THE EFFECT OF PEOPLE JUMPING ON A FLEXIBLE STRUCTURE

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ABSTRACT

This paper addresses the effect of humans jumping on flexible structures which move perceptibly. A unique test rig, developed at the University of Manchester to permit a person to jump on an idealised single degree of freedom system with variable natural frequency and mass, is described and the test methodology explained. A set of results, for different rig natural frequencies (2-6 Hz) and a range of jumping frequencies (1-3.5 Hz), is presented to show the effect of the flexibility of the structure on the levels of force and response that can potentially be generated by humans. The acceleration response shows peaks when the jumping frequency is in the region of half the natural frequency and the natural frequency itself which indicates that the 1st and 2nd harmonic of the human-induced forcing functions are exciting rig's resonance. However, it is shown that for the configuration chosen, it is not possible to jump at exactly the natural frequency of the rig. It is also apparent that the contact ratio, determined from the jumping force time history, increases as the natural frequency reduces. As a consequence, the amplitude of the force harmonics also vary with the natural frequency.

NOMENCLATURE

f_{JA}	Jumping frequency achieved
f_{JT}	Jumping frequency targeted
f_P	Platform natural frequency
α	Contact ratio

INTRODUCTION

There is currently a considerable interest in the UK in the effect that people can have when moving upon flexible structures whose motion can be perceived [1]. In particular, this issue has emerged in recent years due to the changing nature of the design of sports stadia, where long span and cantilevered seating decks are becoming more popular because of the improved sight lines offered to spectators. There has also been a tendency to view stadia as multi-purpose venues, with the possibility of gaining additional income from pop concerts.

The effect of these changes is that modern stadia have low vertical natural frequencies, often in the 2-4 Hz range. Such low frequencies are in the range that may be excited by crowds undergoing sudden or rhythmic motion, the most severe being ‘bouncing’ (where the person is in continuous contact with the structure) or ‘jumping’ (where the person is airborne for some of the time). These motions can occur most strongly around 2-3 Hz. It is well known that the ‘near periodic’ force time history generated when someone jumps may be represented by a series of harmonics, so jumping at 2 Hz will cause harmonic excitation components at 2, 4 and 6 Hz. Thus, the potential exists for the seating deck structure to respond dynamically at one or more of these frequencies, depending upon its natural frequencies. In the UK, design guidelines have been laid down for such problems. For example, the Green Guide to Safety at Sports Grounds [2] states that:

> ”…where a seating deck has a vertical frequency of less than 6 Hz (…) a dynamic evaluation of the structure should be carried out, giving due consideration to the mass of spectators (…) at grounds staging pop concerts or other events involving rhythmic activity, design loads may be greater”.

On the other hand, British Standard 6399 Part 1 [3] states that:

> “…dynamic loads are only significant (…) where movement is synchronised (…) in practice, *this only occurs in conjunction with strong musical beat such as at pop concerts or aerobics* [italicised by the authors of this paper] (…) where significant loads are expected, either design to withstand anticipated loads (limited guidance given in Annex A) or else design by avoiding significant resonant effects (vertical frequency above 8.4 Hz – empty structure)”.

The section in italics above has recently been shown to be misleading. An incident occurred at Liverpool FC in 2000 where significant motion was observed under action of a crowd that was not animated by music and for a seating deck whose vertical natural frequency was found to be only 2 Hz. Many other stands in the UK have relatively low natural frequencies (3-4 Hz), either because they were constructed before guidance was available or because the guidance given in Annex A of BS6399 is currently viewed by many designers as over-conservative and somewhat detached from reality. A similar approach presented in the Canadian code [4] leads to a smaller predicted response, but only because the severity of the anticipated jumping activity is reduced.

The jumping force time histories, presented in Annex A of BS6399 [5-6], are based on the half sine pulse loading. Unfortunately, the only structure for which any validation of this loading model was attempted was a simply supported concrete beam with a natural frequency around 18 Hz. This beam 'feels' extremely rigid for someone jumping at 2Hz. Other experimental measurement of loads produced by people jumping [7-8] took place on rigid floors. It is believed that the nature of the loading that a person introduces to a structure will depend strongly upon the flexibility of the structure and the ability of test subjects to feel the motion. It is also anticipated that the ability of a group to act in a coordinated manner is likely to improve for more flexible structures which motion is perceived, as recently demonstrated in the case of highly publicised excessive lateral sway motion of the Millennium Bridge in London.

In the UK, a national Joint Working Group under the auspices of the UK Institution of Structural Engineers (IStructE) and two government departments (Office of the Deputy Prime Minister – ODPM and Department for Culture, Media and Sports – DCMS) was set up in 2000 to examine this whole problem. So far, Interim Guidance [9] has been issued to provide minimum natural frequencies for new and existing designs. Special treatment is necessary for any existing stadium lying below this threshold. It is hoped in 2003 to provide new guidance for calculation of the dynamic response of flexible structures to crowd loading.

This paper follows initial work [10] and presents results from a series of tests performed by a subject jumping at a range of frequencies on a platform having different natural frequencies.

TEST RIG

In order to understand the interaction between a person and a flexible structure, a fundamental test rig needed to be constructed, where the structure behaved essentially as a single degree of freedom system with motions in other directions constrained to be zero.

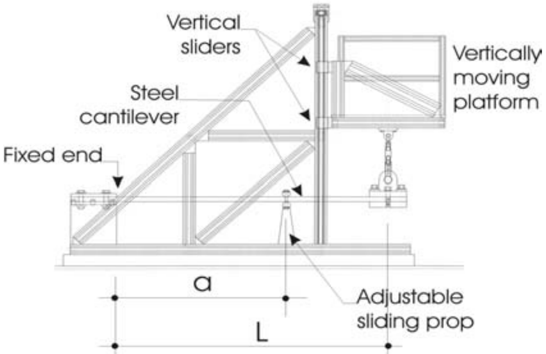

Fig. 1 Rig for Jumping

Fig. 1 shows the test rig designed for this purpose. A support structure carries vertical rails upon which a horizontal platform slides up and down on rollers with low friction. The stiffness required to provide a restoring force to the platform when it moves up or down is provided by a high tensile steel cantilever spring, with an adjustable prop used to vary the natural frequency.

The platform is guarded on all sides so as to prevent any serious accident occurring if the person were to fall. The platform mass for the initial configuration to be tested is 180 kg. The range of natural frequencies for which the support structure was designed is 1.5–6 Hz.

The rig is instrumented as follows. The platform vertical acceleration is measured using a Honeywell QA-700 accelerometer and the corresponding displacement using an RDP DCTH-15000C LVDT. The force in the vertical link just below the platform is measured using an Entran ELHS-T4M-10KN force transducer.

An AMTI OR6-6 force plate is embedded within the platform floor so as to provide measurement of the vertical force produced by the subject jumping, as well as horizontal force components and moments. In this case the inertia force associated with the 'active' mass of the force plate (5 kg) needs to be subtracted from the measured vertical force. An additional estimate of the applied vertical force was found from the force in the link by subtracting the platform inertia force which can be deducted from the known mass and measured acceleration [10]. However, the force plate was found to produce better quality time histories than the force link, particularly where the test subject was not in contact with the platform.

Data were acquired using a PC-based multi-channel National Instruments system with LabVIEW software. It should be noted that all instrumentation was deliberately chosen to operate down to DC, so as to avoid any amplitude and phase errors at the very low frequencies to be considered, especially given that signals had to be combined in different ways.

INITIAL TESTS

One critical issue is whether there are any modes of vibration with significant motion at the position of jumping that will make the rig behave differently to a single degree of freedom system. A modal test was performed, both by exciting the frame with a modal hammer, and by exciting the platform in the vertical direction using an electrodynamic shaker. Several sway (i.e. lateral) modes were found above 15 Hz but these are unlikely to be excited by the small horizontal components of force that will be generated by any person on the platform. However, the first mode with significant vertical motion at the jumping position was above 90 Hz. It may be shown theoretically that this is not likely to be a problem for the excitation frequencies concerned. Considering all this, the platform can realistically enough be assumed to be a single degree of freedom dynamic system.

Of more concern was the behaviour of the platform mass moving as a rigid body upon the cantilever spring in the vertical mode of vibration which was of interest. A swept sine excitation was applied across a narrow frequency band around this mode at different excitation levels and some degree of non-linearity was noted. The behaviour of the Frequency Response Function (FRF) corresponded to what might be expected were friction to be present. Whilst the friction levels experienced by a person standing upon the rig and trying to initiate motion seemed to be negligible, there was a noticeable effect on the FRFs produced at the comparatively low force levels introduced in the modal test.

Given that some relative motion is present in the vertical sliders, in the bearings at each end of the vertical link and in the clamps at the beam root and prop positions, it is considered inevitable that some friction will be present. At this stage, it is considered that the level of friction is not a cause for concern. Measurements of the overall equivalent friction force yielded a value of approximately 40 N which is small and only about 2% of the jumper's weight, or about 1% of the peak force measured. Free decays of the platform motion following a disturbance were very smooth and only a single frequency was apparent. Damping was estimated from a curve fit to the free decay and was around 4% critical.

JUMPING TESTS OVER A RANGE OF FREQUENCIES

Some results will now be presented for several different values of the vertical natural frequency of the platform (flexible at 2, 2.5, 3, 3.5, 4, 5 and 6 Hz and 'pseudo-rigid' at 16 Hz). The test subject aimed to jump at a range of frequencies between 1.0 and 3.5 Hz, with the aid of a metronome. However, these so-called 'targeted' jumping frequencies were not always met so the term 'achieved' jumping frequency (f_{JA}) was adopted to correspond to the frequency of the first spectral peak (i.e. of the fundamental harmonic) in the force time history. In addition to tests where a particular jumping frequency was sought, other tests were performed where the subject was asked to jump 'freely' (i.e. at a frequency that felt most comfortable to them for the platform configuration under test) and also where the subject 'bounced' on the platform; however, these results are being currently processed and will not be presented in this paper.

The mass of the test subject is 75 kg and in the figures which will be referred to in the remainder of the text, all force measurements shown are normalised to the subject's weight. As the moving mass of the platform is 180 kg, the subject/platform mass ratio is approximately 0.41. As to the graphics in this paper, all platform acceleration results are normalised to a gravitational constant 'g'.

For each test, the subject sought to maintain a steady jumping motion for about 20 s. Once the test was complete, a portion of the time history was selected where the force and responses exhibited near steady-state behaviour. This data was then processed to yield maximum and minimum values in the time domain, jumping contact ratio and values of the first, second and third harmonic peaks in the Fourier spectra. Some sample results are shown in Figure 2 for jumping at 2 Hz on a 4 Hz platform and in Figure 3 for attempting to jump at 2 Hz on a 2 Hz platform, but only achieving 1.8 Hz (the result is close to 'bouncing'). Accelerations of 1.5–2 g were achieved.

JUMPING FREQUENCY RESULTS

The ability of the subject to achieve the targeted jumping frequencies is shown in Figure 4 where the ratio f_{JA}/f_{JT} is plotted against the achieved jumping frequency normalised by the platform natural frequency. In interpreting this figure, it should be noted that the frequency resolution of the frequency spectra is of the order 0.25-0.125 Hz because of the limited amount of steady-state data available (typically 4–8 s).

What is apparent from Figure 4 is that the test subject was unable to jump at frequencies very close to the lower platform natural frequencies (2, 2.5, 3 and 3.5 Hz – higher frequency jumping is physically difficult and was not attempted). The flexible 'feel' of the platform meant that it was not possible to 'take off' and maintain jumping at these frequencies. Indeed, in some cases the achieved frequency may be approximately 20% below or 10% above the targeted frequency.

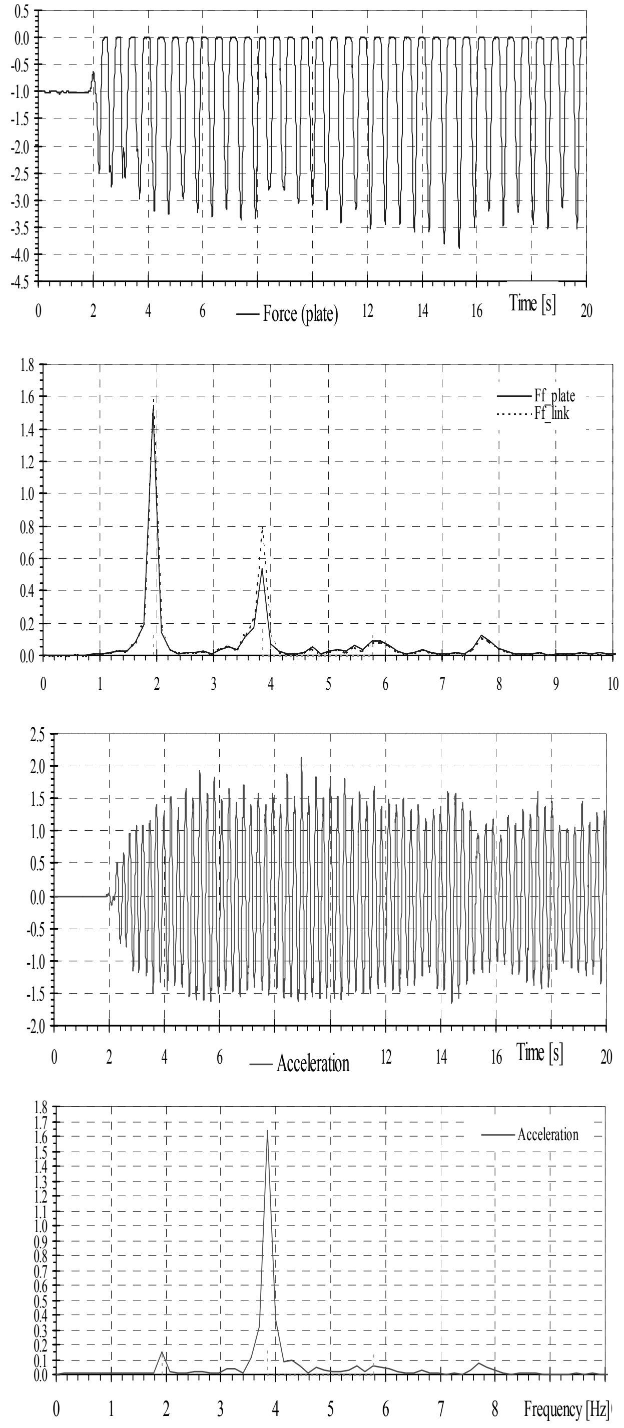

Figure 2 Time histories and spectra for jumping at 2 Hz on a platform with natural frequency of 4 Hz

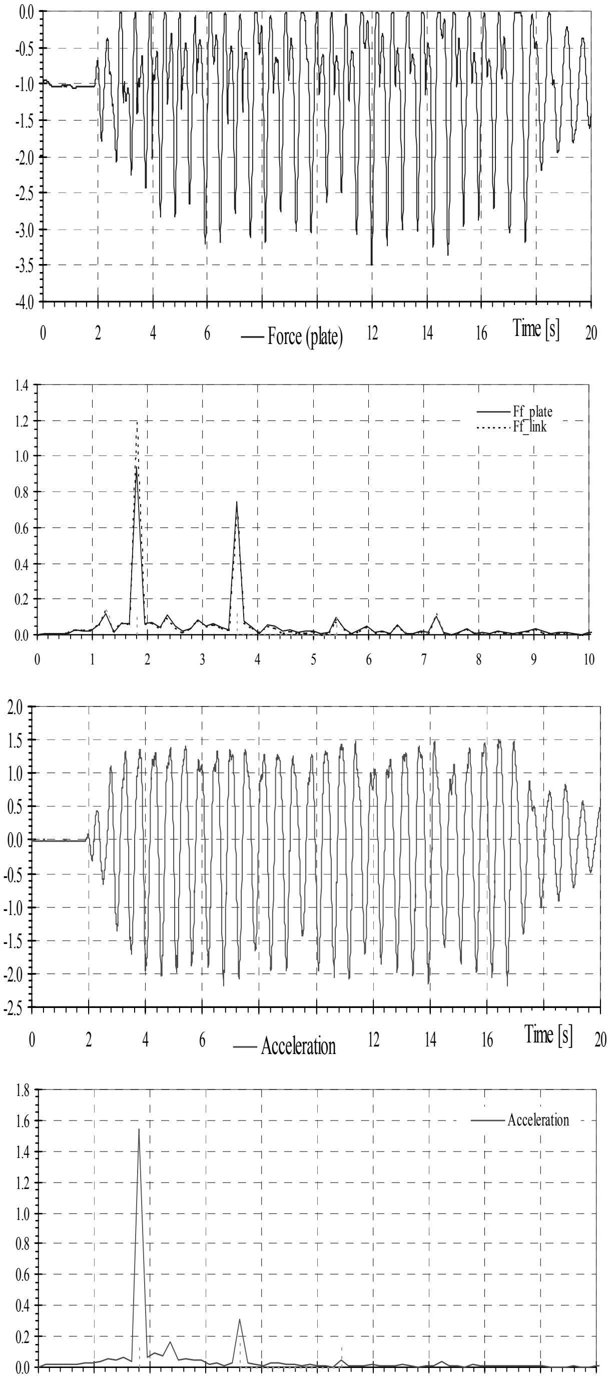

Figure 3 Time histories and spectra for attempting to jump at 2 Hz on a platform with natural frequency of 2 Hz (achieved frequency was only 1.8 Hz)

The reason for this interesting behaviour is not yet fully understood but it is supported by early theoretical studies on a method for predicting human-structure interaction. It may be that higher platform mass and/or higher damping would reduce this effect. It should be noted that when the subject sought to 'bounce' on the platform (i.e. move up and down whilst remaining in contact with the platform – results of this exercise are not reported here), it was possible to achieve the targeted frequency.

CONTACT RATIO RESULTS

When a subject jumps, the contact ratio (α) is defined as the proportion of jumping cycle duration that the subject is in contact with the structure. Because the average force must be equal to the subject's weight, a low contact ratio corresponds to jumping where the force peak is high whereas a high contact ratio corresponds to a much lower force peak. In Annex A of BS6399 [3], force histories are defined for several contact ratios, namely 1/4 (high impact jumping), 1/3 (normal jumping), 1/2 (rhythmic exercise) and 2/3 (low impact jumping). Because no formal tests have ever been reported for jumping on flexible structures, these definitions are believed to correspond to jumping on rigid surfaces.

In the tests carried out here, the contact ratio was estimated from the force time history by determining the time for which the force lay below a low percentage (typically 5-10%) of the peak force. The contact ratios for the entire set of tests at all the natural and jumping frequencies are presented in Figure 5 as a function of f_{JA}/f_P. What is interesting is that a wide range of contact ratios was determined, but none were below 1/2. This is an interesting observation compared with what is suggested in BS6399 [3], which is, apparently based on results of jumping tests on rigid surfaces. Also, as a general trend, the contact ratio increased as the platform natural frequency reduced, i.e. the motion tended towards more of a 'bounce' type at the very low platform frequencies. It is also apparent that there is an increase of contact ratio in the region where jumping occurred at around half the platform natural frequency. This is, almost certainly, as consequence of the greater motion of the platform excited in resonance by the 2^{nd} harmonic of the jumping force. Figure 5 clearly demonstrates that it was not physically possible to achieve contact ratio results for equal jumping and platform frequencies. Again, many of these features are being seen in the theoretical study, but are yet to be fully understood.

Overall, contact ratio was found to vary between 1/2 and 1 for flexible platforms. Indeed, the contact ratio did not fall below 1/2, even for the platform with a natural frequency of 16 Hz ('pseudo-rigid'). It is yet to be seen whether test subjects can adapt their jumping motion to a specific pre-determined contact ratio for a given natural frequency and the corresponding amount motion which is perceived. Early results so far indicate that it is likely that this is very difficult to do and that a test subject feeling vibration 'automatically' selects only the contact ratio he/she is most confortable with when jumping.

FORCE RESULTS

The variation of the first and second harmonics of the force are presented in Figure 6 as a function of f_{JA}/f_P. These results are extracted from the force spectral peaks at the achieved jumping frequency and twice its value.

As seen in Figure 6 (left), the bulk of the first harmonic results lie between 1.2 and 1.7 (normalised to weight of subject). These values correspond to contact ratios in the range 0.7 to 0.4 for the BS6399 half sine force model [3]. However, for jumping at half the platform natural frequency and close to the natural frequency, the first harmonic falls to values between 0.4 and 1, corresponding to contact ratios between 1 and 0.8 (i.e. almost ‘bouncing’).

The second harmonic of force in Figure 6 (right) varies from 0 to 1, corresponding to contact ratios in the BS6399 model between 0.8 and 0.4.

The maximum values of force from the time domain results will depend upon the combination of several harmonics where phase may differ. However, results are shown in Figure 7 and it may be seen that the maximum force varies between 1.8 and 4 times the subject weight, commensurate with the change in contact ratio. There is some noticeable reduction in force level around values f_{JA}/f_P ratio of 1/2 and 1.

What is clear is that the variation of contact ratio found in these tests means that the force harmonic values vary considerably with the f_{JA}/f_P ratio and with the platform natural frequency f_P itself. It is therefore not possible to simply adopt a set of values from the BS 6399 Annex A for a particular type of jumping (e.g. normal jumping). Instead, if a BS6399 approach were to be adopted – and it is by no means certain yet whether this is sensible – then the appropriate contact ratio would need to be chosen and the corresponding force time history determined in the case when it is expected that people may perceive motion of the structure on which they jump or ‘bounce’.

ACCELERATION RESULTS

If the acceleration response of the test structure is assumed to be periodic, amplitudes of its first two harmonics are presented in Figure 8 for a range of tests. The first harmonic results are increasing as the frequency ratio approaches 1 (i.e. jumping near to natural frequency); the results look rather like part of a classical frequency response curve, except that the apparent peak could not be reached, as previously observed. It is interesting that the results for the different platform natural frequencies f_P almost overlay. This is not unreasonable given that most of the first harmonic force values are fairly similar when $f_{JA}/f_P<0.9$ (Figure 6, left) and the appropriate expression for the acceleration response of a single degree of freedom system, expressed as a function of a non-dimensional ratio of the excitation and natural frequencies, shows that results would then collapse onto one curve for constant damping values (Figure 8, left).

It may be seen from Figure 8 that the second harmonic of acceleration peaks when the jumping frequency is around half of the natural frequency, again with a ‘resonance-like’ appearance. The acceleration harmonic values are somewhat larger for the higher natural frequencies, perhaps because the jumping frequencies are higher (2 Hz or more) and easier to achieve than the values of 1 – 1.5 Hz required to provide excitation at half the lower natural frequencies.

Finally, overall acceleration results are presented in Figure 9, with each maximum value extracted from the time history. This figure shows peaks around values of the f_{JA}/f_P ratio of 1/2 and 1, and possibly even at 1/3 where the third harmonic may excite higher values of the fundamental natural frequency of the platform. What is interesting is that the peak acceleration values are similar in the two peak regions whereas it might be expected that the response would be larger near to the natural frequency – perhaps this is because it has not been possible to excite the perceptibly moving structure at the natural frequency where much larger responses might occur.

CONCLUDING REMARKS

The effect of varying the jumping frequency for a range of natural frequencies of the test rig has been examined for a particular combination of mass ratio and damping ratio. It has been seen that it is not possible to jump at exactly the natural frequency of the structure which moves perceptibly. It is also apparent that the contact ratio varies with natural frequency, increasing as natural frequency reduces; contact ratios were not achieved below a value of 1/2 in contrast with the values of 1/4 and 1/3 quoted in BS6399. The corresponding force harmonic values show a range of values consistent with the BS6399 harmonics for similar contact ratios. The acceleration response and its harmonics showed peaks to occur when the jumping frequency was equal or near to the natural frequency or half its value. Finally, the acceleration harmonics were very consistent between different natural frequencies, indicating some non-dimensional behaviour.

ACKNOWLEDGEMENTS

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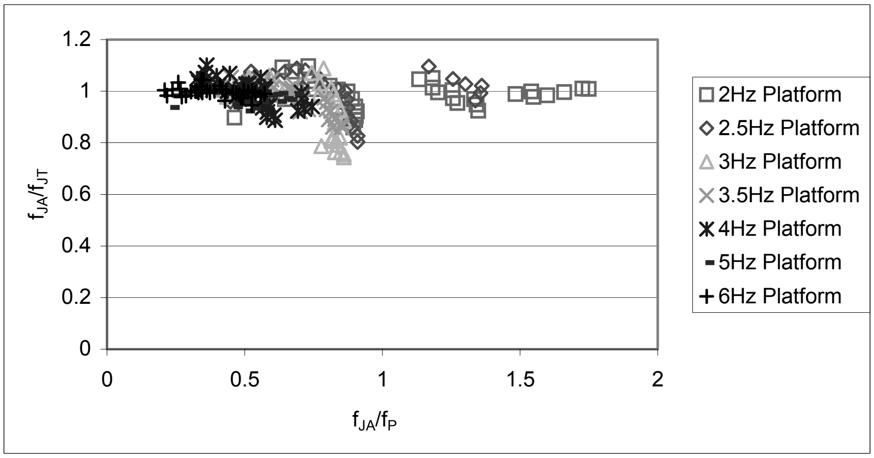

Figure 4 Variation of the f_{JA}/f_P versus f_{JA}/f_P ratios.

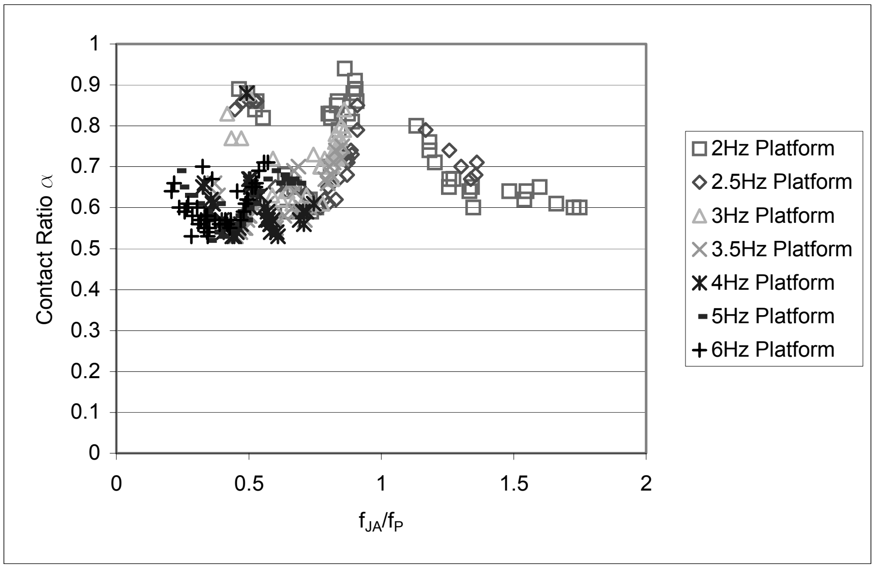

Figure 5 Variation of contact ratio with the ratio of the achieved jumping frequency and platform natural frequency.

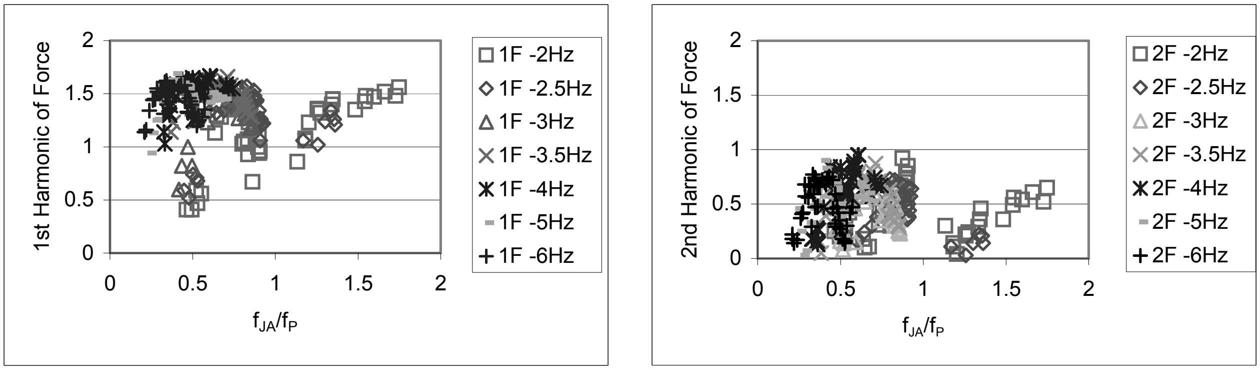

Figure 6 Variation of first and second harmonics of force with the ratio of achieved jumping frequency and platform natural frequency

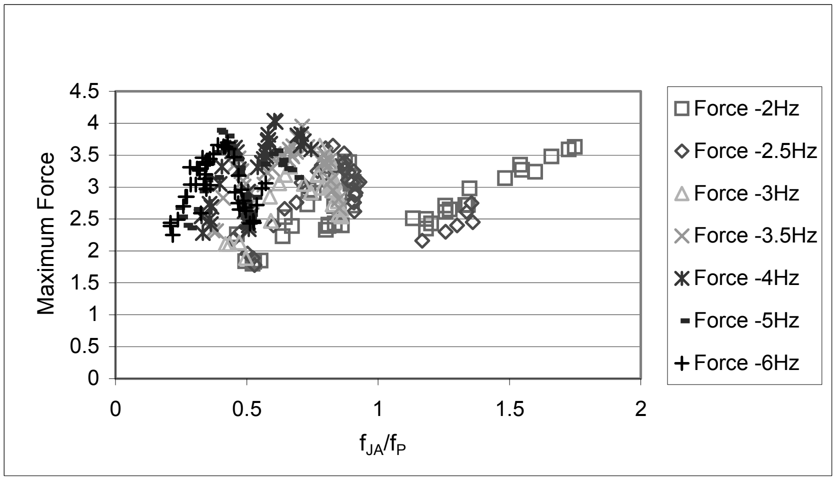

Figure 7 Variation of peak measured force with the ratio of achieved jumping frequency and platform natural frequency

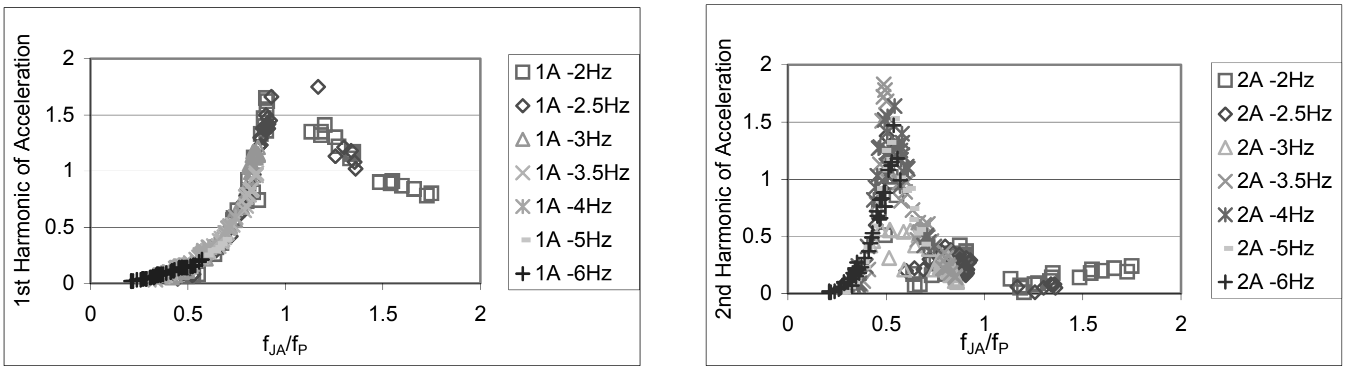

Figure 8 Variation of first and second harmonics of acceleration with the ratio of the achieved jumping frequency and platform natural frequency.

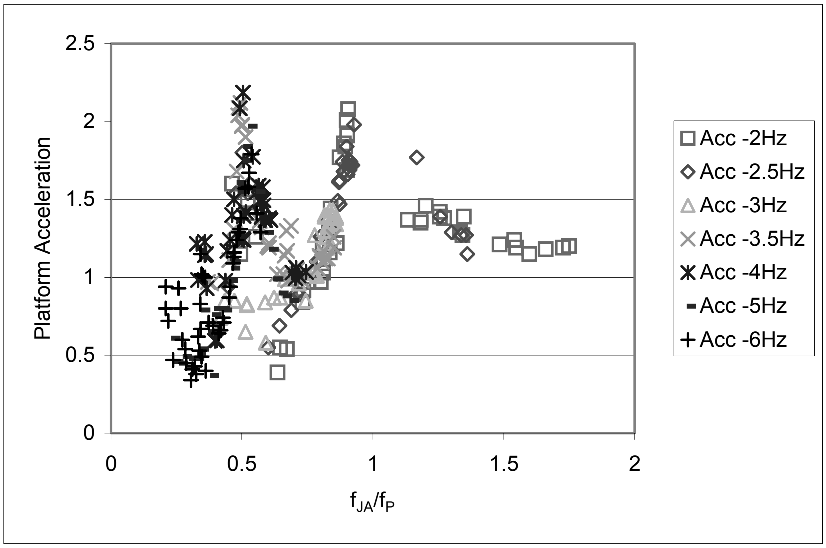

Figure 9 Variation of maximum acceleration with the ratio of the achieved jumping frequency and platform natural frequency.