

VANDALISM PREVENTION OF A FOOTBRIDGE WITH CABLE VIBRATIONS

Thomas CANOR

Research Fellow, PhD student
F.R.S-FNRS
Liège, Belgium
T.Canor@ulg.ac.be

Gaëtan KERSCHEN

Professor
University Of Liège
Liège, Belgium
G.Kerschen@ulg.ac.be

Vincent DENOËL

Associate Professor
University Of Liège
Liège, Belgium
V.Denoel@ulg.ac.be

Summary

This work studies an unusual way to improve comfort of a footbridge with cables. Cables can be seen as a means of dissipating energy in a structure. This complementary source of dissipation does not prohibit resonance from taking place, but it is a way to limit vibrations and to impede vandals' actions. This study is illustrated with measurements realized on a specific footbridge. This structure is a metallic arch characterized by a first natural frequency of 3.2Hz and a corresponding damping ratio of 0.55%. Intolerable accelerations (around 6m/s²) are easily reached when an ill-intentioned person is bouncing at an appropriate frequency. After installation of a single cable at a suitable location in the structure, the measured damping ratios are almost doubled and the maximum accelerations at resonance are reduced by 30%. With three cables on the footbridge, the damping ratio becomes significantly nonlinear: it reaches up to 3% for low amplitude oscillations, but drops down to 1% for moderate to high amplitudes. For higher accelerations, it does not seem to depend on the number of cables. According to these observations, a notable effect of cables is to reduce the maximum acceleration, but the main effect is to prolong the transient phase and to make the resonance frequency hardly identifiable by vandals.

Keywords: dynamic; cable vibrations; experimental; vandalism.

1. Introduction

Aiming at aesthetic and structural performance, architects and engineers try to design lighter and therefore more flexible structures. Steel structures offer a number of design possibilities to meet these demands. Nevertheless, the consequence is a greater susceptibility to undesired dynamic excitations. To avoid excessive vibrations that could lead to uncomfortable acceleration levels or to detrimental damage, some recommendations have to be fulfilled. One of these recommendations is to avoid natural frequencies of footbridges to fall within critical ranges. For transverse vibrations, the range is between 0.5Hz and 2Hz and for vertical vibrations a first range is between 1.25Hz and 2.3Hz and a second one between 2.5Hz and 4.6Hz [1]. This second range may be excited by the second harmonic component of walking or bouncing [1,2]. Natural frequencies indicate immediately if a structure is easily excitable.

Although frequencies are easily calculated by designers, damping ratios ξ are more difficult to evaluate at a design stage. It can just be approximated (e.g. 0.4% or 2% for steel structures respectively for weak or strong vibration levels). This ratio is a key characteristic of the dissipation within structures [3]. From a comfort point of view, the greater the damping, the nicer walking on the bridge. From a human-structure interaction point of view, ill-intentioned persons have more physiologic difficulties to identify structural frequencies if the structural damping is high [4].

This work studies an unusual way to increase damping in a structure with cables. A cable can be seen as a source of dissipation and not only as a component with nonlinear stiffness. Although adding cables to a lightweight structure does not prohibit resonance from taking place, ambient vibrations are however limited. This conjecture is investigated through measurements on a structure; they are presented in this paper.

2. Preliminary Investigations

2.1 Description of the Structure

A specific footbridge was instrumented. The structure spans the Vesdre River in Dohlain, a small town near Liège in Belgium (Fig.1). This steel structure is made up of rectangular hollow cross sections. Its structural behaviour combines an arch and a Vierendeel beam, because the vertical suspenders (140x140x40mm) are rigidly joined to the arches (220x120x10mm) and the tie beams (250x250x8mm). The deck is 31m long and 2.85m wide. The arch shape is parabolic with a midspan height equal to ninth of the span. The frames are welded together.



Fig.1 Dohlain Footbridge

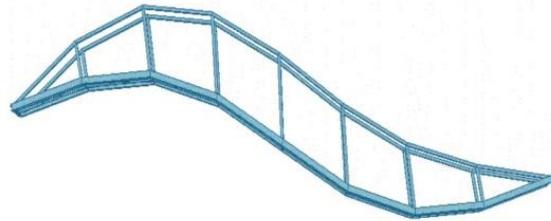


Fig.2 First in-plane vibration mode

A numerical model of the structure is realised with the software FineLg [4]. A finite element analysis is performed to estimate its mode shapes. The first vertical mode is antisymmetric with two half-waves (Fig.2). Therefore, bouncing or jumping on the first or the third quarter span is the way to maximize the vibrations in this mode. The frequency associated with this mode is around 4.5Hz according to an assumption of infinitely stiff connections, which is usually made for welded joints.

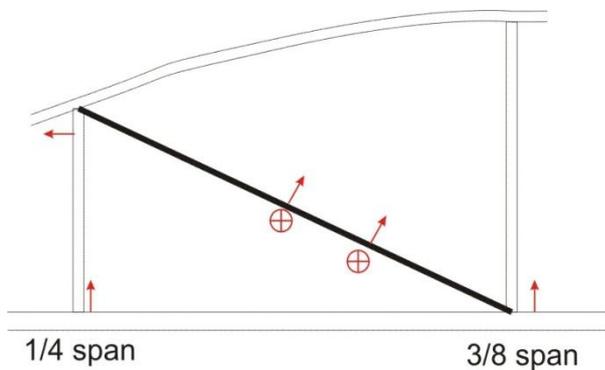


Fig.3 Positions of the accelerometers on the structure and on the instrumented cables. Arrows indicate the orientation of the accelerometers



Fig.4 Dohlain Footbridge. Position of the three cables installed on the footbridge. In red, the instrumented cable

2.2 Measuring Devices and Installation of Cables

Seven accelerometers were installed: three on the structure and four on a cable as represented in Fig.3. Two amplifiers and two data loggers are used. The post-processing software VNA permits a real-time analysis of data. According to the shape of the first mode and the range of frequencies considered, the main accelerations of the structure are measured vertically at the fourth span.

Firstly, a cable is installed between the 1/4th and 3/8th span (Fig.4); only this cable is instrumented. The accelerometers on the cables are set at half and third lengths. Their vibrations are measured in two orthogonal directions (in plane and out-plane). Then, a second cable is installed on the other arch and a last one symmetrically to the second one (Fig.4). Cables are set in deformable meshes, according to the shape of the first mode, to maximize the displacements of their anchors. The aim is not to stiffen the structure with cables, but to initiate cable vibrations and to evaluate their influence on the structure.

2.3 Structure without Cables

To evaluate cable effects, the dynamical behaviour of the structure without cables is first investigated. Three tests were realised: impact with an instrumented hammer, free vibration response and resonant response.

2.3.1 Impact-hammer

Eleven soft impacts are produced at the first quarter span with an instrumented hammer, from which the transfer function is calculated (Fig.5). The eleven transfer functions are averaged. The first peak identified at 3.2Hz is the measured frequency corresponding to the first vertical mode. The difference between the finite element model and the measurements *in situ* can be explained by the stiffness of the joints which are not infinitely stiff, even if joints are welded. According to numerical results, the structure design could meet, more or less, comfort requirements. Nevertheless, after *in situ* modal identification, this footbridge presents critical properties for the second harmonic component of bouncing (or jumping).

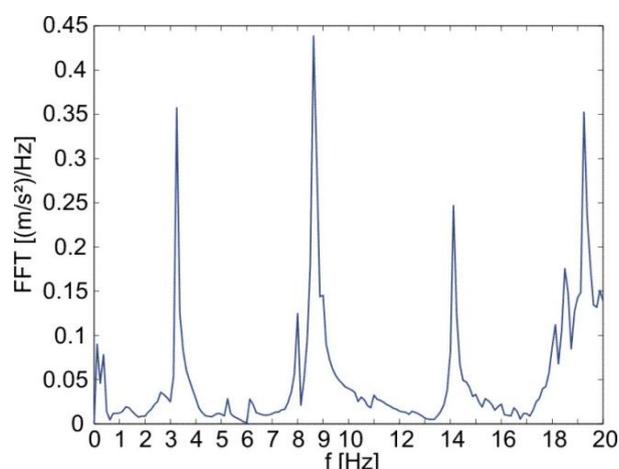


Fig.5 Impact Hammer: Averaged Fourier Transform. The first vertical mode of vibration is identified at a frequency of 3.2Hz

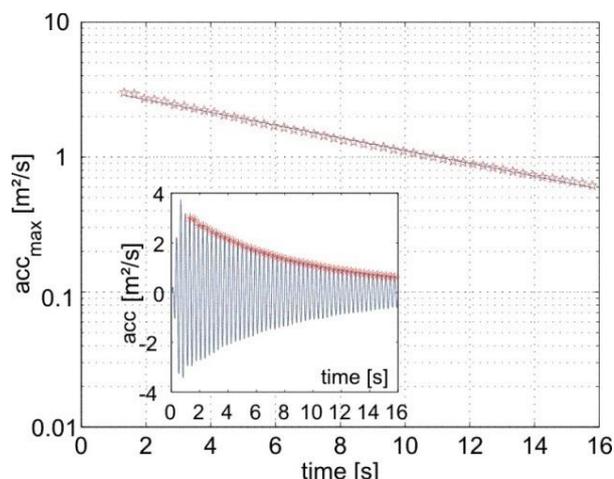


Fig.6 Free Vibration response of the structure without cables (signal filtered around 3.2Hz). The linear regression of the logarithm of the acceleration envelop. Damping ratio is around 0.55%

2.3.2 Free Vibration Response

The analysis of a free vibration response is a simple way to identify modal damping ratio ξ . The measured acceleration at 1/4th span is bandpass filtered around 3.2Hz (Fig.6). The damping ratio is estimated to be 0.55% from a linear regression of the logarithm of the envelope [6]. At this level of amplitudes, the assumption of a prevailing *linear* viscous damping in the structure is actually reinforced with a correlation coefficient of this fitting around 0.999%. This damping ratio is a common value for welded structures. It is generally accepted that less energy is dissipated in welded connections than in bolted joints.

2.3.3 Resonant Response

A way to excite a structure as a vandal consists in bouncing on the structure at a frequency close to 3.2Hz, to maximize the vibrations [7]. Bouncing is a fast and alternate knee-bending. The mass of the subject is 81kg. No metronome is used, thus the physiological ability of the subject to bounce with an appropriate frequency was also assessed. Fig.7 shows measured accelerations at 1/4th span and Fig.8 the corresponding power spectral density. The transient regime is typical of linear system response with an exponential envelope. From the rest, the subject needs 12s to reach accelerations around 6m/s² which are totally intolerable [8]. These measurements illustrate also the ease and the quickness with which the subject has adjusted his motion and the bouncing frequency to maximize energy injected into the structure.

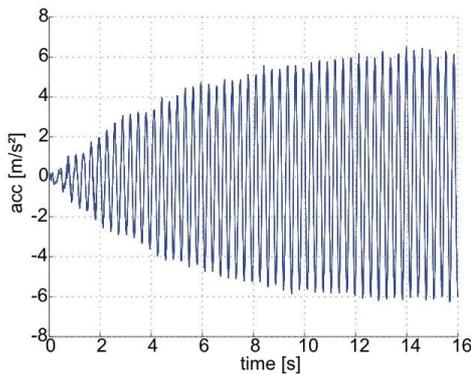


Fig. 7 Acceleration measured (non-filtered) at resonance. The maximum reached is around 6m/s^2

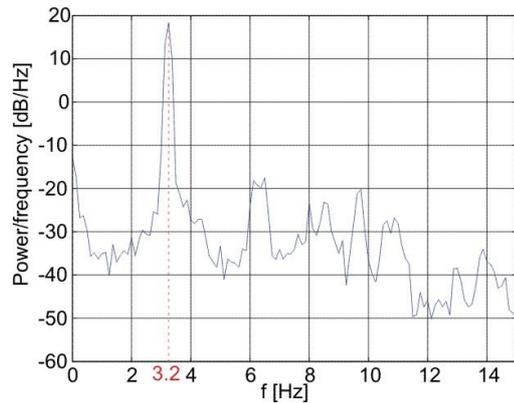


Fig. 8 Welch power spectral density estimate of the signal at Fig. 7

3. Influence of Cables on the Structural Vibrations

3.1 Cable Properties

A single cable is first installed in a mesh and then two cables in two other meshes. The diameter of the cables is 10mm and the distance between the anchors is 4.76m. The tension in the cables is tuned with a thread-nut system at an extremity of the cables. Tensions were estimated from free vibration tests (Fig. 9). The measured frequencies and the estimated tensions in three different configurations are given in Table 1.

In Table 1, the Irvine parameter λ^2 is also calculated. This parameter expresses a ratio between weight and tension effects in cable. The smaller the tension, the higher the parameter. According to Irvine [9], in cable structures, an increase in structural damping could be expected if cables are *slack rather than taut*. Although there is no clear quantifiable distinction between taut and slack cables, the greater λ^2 , the greater the structural damping ratio. This property is used in this work. Nevertheless, for some aesthetic constraints the tension is also chosen to limit the static deflection. After the installation of cables, structural natural frequencies are not modified because tension in cables is sufficiently low.

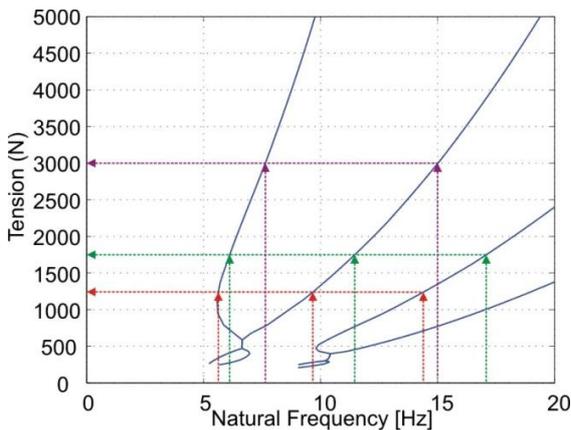


Fig. 9 Relation between frequency and tension. The cable has a diameter of 10mm and an inclination of 35°

Table 1 Tension measured in the cable at rest by identification of the natural frequencies (Fig. 9)

| | f1 [Hz] | f2 [Hz] | f3 [Hz] | T0 [N] | λ^2 |
|---------|---------|---------|---------|--------|-------------|
| Conf. 1 | 4.75 | 9.80 | 14.50 | 1250 | 12.5 |
| Conf. 2 | 5.75 | 11.70 | 17.50 | 1750 | 4.42 |
| Conf. 3 | 7.50 | 15.70 | 32.0 | 3000 | 0.68 |

3.2 Influence on the Damping Ratio

Free response accelerations measured on the structure with cables decrease faster than those on the structure without cables. The best result is obtained when three cables are installed. The post-processed results are presented below.

As previously, the dissipation in the structure is quantified by the damping ratio. Nevertheless, the cables modify the dynamical behaviour of the structure. The damping is not strictly viscous and linear anymore. For these reasons, an equivalent viscous damping ratio, noted ξ^* , is calculated by fitting a polynomial regression on the logarithm of the acceleration envelope.

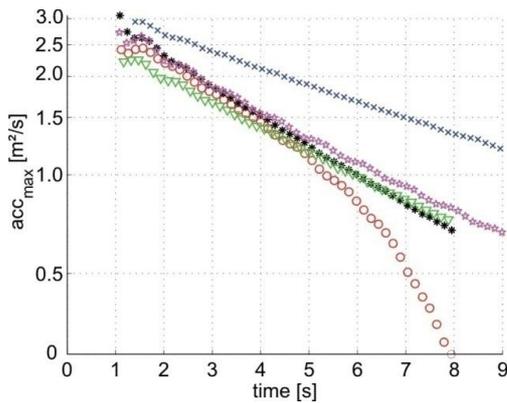


Fig.10 Acceleration envelopes. Signals are filtered around 3.2Hz. Legend: no cable (x), one cable in conf.1 (∇), conf. 2 (*), conf. 3 (★) and three cables (o)

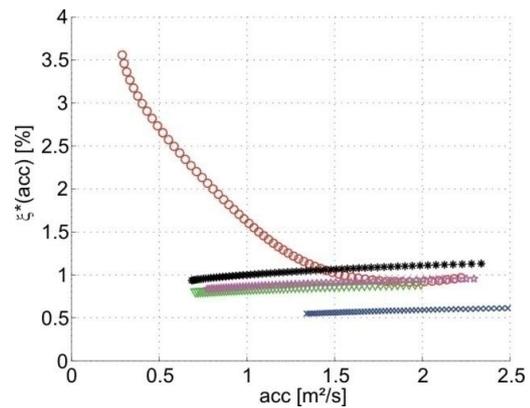


Fig.11 Equivalent damping ratio ξ^* depending on the acceleration amplitudes (Legend: cf. Fig.10)

Fig.10 shows the envelope curves for the five considered situations and Fig.11 presents the corresponding evolution of the equivalent damping ratio with the accelerations. For the structure with only one cable, envelopes are quite linear but the slopes increase compared with the initial situation. An increase of the damping ratio with the acceleration level is also significant. For the structure with three cables, the envelope is clearly nonlinear. In this case, the damping ratio reaches values as large as 3% for low amplitude vibrations. For higher accelerations, the damping ratio does not depend on the number of cables. According to these observations, the cables have an effect for bouncing or vandalism actions (greater accelerations) and for walking or running (lower accelerations). Note that the fittings of Fig.10 and Fig.11 are realized on the filtered signal without considering the first second (4 cycles) of the signal, to avoid filter effects and because the first few cycles are usually unreliable [10].

Another way to qualify nonlinear damping properties of a dynamical system is to find a relation between the acceleration and the velocity by considering the whole signal (not only the acceleration envelopes). In the context of free vibrations, the system is *autonomous* and can be described in phase space (position-velocity-acceleration). For a linear system, the trajectory in the phase space is planar. The trajectory in the first mode (filtered signal) for the structure with three cables is represented in Fig.12. A plan is fitted with a least square method on the trajectory and then subtracted from the complete trajectory. This method is a simple way to highlight possible nonlinear behaviours of a system. As shown in Fig.13, the residual trajectory around the fitted plan is erratic. The behaviour of the cable structure is mildly nonlinear and the qualitative evaluation of the damping as a function of the velocity remains difficult, for this set of measurements.

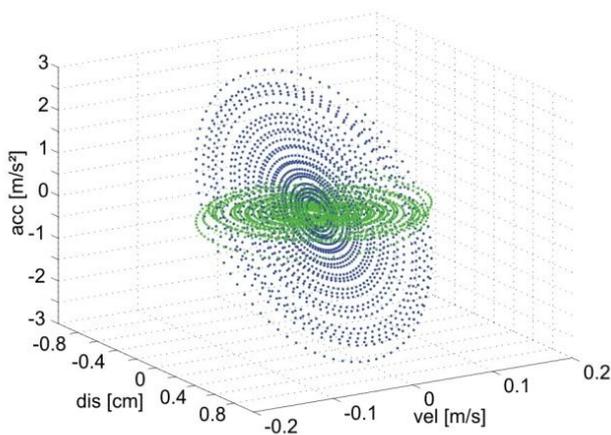


Fig.12 Trajectory (blue) in the phase space in the first mode (signal filtered around 3.2Hz) when three cables are installed on the structure. Residual trajectory (green) around the midplan

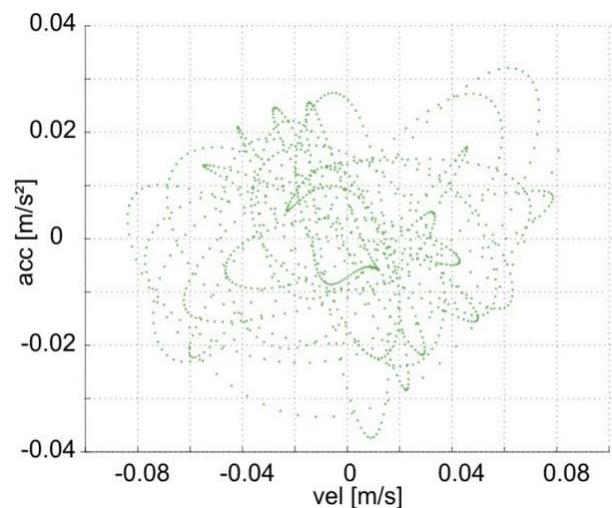


Fig.13 Residual trajectory (green) around the midplan. Projection in the plane velocity-acceleration

3.3 Resonance of the Cable Structure

Cables introduce a complementary dissipation in the structure as noted from free vibrations. For higher levels of acceleration, reached during resonance, the phenomenon is quite the same. If one cable is installed, the maximum acceleration is around 4.5m/s^2 against 6m/s^2 without cable (Fig.14). Although this acceleration remains intolerable, the reduction is significant (around 30%). No important differences in the dynamical response have been observed for the three different cable tensions.

From a physiological point of view, the subject bouncing on the footbridge expressed more difficulties to maintain the resonance than on the footbridge without cable. This feeling is hardly measured *in situ* and is not notable on the measured signals, but can be linked to an increase of damping. More energy must be injected by the subject in the structure to keep the excitation up.

Fig.15 shows the displacement of cable 2 and the corresponding Fourier transform at resonance. The vibration amplitudes of the cable are quite important (max. 9cm peak to peak), which may be a weak point of the proposed system. The cable vibrates at a frequency of 3.2Hz (i.e. the excitation frequency), but the Fourier transform also shows the contribution of four super harmonics at multiples of the excitation frequency [11]. The cable internal resonance, leading to these vibration amplitudes, explains the increase of the structural damping.

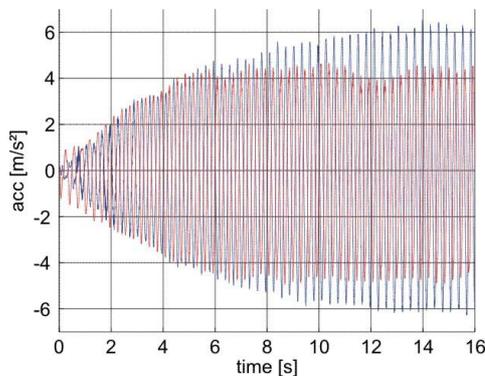


Fig.14 Accelerations measured at quarter span when the structure is resonating. Cable 2 is installed. Legend: structure without cable (blue), structure with cable (red)

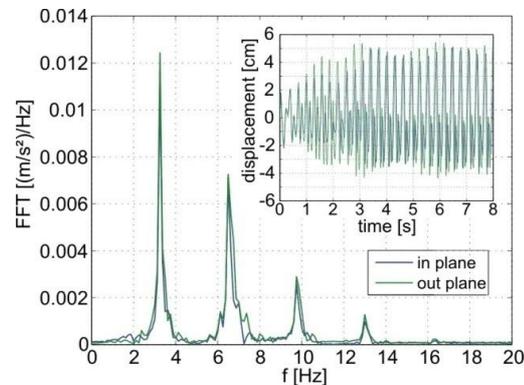


Fig.15 Vibrations at mid-span of cable 2 at resonance. Fourier transforms of signals and corresponding measures

For three cables installed on the footbridge, the structure does not start resonating so easily (Fig.16). The maximum acceleration is reduced by 50% when compared with the structure without cables. Fig.16 shows a typical response measured on the structure and a certain difficulty to keep the excitation constant. Indeed if the subject reduces slightly the applied forces or changes barely the bouncing frequency, acceleration of structure decreases quickly. The rise to resonance is therefore stopped. Nevertheless, after some trials, the subject manages to reach maximum accelerations around 4.5m/s^2 , the same level reached for one cable (Fig. 17). This observation is in agreement with Fig.11 because ξ^* does not depend on the number of cables for higher acceleration levels. The main effect of the cables is to prolong the transient phase and at this stage to make hardly identifiable the resonance frequency by an ill-intentioned person.

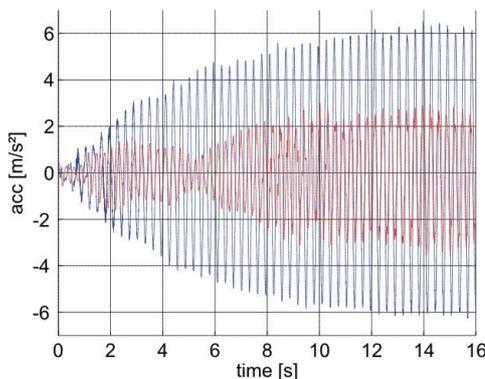


Fig.16 Accelerations measured at quarter span when the structure is resonating. Three cables are installed. Legend: structure without cable (blue), structure with cables (red)

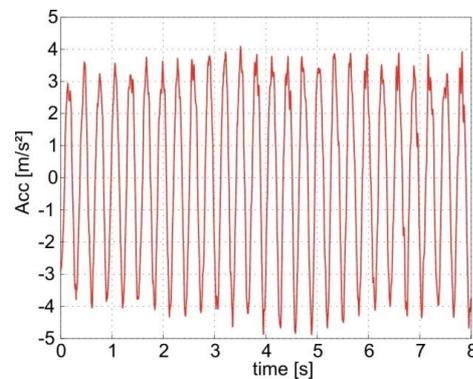


Fig. 17 Accelerations measured at quarter span when the structure is resonating. The subject reaches a same level as Fig.14. Three cables are installed

4. Conclusions

The vibrations of a footbridge are investigated by means of experimental measurements. When an ill-intentioned person or a vandal is bouncing on the structure, intolerable accelerations are easily reached. To limit the possible resonance of the structure, cables are installed in the footbridge. These cables can be seen as a complementary source of dissipation in the structure.

When cables are installed, for high acceleration levels, the number of cables does not seem to influence the damping properties. Nevertheless, for low levels, the damping properties are increased which creates difficulties in bouncing on the structure for the subject. More energy must be injected in the system for the transient phase to identify the frequency resonance and to maintain the excitation. Even if the installation of cable does not prohibit resonance from taking place, they improve comfort and safety of the footbridge with a modest investment.

5. Acknowledgements

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6. References

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