EVALUATION OF POWER LINE CABLE FATIGUE PARAMETERS BASED ON MEASUREMENTS ON A LABORATORY CABLE TEST SPAN

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Abstract

The present paper describes experiments carried out on IREQ[1] *laboratory cable test bench. Test span arrangement is a 63.15m cable span with termination ends designed so as to minimize energy dissipation. A shaker provides a vertical alternating force to the conductor. During the experiments, a maximum of information on mode shape is collected: location of nodes, antinode amplitude of vibration, relative displacement at 44.5, 89, and 178mm from the last point of contact with the metallic clamp. Several configurations are studied: span equipped with an homogeneous steel cable, span equipped with an ACSR Crow conductor, sometimes in combination with other equipments such as a vibration damper or a local mass, to investigate how the presence of such devices impacts conductor vibrations. It results from these experiments an interesting comparison of two widely used fatigue indicators, the relative displacement* Y_b[2] *(also called "bending amplitude") and* fy_{max} *(the product of antinode amplitude of vibration by frequency). Also, collected data gives indirect information on conductor variable bending stiffness.*

INTRODUCTION

Recognized vibration intensity indicators are the product of antinode amplitude of vibration by frequency (fy_{max}) [1-3], angle through which the conductor is bent at the clamp [5-7], relative displacement (Y_b) [9-11] and dynamic strain at the surface of an outer-layer strand (usually measured at the top of conductor [22]) in the vicinity of the clamp [12,13]. Fatigue curves may be obtained through tests on laboratory spans using any of these parameters as the measure of vibration intensity, but it is more common to see fatigue curve drawn as a function of relative displacement, fy_{max} or an equivalent idealized stress [18].

Among those vibration intensity indicators, relative displacement has been used for field measurement for decades [14]. However, nowadays, new technologies are being developed, which allow continuous antinode amplitude monitoring. Given this context, it is interesting to investigate what are the opportunities associated with real time field measurement of antinode amplitude of vibration, in order to perform a vibration risk diagnosis of a line. The tests performed on IREQ test span allow to compare relative displacement and fy_{max} as vibration intensity indicators and to bring interesting arguments in this discussion.

The tests performed also meet the following objectives:

- Collect all the required data to validate the modelization of a conductor vibrating at its natural vibration modes.

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[2] Peak-to-peak displacement of conductor relative to the clamp, generally measured at 89mm from the last point of contact between the conductor and the metallic clamp. In this paper, Y_{b1}, Y_{b2} (=Y_b) and Y_{b3} stand for relative displacement measured respectively at 44.5, 89 and 178mm from the last point of contact between the conductor and the metallic clamp.

- Improve the understanding of conductor behaviour at singularities along the span where the impact of conductor bending stiffness is particularly important. Examples of such singularities are suspension clamps, damper clamps, aerial warning markers, real time monitoring devices, spacer dampers, etc.
- Improve the understanding of the interaction between parameters Y_b and fy_{max}.
- Finally, collected data also enables the assessment of conductor self damping.

PRESENTATION OF TEST EQUIPMENT

A sketch of IREQ 63.15m long laboratory test span is shown in figure 1. The conductor is installed into rigid clamps which are part of an extremely stiff concrete block embedded in the rock underground in order to minimize end losses. Conductors are tensioned at least 24h before the beginning of tests, in order to get a final tension value of approximately either 15 or 25% of their RTS (rated tensile strength). An electrodynamic shaker located at 1.69 m from the anchoring block provides a vertical alternating force to the conductor.

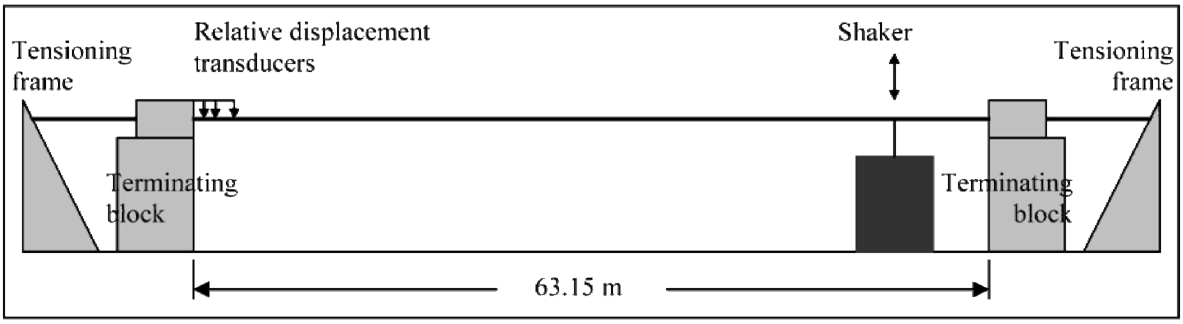
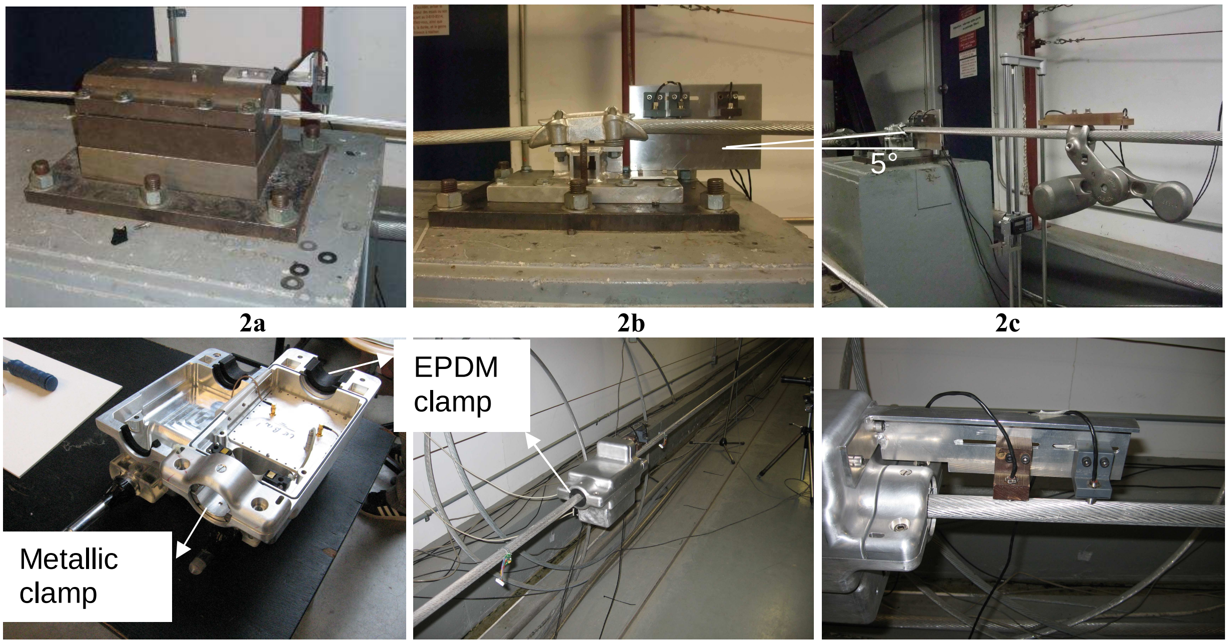


Fig. 1: IREQ 63.15m long laboratory test span

Two cables have been tested: a ground cable (7 steel wires, diameter: 11.0 mm, mass per unit length: 0.577 kg/m, rated tensile strength (RTS): 86.7 kN) and a Crow conductor (54 aluminum wires over 7 steel wires, diameter: 26.3 mm, mass per unit length: 1.369 kg/m, RTS: 117.2 kN).
Other equipments used during the tests include:

- A conventional saddle metal-to-metal suspension clamp, which was installed on the span with a 5° inclination angle relative to horizontal to reproduce the exit angle of the cable in a standard span length.
- An aeolian vibration damper developed by IREQ and commercialized by Helix Uniforme Ltd [21]. Energy dissipation is obtained through an elastomeric articulation. The damper is installed at a distance of 1 m from the last point of contact with the clamp. Two non-contact sensors measured the relative displacement of the conductor on each side of the damper clamp, at 89mm from the last point of contact with the conductor.
- A fake vibration damper, with the same geometry and located at the same place as in the previous set-up, but without articulations and thus no energy dissipation.
- A prototype of a real time monitoring device based on vibration measurement. It consists of a microsystem array in its aluminium housing. The housing dimensions are 370 mm x 173 mm x 255 mm and it is fixed on the conductor with a metallic clamp on one side and an EPDM clamp on the other side. The mass of this prototype is approximately 7 kg. During the tests, the position of the housing on the span was slightly modified, but remained between 5 and 9 m from the suspension clamp. Two non-contact sensors, located at a distance of respectively 89 mm and 178 mm from the metallic clamp recorded the conductor displacement relative to the device.



2a 2b 2c

2d 2e 2f

Figure 2: Span end opposed to the shaker was equipped with either a rigid clamp embedded in a concrete block (2a) or a suspension clamp (2b); tests with in-span line equipment such as an aeolian vibration damper (2e) (sometimes without articulations) or a prototype of a real time monitoring device (2c-2e) have been performed

EXPERIMENTS DESCRIPTION

For each experiment, excitation frequency has been tuned so as to correspond with one of the natural frequencies of vibration of the conductor and the followings have been measured:

- Conductor’s excitation frequency.
- Antinode amplitude of vibration (using a Zimmer camera).
- Location and vibration amplitude of 4 nodes on the span (three nodes located near the span end, and one node located near the shaker), so as to deduce conductor self damping. The vibration amplitude of nodes is measured with non-contact sensors.
- Conductor “relative displacement”, i.e. peak-to-peak displacement amplitude measured respectively at 44.5 (Y_{b1}), 89 (Y_b or Y_{b2}), and 178mm (Y_{b3}) from the last point of contact with the metallic clamp, using non-contact sensors.
- In case there is some equipment installed on the span, relative displacements at 89 mm (Y_b or Y_{b2}) and/or 44.5mm (Y_{b1}), and/or 178mm (Y_{b3}) from the device's clamp is measured.

ANALYSIS OF THE RESULTS

CONDUCTOR BENDING STIFFNESS

In literature, a formula which expresses how conductor natural frequencies depend on conductor bending stiffness can be found [17]:

$$f_n = \frac{1}{2\pi}\sqrt{\left(\frac{n\pi}{L}\right)^2 \frac{T}{m_L}\left[1+\left(\frac{n\pi}{L}\right)^2 \frac{EI}{T}\right]} \qquad (1)$$

Knowing the value of several natural frequencies of vibration as well as their mode number, it becomes possible to estimate the evolution of conductor bending stiffness as a function of frequency. This information was collected on a Crow conductor tensioned at approximately 22.7%RTS and a saddle metal-to-metal suspension clamp on the span extremity opposed to the shaker. A special attention was drawn to fy_{max} amplitudes of vibrations, which were kept as constant as possible.

An average value of 591.3 N.m^2 for conductor bending stiffness can be estimated combining the data from the previous figure with equation (1). This value is comprised between the minimum and maximum bending stiffness values [18] being respectively 18 and 1208 N.m^2 and is equal to 49% of EI_{max}.

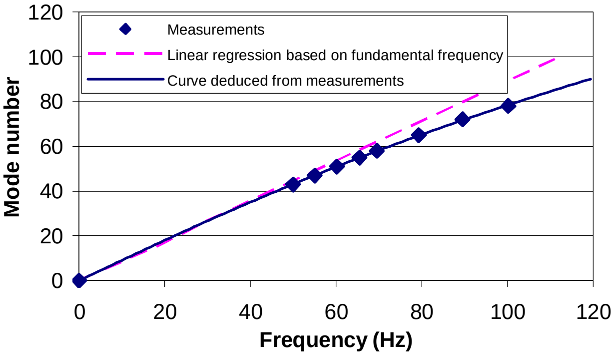


Fig. 3: Evolution of frequency with mode number for test span equipped with conductor Crow and a suspension clamp at the extremity opposed to shaker

RELATIONSHIP BETWEEN Y_b AND fy_{max}

A steel ground wire and Crow conductors have been tested at several eigen frequencies, comprised respectively between 18 and 113 Hz and between 7 and 62 Hz. For each frequency, tests were repeated with three different amplitudes which corresponded to fy_{max} values of 40, 80 and 160 mm/s. Free-loop amplitudes were measured, as well as “relative displacements” at 44.5, 89 and 178 mm from the last point of contact with the clamp. The following figures represent the evolution of the ratio Y_b over fy_{max} as a function of frequency.

As can be seen in these figures, for all cases without any particular in-span equipment, the ratio between conductor bending stiffness and free-loop amplitude of vibration is almost constant with frequency and close to:

- 0.0030 s for steel cable equipped with a rigid clamp and tensioned at 25% RTS and for ACSR Crow conductor equipped with a suspension clamp and tensioned at 15% RTS,
- 0.0023 s for Crow ACSR conductor equipped with a rigid clamp, whatever its tension.

There is a considerable difference (superior to 20%) between the Y_b/fy_{max} ratio of the Crow ACSR conductor as the span extremity changes from suspension to rigid clamp.

The correlation coefficient between measured data and linear regression is for all cases superior to 0.95, and most of the time very close to unity, even when “relative displacements” are measured at a distance of 44.5 mm or 178 mm from the clamp. The ratio between Y_b and fy_{max} tends to decrease slightly with an increase of fy_{max}.

As could be expected, the situation is different when in-span devices such as vibration dampers are installed. Figure 5 represents the evolution of the ratio Y_b measured at 89mm over fy_{max} as a function of frequency for three different configurations:

- A suspension clamp (figure 2b) is installed at the span end remote from the shaker and one aeolian vibration damper (figure 2c) is installed at a distance of 1 m from the suspension clamp. The conductor is tensioned at 24%RTS.
- Same set-up but with a fake (rigid) aeolian vibration damper.

- Same set-up but with a real-time monitoring device (figure 2c) installed at 5 to 9 m from the suspension clamp.

One can see in the previous figure that there is no obvious relationship between Y_b and fy_{max} whenever some equipment which can be considered as an "obstacle" to wave propagation is installed in the vicinity of the span end. The correlation coefficients between measured data and a linear regression are low (lower than 0.55), which means that amplitude near the clamp is no longer an image of in-span amplitude (and vice versa).

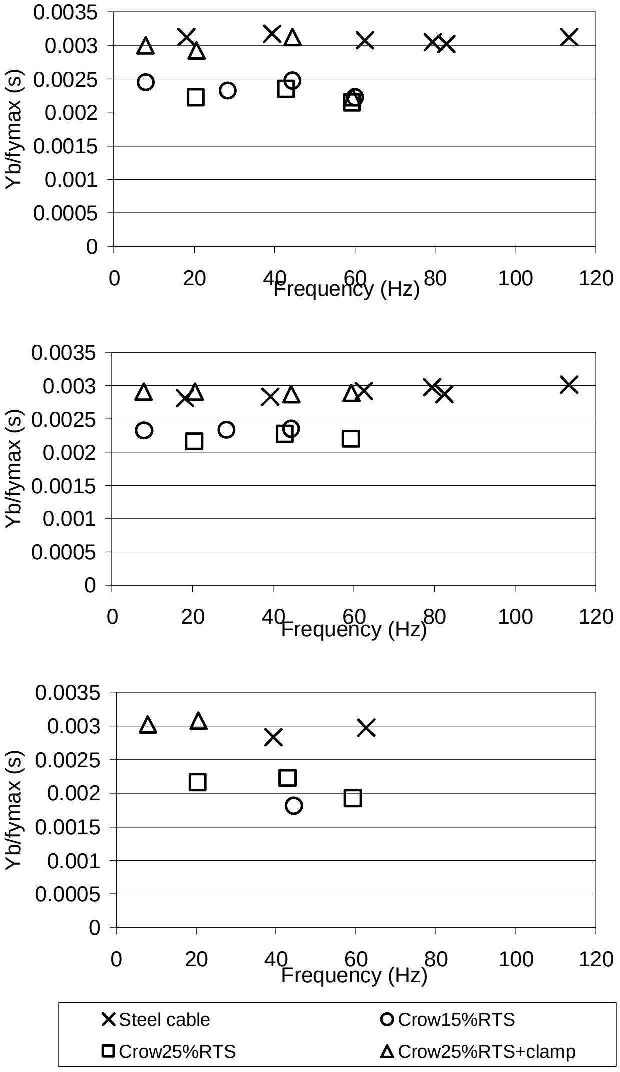


Fig. 4: Evolution of the ratio of Y_b over fy_{max} as a function of frequency for fy_{max}=40 mm/s (top), fy_{max}=80 mm/s (middle) and fy_{max}=160 mm/s (bottom)

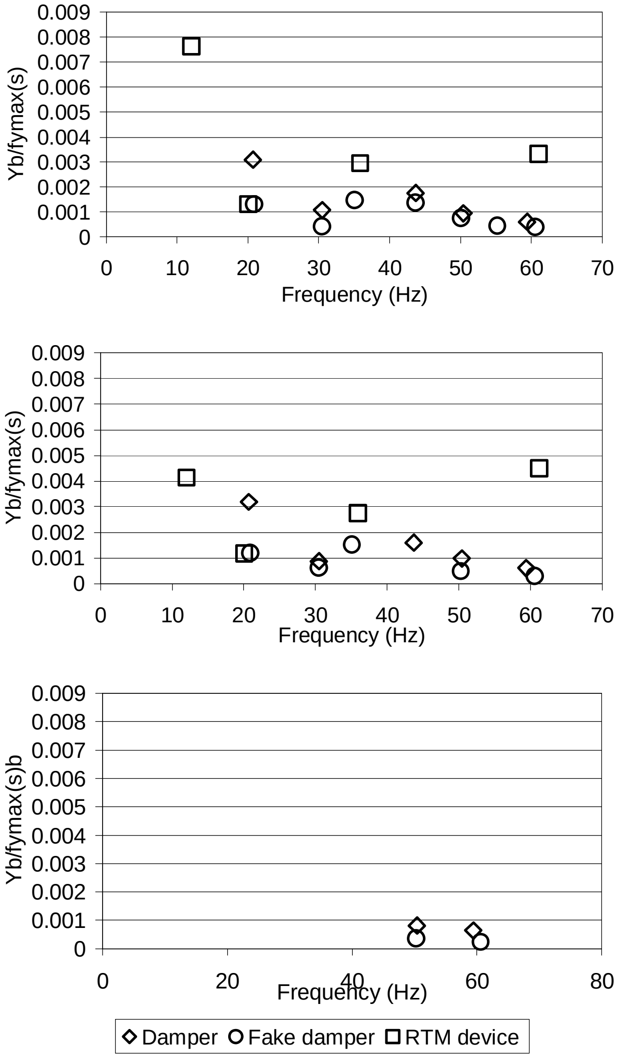


Fig. 5: Evolution of ratio Y_b over fy_{max} as a function of frequency for fy_{max}= 40 mm/s (top), fy_{max}=80 mm/s (middle) and fy_{max}=160 mm/s (bottom)

INFLUENCE OF A SUSPENSION CLAMP ON Y_b MEASURED NEAR SPAN END

When a suspension clamp is introduced at the extremity of the span opposed to the shaker (to replace the rigid clamp visible in figure 2a), an increase of 30% in average of relative displacements measured at 89 mm from the last point of contact between conductor and clamp is obtained. This phenomenon is illustrated in figure 6.

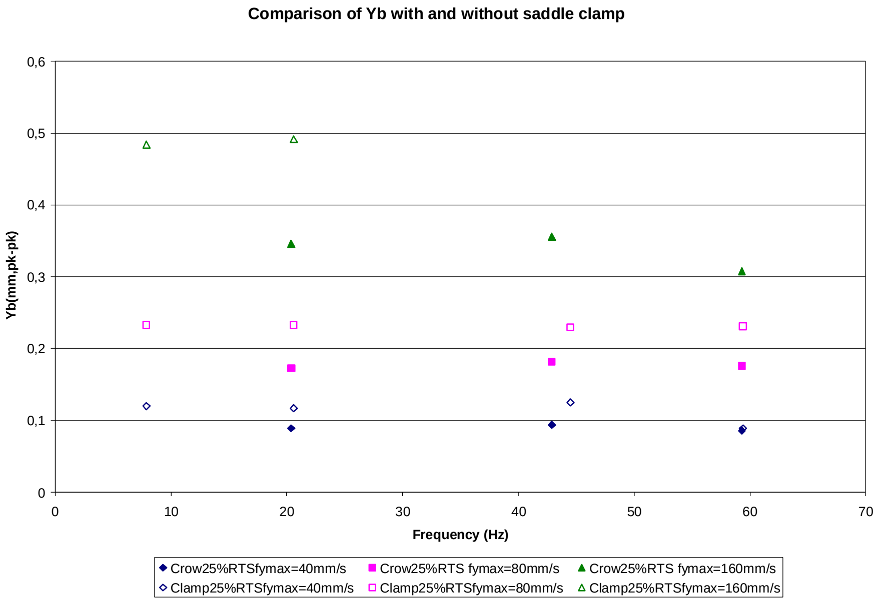


Fig. 6: Relative displacements (measured at 89mm from the last point of contact between conductor and suspension clamp) at span end with and without the presence of a suspension clamp

This increase in relative displacement values measured is probably due to the fact that with a suspension clamp, the mode shape begins slightly further inside the clamp since the keeper is slightly shorter than the length of the clamp in contact with the conductor. Moreover, there may be some deformation of the saddle clamp itself since it is made of aluminium while the rigid clamp which is thicker, made of steel, and held in place with eight bolts is much more rigid.

These results show that the last point of contact between conductor and clamp may not be perfectly still and its behaviour may change with amplitude and frequency. Moreover, while the suspension clamp is held in place on the laboratory span end, in the field, a real suspension clamp may rock at amplitudes depending on the mode excited in the adjacent spans. Therefore, the relationship between fY_{max} and Y_b is sometime difficult to obtain and it may have an impact on damage and residual lifetime estimation with fatigue curves and cumulative damage law. In the rest of this paper, a suspension clamp will systematically be present at the span end opposed to the shaker.

COMPARISON BETWEEN Y_b AT THE SUSPENSION CLAMP AND AT THE EQUIPMENT CLAMP

In this paragraph, the introduction of line devices on the span is considered, and a comparison of relative displacements measured at the suspension clamp and at the device clamp is performed. Let us first consider the case of Crow conductor tensioned at 23.8% RTS, with an aeolian vibration damper 1 m apart from the suspension clamp. Figure 7 compares relative displacements measured on both sides of the damper clamp (one side is oriented towards the suspension clamp and the other one towards the vibration shaker) with relative displacement at the suspension clamp.

The highest relative displacements are observed at the clamp of the damper, on the side oriented towards the shaker[3]. The fact that relative displacements may be higher at the damper clamp than at the suspension clamp at some frequencies has already been observed (e.g. by IREQ) during previous measurements made with Stockbridge dampers. Relative displacements at the Aeolian vibration

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[3] When the vibration damper is installed at a distance of 1m from the suspension clamp, it subdivides the initial span in a two portions, a long one (L-1) m and a short one (1m). With regard to propagation of waves created by the shaker, we can say the long portion of span is "before the obstacle to vibrations (the damper)" and the short portion is "after" this same "obstacle".

damper's clamp, but on the suspension clamp's side are significantly less important as the suspension clamp's ones.

Let us now consider the case of Crow conductor tensioned at 23.8%RTS, with a suspension clamp and a real time monitoring device in the vicinity of the clamp (note that the metallic clamp of the monitoring device is oriented towards the suspension clamp). Relative displacements are measured at 44.5, 89 and 178 mm from the last point of contact with the Slater clamp, and at 89 and 178 mm from the last point of contact with the clamp of the monitoring device during a test where excitation is at an eigen frequency of 12 Hz.

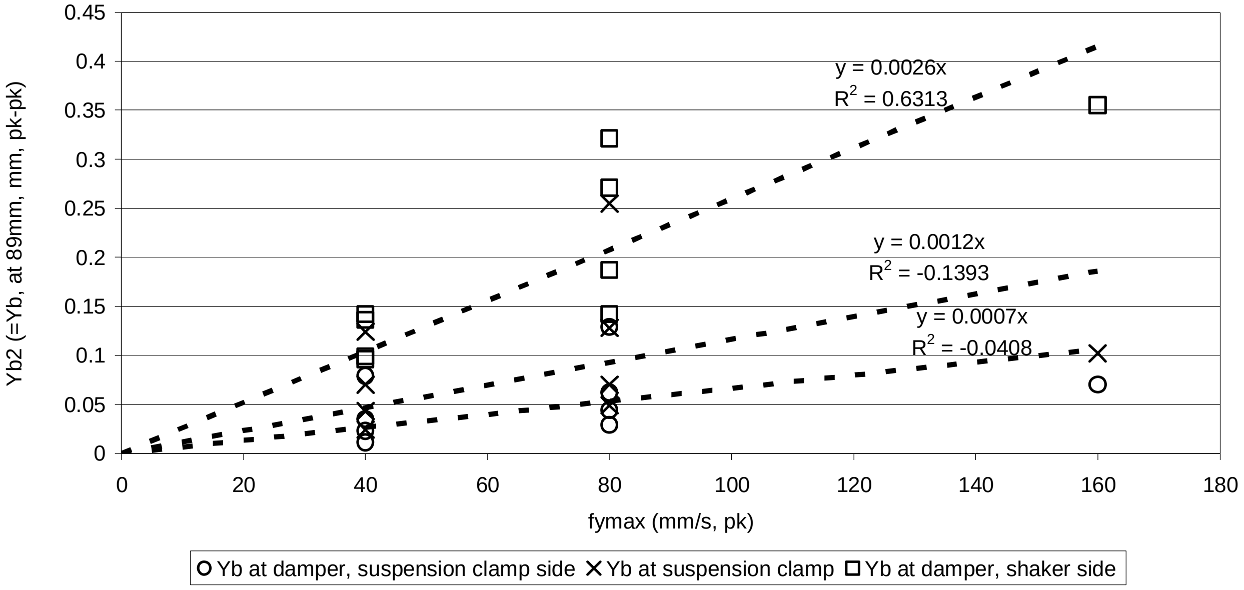

Fig. 7 : Comparison of relative displacements measured at 89 mm from suspension and damper's clamp, Crow conductor tensioned at 23.8% RTS

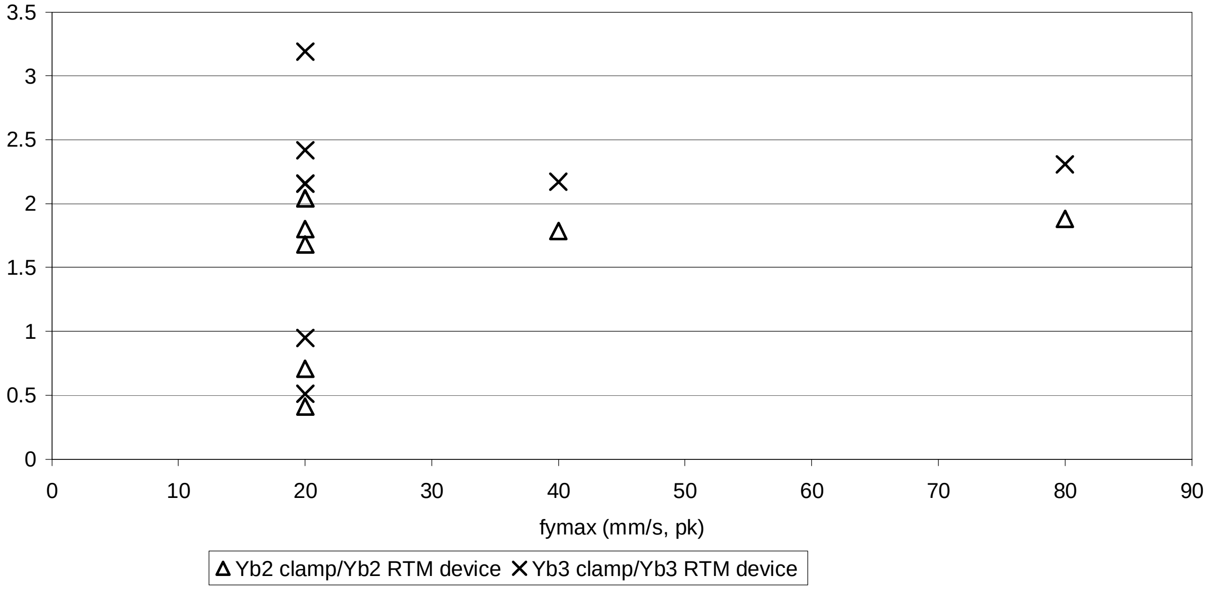

Fig. 8 : Comparison of ratios of relative displacements measured at 89 mm and 178 mm from the suspension and real time monitoring device clamp, Crow conductor tensioned at 23.8% RTS

For most measurements, relative displacements (at 89 and 178 mm of the last point of contact between conductor and clamp) at the equipment clamp are inferior to those at the Slater clamp. Nevertheless, there is one exception. When the monitoring device is located at 8.45 m from the Slater clamp, for fy_{max} equal to 20 mm/s pk, the relative displacement at the monitoring device was more important than at the Slater clamp. This will be further investigated through modelization.
It results from this paragraph that the study of relative amplitudes in the vicinity of suspension clamps is only part of the vibration information. It must be completed by in-span measurements to perform an adequate vibration risk analysis because all span locations where the movement of the conductor is restrained may be at risk (e.g. near the clamp of vibration dampers, air warning markers, spacers…).

CONCLUSIONS

When no particular in-span equipment (such as vibration damper, aircraft warning marker, spacer…) is installed in a span, fatigue parameters Y_b measured at the extremity of the span and fy_{max} lead to similar information: the ratio between conductor bending stiffness and free-loop amplitude of vibration is almost constant with frequency for all test cases without any particular in-span equipment. It has also been observed that the ratio between Y_b and fy_{max} decreases slightly with an increase of fy_{max}.
The situation is completely different when in-span devices such as vibration dampers are installed. Free-loop amplitude of vibration is no more an image of relative displacement at the suspension clamp. Tests have shown that

- The most important relative displacement may be present at the clamp of in-span devices, particularly when their mass may disturb locally the modal shape of the span. Such case depends on the system location and the ratio “mass of the device/mass of the conductor”. This appears to be quite disturbing. A fixed point (like a span end) could have been considered at first as more rigid than a moving point, but it has been observed that local mode shape may be significantly affected. Also, it has been observed that “resonances” may occur when “subspans” are present (between two systems or between a system and the suspension clamp), and may catch more energy than in the free span situation. In the reality, such resonances may probably occur between the span extremity and some line equipment or between two line equipments such as aircraft warning markers for example.
- The last point of contact between conductor and clamp may not be perfectly still and its behaviour may change with amplitude and frequency. Moreover, while the suspension clamp is held in place on the laboratory span end, in the field, a real suspension clamp may rock at amplitudes depending on the mode excited in the adjacent spans. Therefore, the relationship between fY_{max} and Y_b is sometimes difficult to obtain and it may have an impact on damage and residual lifetime estimation with fatigue curves and cumulative damage law.

The present paper will be completed by a modelization of the observed phenomena, but an important conclusion can already be drawn: the study of relative amplitudes in the vicinity of span extremities is only part of the vibration information. It must be completed by in-span measurements to perform an adequate vibration risk analysis because all span locations where the movement of the conductor is restrained may be at risk (e.g. near the clamp of vibration dampers, air warning markers, spacers…).

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