44.44	188.88
500	2.12	-3.34	60	200
600	4.05	3.28	23.19	168.33
Mean difference [%]:	3.72	6.07	-5.55	51.11

3.3 Normalized data

The graphical data shown in Figure 3 can be presented in a normalized format by dividing the horizontal frequency axis values by the "natural" frequency at which the jumper bobs up and down and the vertical axis force values by the mass of the jumper multiplied by the gravitational constant 9.81 ms^{-2}. A view of some of the calculated normalized values is given in columns 5 and 6 of Table 5.

Table 5 -Fundamental natural reciprocating frequency, peak jumper transmitted force and normalized data are given in this table for both jumper masses.

Jumper mass [kg]	Disk diameter [mm]	NRF (Fund. Freq.) [Hz]	Peak force amplitude at NRF [N]	Normalized NRF	Normalized force* amplitude at normalized NRF [N]
55	200	1.95	620.5	1	1.15
55	300	2.30	517	1	0.96
55	400	2.45	572	1	1.05
55	500	2.68	359	1	0.67
100	200	1.89	888	1	0.91
100	300	1.94	746	1	0.76
100	400	2.12	731	1	0.75
100	500	2.26	604	1	0.62
100	600	2.46	946	1	0.96

* transmitted force / mg

Although the jumpers were instructed just not to lift off the disk on the mini-trampoline membrane the data in Table 5 (last column) demonstrates that a quite large variance in the normalized peak force and thus peak acceleration at the fundamental natural frequency existed. A complete view of normalized transmitted force spectra is given in Figure 4. The overtone frequencies and force amplitudes do not match as well as those at the fundamental frequency and is most probably due to slight variations in the natural reciprocating frequency.

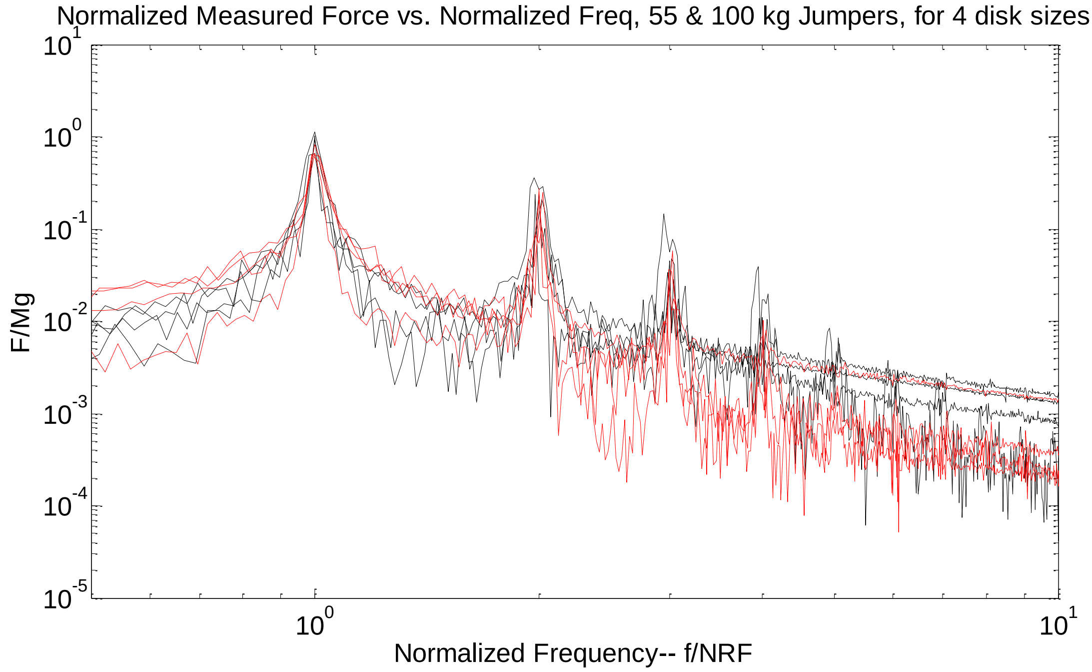

Figure 4. Eight normalized transmitted force spectra are shown in this figure for the two jumpers that generated the forces while bobbing and just not lifting off.

4. CONCLUSIONS

Data presented in this work demonstrates that tonal high amplitude low frequency forces can be developed and transmitted to a floor or bridge deck by a jumper bobbing on a mini-trampoline. The force amplitude is on the order of 0.5 kN to1 kN and the fundamental frequency can be made to vary between 1.9 Hz and 2.6 Hz by choosing an appropriate disk size to be placed on the membrane of the min-trampoline.

Measured transmitted force spectra amplitudes and inertial force spectra amplitudes for the fundamental frequency and first overtone agree well for the 55 kg jumper whereas large disagreement exists for the 100 kg jumper. Thus, an accelerometer can be used in place of three force transducers to compute the transmitted force to a floor by multiplying the acceleration by the jumper mass for the 55 kg jumper.

Much further work is required to develop a Mini-trampoline into a standard testing device but obtaining tonal high amplitude low frequency forces for a very small cost is a very worthwhile effort.

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