EXPERIMENTAL INVESTIGATION OF THE DYNAMIC BEHAVIOR OF A TRANSMISSION LINE CONDUCTOR WITH STOCKBRIDGE DAMPERS

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Abstract. *The purpose of this work is to provide a deeper understanding on the dynamics of a transmission line conductor equipped with Stockbridge dampers. To this end an experimental set-up containing the transmission line conductor with a set of dampers was designed such that one may evaluate the effectiveness of the dampers as a function of their number and positions, excitation frequency and conductor parameters. Experimental tests are performed on a laboratory span for three different configurations (varying the number and position) of the dampers. On all the laboratory tests performed, the whole system which is composed of the conductor and the dampers is subjected to forced vibrations by means of a frequency- and amplitude-controlled electrodynamic shaker. The conductor is appropriately instrumented with force transducers and piezoelectric accelerometers in order to measure the frequency response functions. The experimental results reported here are new in the literature and clearly indicate a linear behavior for the conductor in the absence of Stockbridge dampers and a nonlinear behavior when Stockbridge dampers are attached to the conductor. These results may be used for the development and/or improvement of theoretical models proposed to describe the wind-excited vibrations of transmission line conductors equipped with Stockbridge dampers.*

Keywords*: wind-excited vibrations, transmission line conductor, Stockbridge dampers, experimental measurements*

1. Introduction

Wind-induced mechanical vibrations (or aeolian vibrations) on overhead conductors of transmission lines are understood as critical problems for the safety and reliability of the transmission line. Different types of mechanical vibrations may occur; however, the most common type corresponds to wind-excited vibrations in the frequency range of 3 Hz to 150 Hz, caused by vortex-shedding (Rawlins, 1979; Hagedorn, 1982; Meynen et al., 2005; Sinha and Hagedorn, 2007). The aerodynamic lift forces arising from the periodic shedding of vortices in the wake of the conductor are the responsible for its subsequent vibrations in a direction transverse to the wind flow.

Aeolian vibrations on transmission line conductors arise for wind speeds in the range of 1 m/s to 10 m/s. Based on typical values for conductor diameters (15 mm to 30 mm) and on the values of the dynamic viscosity and specific mass of the standard air, a simple calculation reveals that such vibrations arise in wind flows with Reynolds number in the range of 10^3 to 10^4. For subsonic flows in this range of Reynolds number, also called sub-critical range (Gabbai and Benaroya, 2005), it is well-known that the vortex-shedding phenomenon has a well-defined frequency, commonly referred to as the shedding frequency (Gabbai and Benaroya, 2005; Sarpkaya, 2004). Experimental observations indicate that the shedding frequency, f_s, is directly proportional to the wind speed normal to the conductor, U, and inversely proportional to the conductor diameter, D; the proportionality constant being the Strouhal number, St. It is also well-known that the Strouhal number is a function of both the geometry and Reynolds number for low Mach number flows (Tsui, 1982); for example, for smooth circular cylinders $St \approx 0.2$ such that the shedding frequency may be computed as $f_s = 0.2\ U/D$. Typical conductors of high voltage transmission lines are composed of wires helically wrapped around a central core. Although transmission line conductors are not geometrically identical to smooth circular cylinders, experimental measurements in the field have revealed that the Strouhal number for the former ones lies in the range 0.185 to 0.22 (Rawlins, 1979; Kraus and Hagedorn, 1991). Under operational conditions, overhead conductors are strung to a specified mechanical load, frequently in the range of 15% to 30% of their rated tensile strengths, and their ends are fixed at the suspension clamps.

The span length of a typical transmission line generally ranges from one hundred to one thousand meters and, thereby, the conductor's frequency spectrum is almost continuous. Two consecutive natural frequencies of a typical conductor are quite close, separated by approximately 0.1 Hz to 0.2 Hz (Hagedorn, 1982; Schäfer, 1984); therefore, in the range of wind speeds expected for the aeolian vibrations, the conductors are almost always excited into forced resonant vibrations, that is, the shedding frequency is often close to one natural frequency of the conductor. Because transmission line conductors have very low internal damping, the dynamic stresses and strains induced on their constituent wires may become dangerously high, especially at the suspension clamps. These stresses and strains may lead to fatigue damage on the wires with catastrophic consequences such as the complete rupture of the conductor and interruption on the supply of electric energy. In order to reduce these dynamic stresses and strains caused by the wind-induced vibrations a common strategy is to attach dynamic absorbers to the conductors, among which the Stockbridge dampers are the most widely used. The Stockbridge damper was originally designed by George Stockbridge in 1925 and since then different modifications on the original design were proposed; nevertheless, most of the Stockbridge dampers used nowadays are composed of a flexible steel wire cable (also referred to as messenger cable), two inertial masses and a suspension clamp to attach it to the conductor, as shown in Fig. 1. The messenger cable is composed of a core wire and one or two layers of wires helically wrapped around. The friction among the constituent wires of the messenger cable during its flexural vibrations is the mechanism responsible for the dissipation of mechanical energy on these devices. Actually, these dampers act as dynamic absorbers, removing part of the mechanical energy input by the wind and interacting with the conductor by exerting a transverse force and a bending moment at the attachment point. The effectiveness of a typical Stockbridge damper is sharply influenced by its location and dynamic behavior (Hagedorn, 1982). Depending on the damper type and location, and on the excitation frequency, the force and moment exerted by the damper may increase too much the local curvature of the conductor, leading thus to large strains at the attachment points (Hagedorn, 1982; Wagner et al., 1973; Markiewicz, 1995). In these situations, the presence of Stockbridge dampers contributes to increase the fatigue risk. Recently, Brazilian engineers have verified severe fatigue damages on transmission line conductors in the neighborhood of damper clamps (Azevedo and Cescon, 2002). Therefore, the understanding of the wind-induced vibrations on overhead conductors is indeed a relevant issue.

The common practice adopted in the literature is to assume that the dampers interact with the conductor by exerting a transverse force and bending moment at the attachment points (Hagedorn, 1982). Such strategy based on the decoupling of the whole system (conductor plus dampers) into subsystems is viable inasmuch as there are families of coupling techniques such as the component-mode synthesis and substructure synthesis (Meirovitch, 1997), to cite just a few. However, to the authors belief, it has not been done effectivelly for the problem under analysis because, although experimental data have clearly indicated that the Stockbridge damper possesses a nonlinear behavior (Sauter and Hagedorn, 2002; Sauter, 2003), many authors have treated the whole system as a linear one. Hence, in order to built reliable models for a transmission line conductor equipped with Stockbridge dampers, the first step is to characterize the transmission line conductor (Matt and Castello, 2007; Castello and Matt, 2007) and the second one is to characterize the dampers and the nonlinear coupling (Čermelj and Boltežar, 2006; Ferreira, 1998).

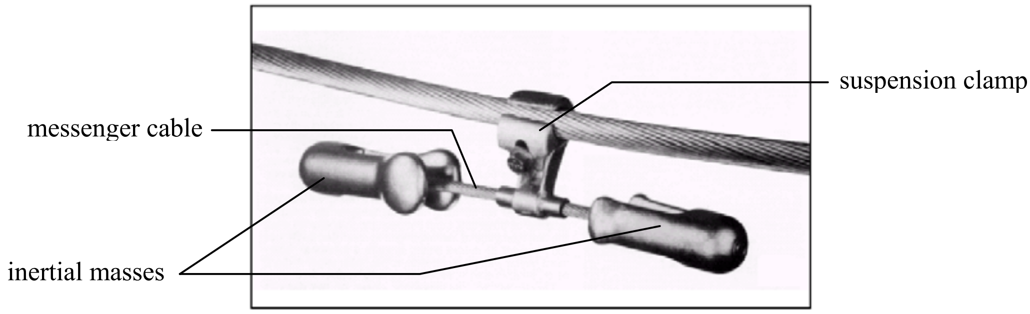

Figure 1. Stockbridge damper attached to a transmission line conductor.

The purpose of this work is thus to provide a deeper understanding on the dynamics of a transmission line conductor equipped with Stockbridge dampers. More specifically, it is aimed at verifying the common hypothesis adopted by some authors that the whole system (the conductor plus the Stockbridge dampers) acts as a linear system. To this end, an experimental set-up containing the transmission line conductor with a set of dampers was designed such that one may evaluate the effectiveness of the dampers as a function of their number and positions, excitation frequency and conductor parameters. Experimental tests are performed on a laboratory span for four different configurations (number and position) of the dampers. On all the laboratory tests performed, the whole system is subjected to forced vibrations by means of a frequency- and amplitude-controlled electrodynamic shaker. The conductor is appropriately instrumented with force transducers and piezoelectric accelerometers in order to measure the frequency response functions (*FRFs*). The experimental results reported here are new in the literature and clearly indicate a linear behavior for the conductor in the absence of Stockbridge dampers and a nonlinear behavior when Stockbridge dampers are attached to the conductor. These results may be used for the development and/or improvement of theoretical models proposed to describe the wind-excited vibrations of transmission line conductors equipped with Stockbridge dampers. This work is organized as follows. In section 2 we describe the experimental tests performed at CEPEL's laboratory span. In section

3 we present and analyze the measured frequency response functions for four different configurations of the dynamic system. In section 4 we finish by offering the final remarks and comments about future works.

2. Experimental Tests

Experimental tests are performed at CEPEL's laboratory span in order to measure the *FRFs* at prescribed positions along the conductor. Figure 2 illustrates a schematic view of the experimental apparatus for the laboratory tests performed. The frequency response functions measured here are defined as the ratio between the acceleration (response) at a prescribed position and the force (excitation) transmitted to the conductor by the electrodynamic shaker at the driving point. The prescribed positions are the driving point itself given by the coordinate x = 50.348 m, and two positions near one conductor's clamped end given by the coordinates x = 1.39 m and x = 0.70 m. The tests are performed for four different configurations of the dynamic system under analysis. Configuration I comprises the conductor without Stockbridge dampers. Configuration II comprises one Stockbridge damper attached to the conductor at the position given by the coordinate x = 1.39 m. Configuration III comprises one Stockbridge damper attached to the conductor at the position given by the coordinate x = 0.70 m. Configuration IV comprises two Stockbridge dampers attached to the conductor at the positions given by the coordinates x = 1.39 m and x = 0.70 m. Table 1 summarizes the main characteristics of the four configurations tested.

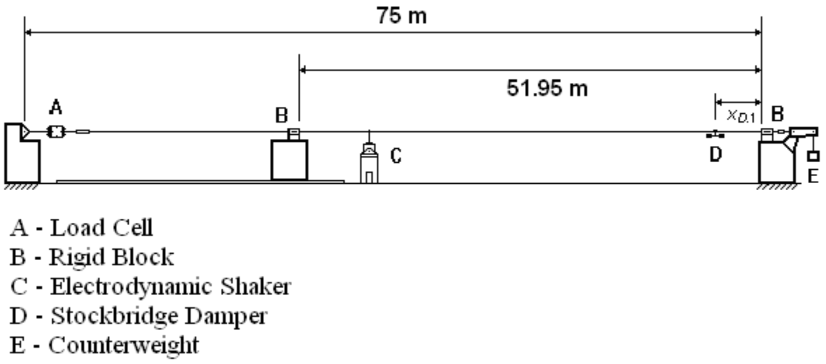

Figure 2. Schematic view of the experimental apparatus for the laboratory tests performed.

Table 1. The four configurations used in the frequency response tests performed at CEPEL's laboratory span.

Configuration	Number of dampers	Position of the dampers (m)
I	0	----
II	1	1.39
III	1	0.70
IV	2	0.70/1.39

For all the laboratory tests performed, the dynamic system under analysis (the conductor or the conductor plus the dampers) is subjected to white-noise forced vibrations in the frequency range of 5 Hz to 17.5 Hz by means of a frequency- and amplitude-controlled electrodynamic shaker. The tests are repeated for two excitation levels for the four configurations above described. The two excitation levels used. Our intention was to verify if the measured *FRFs* change with the excitation level, in order to classify the dynamic behavior of the system as linear or nonlinear, as will be seen later on section 3. The electrodynamic shaker is positioned close to the conductor's clamped end far away from the dampers, as indicated on Fig. 2 by the capital letter C. The conductor is appropriately instrumented with a force transducer and three piezoelectric accelerometers for the measurements of the excitation force and response accelerations. The force transducer is placed at the driving point and the piezoelectric accelerometers are placed at the prescribed positions previously reported. At the driving point, a thin rigid rod connects the electrodynamic shaker to the conductor in order to transmit the oscillatory movement. The force transducer is carefully fixed at the tip of the thin rod in order to measure the force transmitted by the excitation source to the conductor.

2.1. Stockbridge damper tested

The damper used in the laboratory tests is an asymmetrical Stockbridge damper, as shown in Fig. 3. Stockbridge dampers with different inertial masses and different lengths of messenger cable on each side of the clamp are referred to as asymmetrical dampers. The clamp is made of an aluminum alloy weighting around 0.500 ± 0.005 kg. The two inertial masses are made of galvanized casting iron; the left one weights 1.450 ± 0.005 kg while the right one weights 0.760 ± 0.005 kg. The messenger cable is composed of one core wire and one layer with six wires helically wrapped around, as shown on the right-side of Fig. 3. All the wires are made of galvanized steel and the overall diameter of the messenger cable is 9.00 ± 0.05 mm. The main dimensions of the Stockbridge damper tested are shown in millimeters in Fig. 3. The position 1.39 m is the position recommended by the manufacturer of the Stockbridge damper tested, when one damper is attached to the conductor under analysis here. The position for the second Stockbridge damper was arbitrarily chosen as 0.70 m.

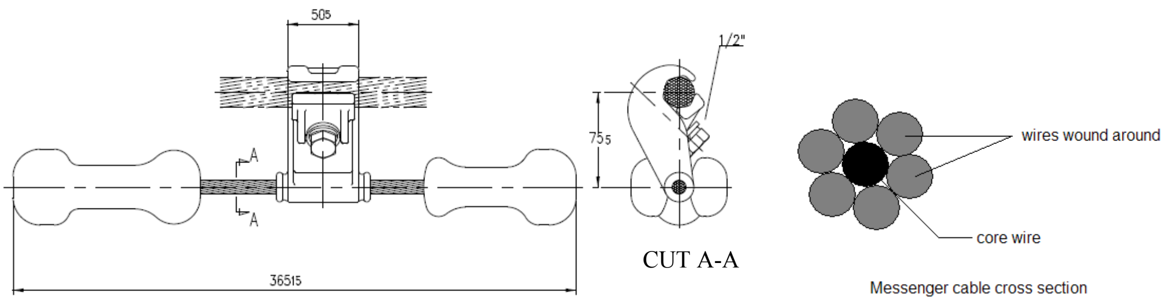

Figure 3. The Stockbridge damper used in the laboratory tests.

2.2. Transmission line conductor tested

The transmission line conductor used in the laboratory tests is the ACSR (Aluminum Conductor Steel Reinforced) Grosbeak. The tests are performed for the conductor Grosbeak subjected to a mechanical load equivalent to 20% of its rated tensile strength. During the tests performed, the mechanical load applied to the conductor is held fixed by means of the counterweight device shown on Fig. 2 (indicated by the capital letter E). The mechanical load applied to the conductor is monitored during all the tests by the load cell indicated on Fig. 2 by the capital letter A. The main geometric and physical properties of the ACSR conductor Grosbeak are indicated on Table 2. It should be noted that in the test performed with the ACSR Grosbeak the sag to span ratio was equal to 0.0039.

Table 2. Geometric and physical properties of the ACSR conductor Grosbeak.

Geometric/Physical Properties	SI Unity	Value
Number of aluminum wires	---	26
Number of steel wires	---	7
Nominal diameter	mm	25.15
Aluminum wire diameter	mm	3.973
Steel wire diameter	mm	3.086
Rated tensile strength	kN	112.8
Weight per unit length	kg/m	1.3025
Minimum bending stiffness (Torres, 1994)	Nm^2	28.4
Maximum bending stiffness (Torres, 1994)	Nm^2	1027

2.3. Experimental setup

The basic setup used in the laboratory tests comprises a frequency- and amplitude-controlled electrodynamic shaker, a four input/one output channel spectral analyzer whose code is HP 35670A, one charge force transducer PCB serial number 172, three Bruel & Kjäer piezoelectric accelerometers Deltatron 4519-0001 and the eight input channel dynamic strain-gauge amplifier/conditioner whose code is Kyowa DPM-8G.

The tests are started by generating a white-noise in the frequency range of 5 Hz to 17.5 Hz with a prescribed amplitude level. The generated signal is then sent to our electrodynamic shaker and measured by the piezoelectric accelerometer placed at the driving point. The force and acceleration signals are read by our spectral analyzer, which computes the desired frequency response functions. Before the beginning of the tests, the spectral analyzer is configured to measure the *FRFs* in the range of 5 Hz to 17.5 Hz with four hundred frequency data points, twenty-five RMS averages with 10% overlap (Ewins, 2000). The high frequency resolution becomes necessary since the eigenfrequencies of the dynamic system under analysis are closely spaced; therefore, only with a large number of frequency data points we are able to obtain well-defined peaks near the resonance frequencies. The acceleration at the driving point is measured by the Bruel & Kjäer piezoelectric accelerometer Deltatron 4519-001 serial number 52031 whose sensitivity is equal 97.09 ± 0.01 mVpeak/g. At the positions given by the coordinates x = 1.39 m and x = 0.70 m, the accelerations are measured by the Bruel & Kjäer piezoelectric accelerometers Deltatron 4519-001 serial numbers 51780 and 52030, whose sensitivities are equal to 98.11 ± 0.01 mVpeak/g and 98.18 ± 0.01 mVpeak/g, respectively. The excitation force is measured by the force transducer PCB serial number 172 whose sensitivity is equal to 20.0 ± 0.2 mVpeak/N.

3. Results and Conclusions

In this section, we present and analyze the experimental *FRFs* for the four configurations described in the previous section. For each configuration, we plot the magnitude of the frequency response function (in unities of g/N) as a function of the excitation frequency for two excitation levels tested: 60 mVpeak and 120 mVpeak. The plots are generated for the driving point and for the other two prescribed positions. The solid line in the plots represents the measured *FRF* for the lowest excitation level while the dashed line represents the measured *FRF* for the highest excitation level. Figure 4 illustrates the magnitude of the *FRFs* measured at the driving point. Figures 5 and 6 illustrates the magnitude of the frequency response functions measured at the positions given by the coordinates x = 1.39 m and x = 0.70 m, respectively. From the experimental curves shown in Figs. 4, 5 and 6 we can draw the following important conclusions for this system presenting the previously specified characteristics:

- the dynamic behavior of the conductor in the absence of Stockbridge dampers may be indeed considered as linear since the magnitude of the *FRFs* remains almost unchanged when the excitation level is duplicated; therefore, the commonly adopted hypothesis of linear dynamic behavior for the overhead conductors (Matt and Castello, 2007; Castello and Matt, 2007) is indeed an acceptable one;
- on the other hand, when the Stockbridge damper tested is attached to the conductor, the dynamic behavior of the system composed by the conductor plus the dampers becomes nonlinear, since the *FRF* is significantly changed by the excitation level; hence, the commonly adopted hypothesis of linear behavior for a Stockbridge damper in order to simplify its interaction with the conductor are in disagreement with regard to the experimental data reported here;
- depending on the frequency range expected for the aeolian vibrations, an increase in the number of Stockbridge dampers may not be the best strategy in order to minimize the conductor vibration amplitudes; and
- indeed, the number and position of the Stockbridge damper tested largely affect the conductor vibration amplitudes.

The conclusions stated above confirm a nonlinear behavior for the system composed by the conductor and the Stockbridge damper tested. Such a similar nonlinear behavior was already verified by other authors for the Stockbridge damper only (Sauter and Hagedorn, 2002; Sauter, 2003). Even though, when dealing with the wind-induced vibrations on overhead conductors equipped with these damping devices, the majority of the theoretical approaches treats both the conductor and the dampers as linear dynamical systems. Moreover, as described in the introduction, the interaction between the conductor and the dampers is commonly idealized by a concentrated force and bending moment, whose magnitude changes linearly with the velocity of the conductor at the attachment points. These assumptions are not supported by the experimental findings reported here. Hence, as stated previously, the linear models available in the literature to compute the response of transmission line conductors with Stockbridge dampers seem to be inappropriate since they are unable to reproduce the nonlinear dynamic behavior of this system.

4. Final Remarks and Comments on Future Works

In this work, we described an experimental set-up built to analyze the dynamic behavior of a typical transmission line conductor equipped with Stockbridge dampers, based on frequency response functions measured at prescribed positions during experimental tests performed at CEPEL's laboratory span. Our intention with these first analyses was to assess the validity of the commonly adopted hypothesis of linear behavior for the dynamic system composed by a transmission line conductor equipped with Stockbridge dampers. The experimental data reported here are new in the literature. These results clearly indicated a linear behavior for the conductor without Stockbridge dampers. However, when Stockbridge dampers were attached to the conductor, the dynamic behavior of the whole system became nonlinear. The experimental data reported here highlight the current need for the improvement of existing theoretical models in order to satisfactorily understand the dynamic response of a transmission line conductor equipped with Stockbridge dampers. With such theoretical models at hands, we will be able to sophisticate the existing computational methodologies in order to provide the optimum damper's number and position.

5. References

Azevedo, C. R. F. and Cescon, T., 2002, "Failure analysis of aluminum cable steel reinforced (ACSR) conductor of the transmission line crossing the Paraná river", Engineering Failure Analysis, Vol. 9, pp. 645-664.

Castello, D. A. and Matt, C. F., 2007, "Estimation of bending stiffness and damping of transmission line conductors", Proceedings of the Inverse Problems, Design and Optimization Symposium (IPDO), Miami, Florida, USA, April 16-18.

Claren, R. and Diana, G., 1969, "Mathematical analysis of transmission line vibration", IEEE Transactions on Power Apparatus and Systems, Vol. 88(12), pp. 1741-1771.

Čermelj, P. and Boltežar, M., 2006, "Modelling localised nonlinearities using the harmonic nonlinear super model", Journal of Sound and Vibration, Vol. 298, pp. 1099-1112.

Dhotarad, M. S., Ganesan, N. and Rao, B. V. A., 1978, "Transmission line vibrations", Journal of Sound and Vibration, Vol. 60(2), pp. 217-237.

Ewins, D. J., 2000, "Modal testing: theory, practice and application", Taylor & Francis Group, 2nd edition, 400p.

Ferreira, J. V., 1998, "Dynamic response analysis of structures with nonlinear components", Ph.D. Thesis, Imperial College of Science, Technology and Medicine, University of London, 283p.

Gabbai, R. D. and Benaroya, H., 2005, "An overview of modelling and experiments of vortex-induced vibration of circular cylinders", Journal of Sound and Vibration, Vol. 282(3-5), pp.575-616.

Hagedorn, P., 1982, "On the computation of damped wind-excited vibrations of overhead transmission lines", Journal of Sound and Vibration, Vol. 83(2), pp. 253-271.

Kraus, M. and Hagedorn, P., 1991, "Aeolian vibration: wind energy input evaluated from measurements on an energized transmission line", IEEE Transactions on Power Delivery, Vol. 6(3), pp. 1264-1270.

Markiewicz, M., 1995, "Optimum dynamic characteristics of Stockbridge dampers for dead-end spans", Journal of Sound and Vibration, Vol. 188(2), pp. 243-256.

Matt, C. F. and Castello, D. A., 2007, "On the numerical identification of the bending stiffness and the damping of transmission line conductors", Proceedings of the 12th International Symposium on Dynamic Problems of Mechanics (XII DINAME), Ilha Bela, São Paulo, Brazil, February 26 – March 2.

Meirovitch, L., 1997, "Principles and techniques of vibrations", Prentice-Hall, 694p.

Meynen, S., Verma, H., Hagedorn, P. and Schäfer, M., 2005, "On the numerical simulation of vortex-induced vibrations of oscillating conductors", Journal of Fluids and Structures, Vol. 21(1), pp. 41-48.

Rawlins, C. B., 1979, "Transmission Line Reference Book: Wind-Induced Conductor Motion", Ed. EPRI, Palo Alto, California, 244p.

Sarpkaya, T., 2004, "A critical review of the intrinsic nature of vortex-induced vibrations", Journal of Fluids and Structures, Vol. 19(4), pp. 389-447.

Sauter, D. and Hagedorn, P., 2002, "On the hysteresis of wire cables in Stockbridge dampers", International Journal of Non-Linear Mechanics, Vol. 37, pp. 1453-1459.

Sauter, D., 2003, "Modelling the dynamic characteristics of slack wire cables in Stockbridge dampers", Dr.-Ing. Thesis (in English), Von Fachbereich Mechanik, Technischen Universität Darmstadt, Germany, 89p.

Schäfer, B., 1984, "Dynamical modelling of wind-induced vibrations of overhead lines", International Journal of Non-Linear Mechanics, Vol. 19(5), pp. 455-467.

Sinha, N. K. and Hagedorn, P., 2007, "Wind-excited overhead transmission lines: estimation of connection stresses at junctions", Journal of Sound and Vibration, Vol. 301, pp. 400-409 (Short Communication).

Torres, M. S., 1994, "Measurement of conductor self-damping by using the concept of travelling waves", Technical Report No. 461 (in Portuguese), Project 3300/2047, Electric Power Research Center, Rio de Janeiro, Brazil.

Tsui, Y. T., 1982, "Recent advances in engineering science as applied to aeolian vibration: an alternative approach", Electric Power Systems Research, Vol. 5, pp. 73-85.

Wagner, H., Ramamurti, V., Shastry, R. V. R. and Hartmann, K., 1973, "Dynamics of Stockbridge dampers", Journal of Sound and Vibration, Vol. 30, pp. 207-220.

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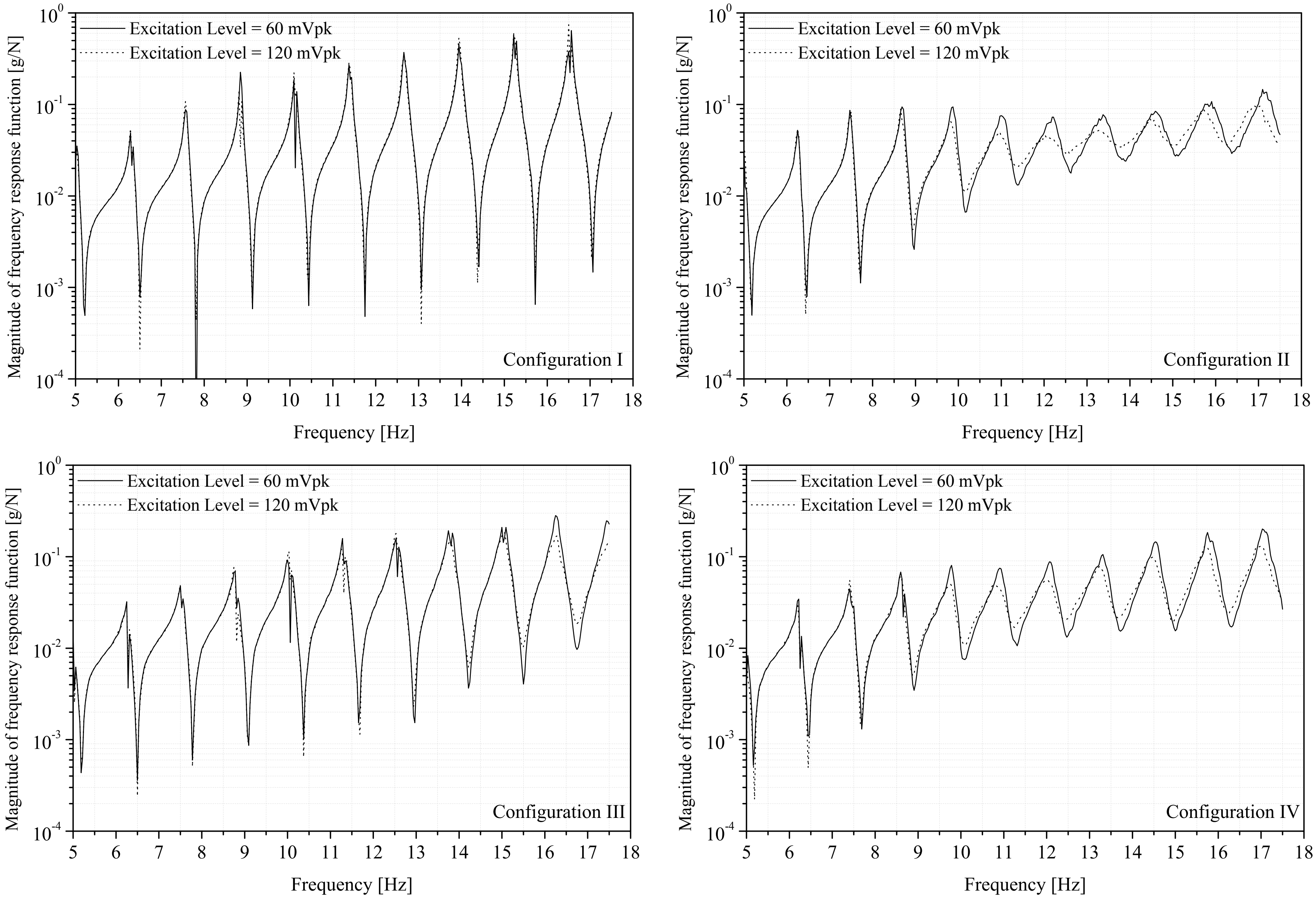

Figure 4. Magnitude of the frequency response function at the driving point for the four configurations tested and for two excitation levels: 60 mVpeak and 120 mVpeak.

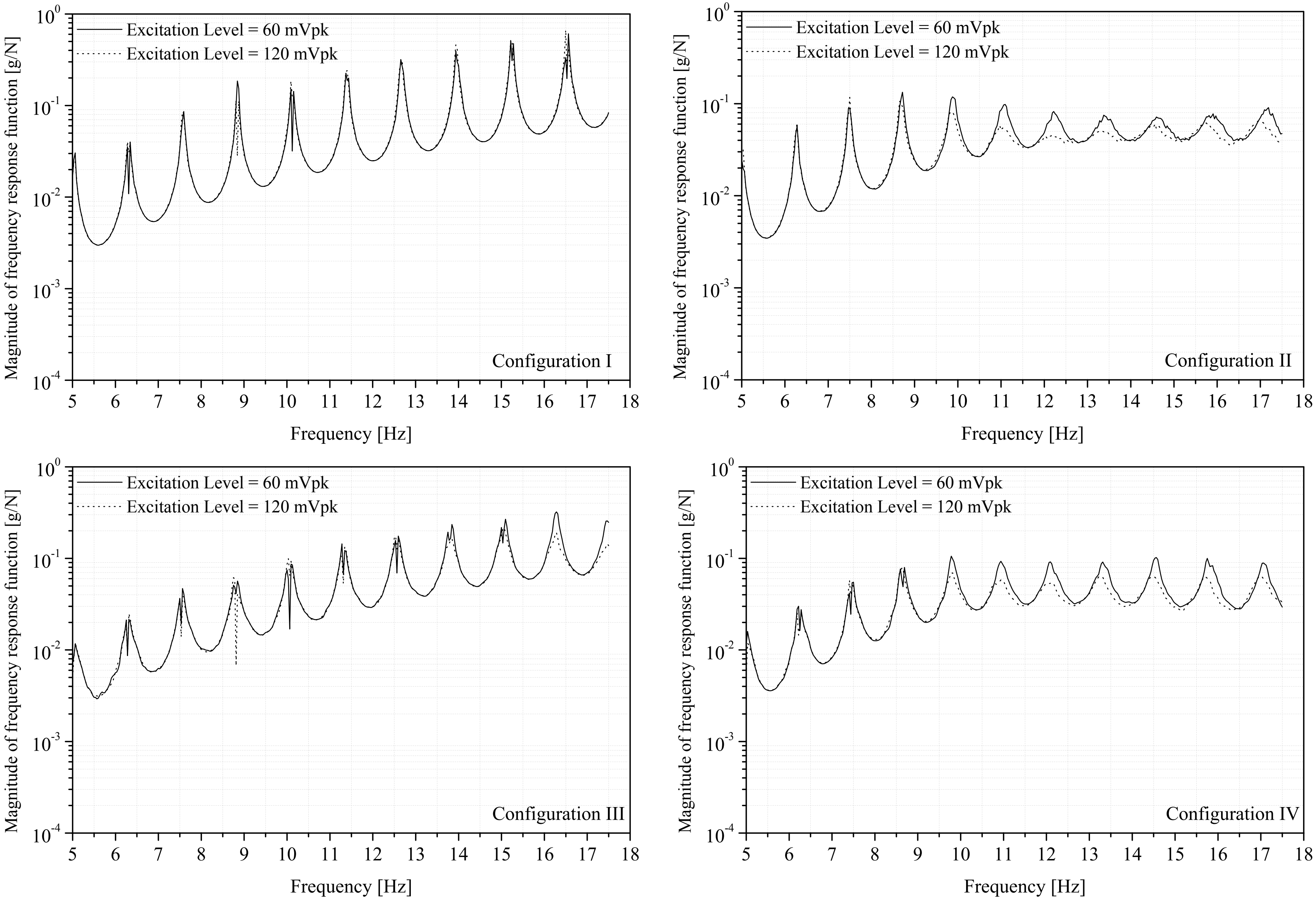

Figure 5. Magnitude of the frequency response function at x = 1.39 m for the four configurations tested and for two excitation levels: 60 mVpeak and 120 mVpeak.

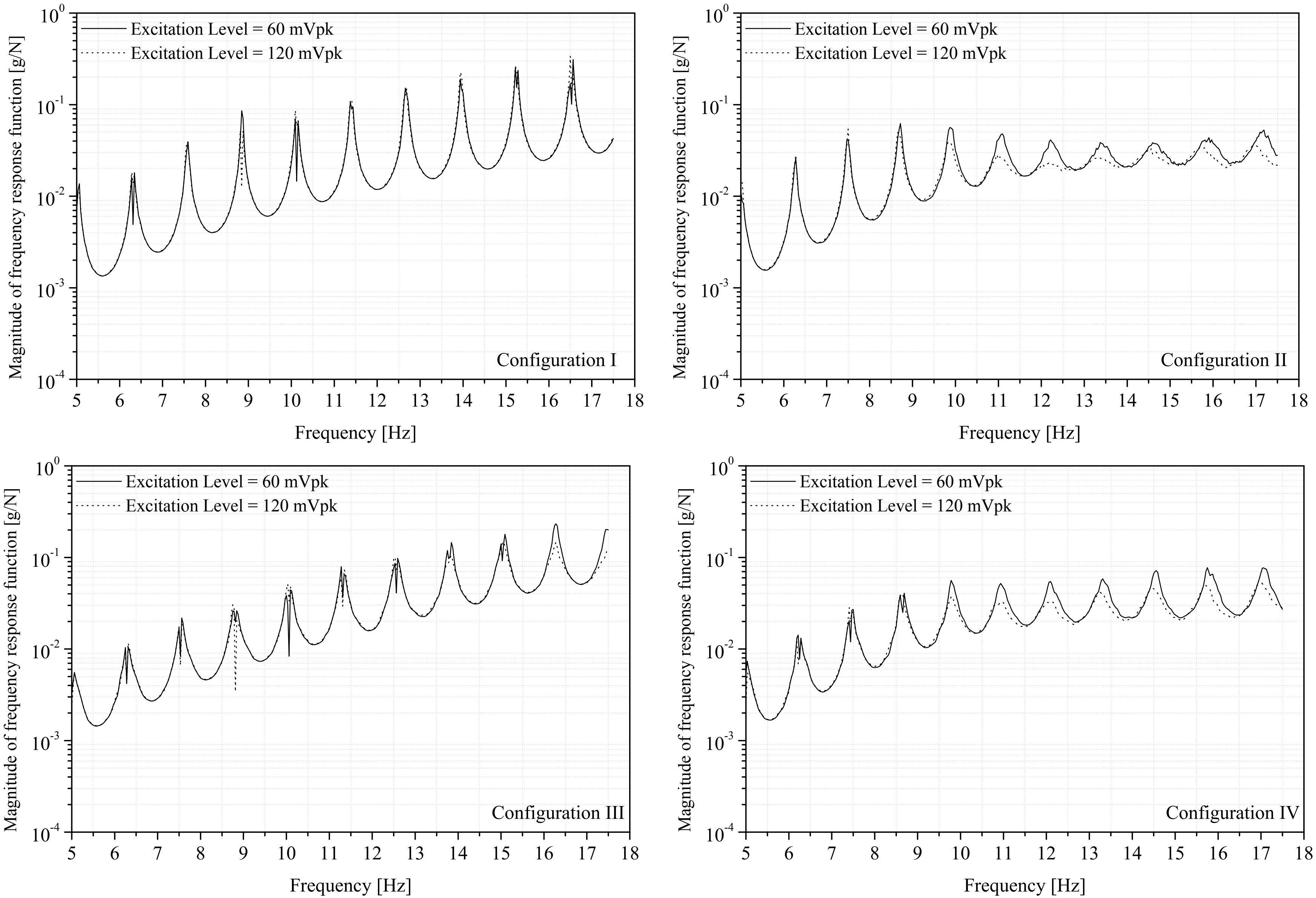

Figure 6. Magnitude of the frequency response function at x = 0.70 m for the four configurations tested and for two excitation levels: 60 mVpeak and 120 mVpeak.