General Conclusions

This brochure has highlighted what can be expected from numerical models regarding conductor vibrations. In the first chapter, the aeolian vibrations of single conductors are obtained using the EBP and compared with experimental results. If the range of uncertainty of the wind power functions and self-damping models which are the main input of those models is indicative of the range of uncertainty of the predicted amplitudes, then the range of uncertainty in EBP predictions of vibration amplitude is about ±50–60%.

Generally, the highest vibration strains are found at relatively low frequencies, where the contribution of dampers to overall damping is much more important than that of conductor self-damping. This is not true at high frequencies. Thus, the largest deviations between models for self-damping, which occur at the lowest frequencies are less important than they may appear.

In practice, assessment of the aeolian vibration condition of particular lines, with conductors whose mechanical properties are poorly defined, or with special terrain conditions, may require field measurements. Techniques to perform such measurements have already been described [CIGRE SC22 WG11 TF2, 1995].

The same exercise has been performed on single conductors equipped with one damper at the end of the span. Benchmark results show a wide dispersion of the predicted maximum amplitude values, and large discrepancies between the analytical predictions and the measured behaviour of the test span. On the other hand, while the dispersion of the dynamic stiffness of different damper samples was reflected in corresponding dispersion in predicted amplitudes, it is not a reflection on the technology, since this dispersion will remain the same, independently of the technology used. Nevertheless, analytical methods based on the EBP and shaker-based technology can provide a useful tool for use in the design of damping systems for the protection of single conductors against aeolian vibrations. It should be used with circumspection and be supplemented by references to field experience.

The modelling of aeolian vibrations has also been evaluated for very long spans strung at relatively high tensions with multi-damper arrangements. It is more challenging since the wind velocity is not homogeneous along such long spans. Furthermore, tension at the support can be significantly greater than at mid-span due

G. Diana (ed.), *Modelling of Vibrations of Overhead Line Conductors*,
CIGRE Green Books, https://doi.org/10.1007/978-3-319-72808-7

to the large sag involved. This can cause the coupling between the vortex-induced forces and the conductor, as well as self-damping, to vary along the span.

The details of the calculation results revealed large differences in predicted clamp amplitudes among the dampers under consideration during steady vibration at a constant frequency, for most of the frequencies covered. Furthermore, these predicted clamp amplitudes were in general very different from the amplitudes on which the damper characteristics were based and, as already observed, represent one of the reasons for the discrepancies between experimental and analytical results.

Future research work is needed to improve the EBP technology, which generally produces a safe design of the damping system.

On bundles aeolian vibrations, the numerical results generally exceed the experimental ones, consequently, they are conservative, at least at low frequencies, however, the comparison was made only with a quad bundle. Other published work (Diana et al. 1976, 1982) has shown that, generally, when dealing with twin bundles, numerical results appear to be less conservative with respect to experimental data.

The sensitivity analysis demonstrated that a non-negligible influence in the assessment of conductor behaviour, when dealing with aeolian vibrations, is given by the introduction of tension differentials and variable wind turbulence with wind speed. Clearly, it is not straightforward knowing the real value to assign to the turbulence and to the tension differentials when the bundle behaviour for aeolian vibrations must be analysed.

Four models have been presented to evaluate the subspan oscillation phenomenon. FEM modelling has been applied with success but it needs a very cumbersome analysis which provides results that depend strongly on details that are not easy to quantify. Methods based on the modal analysis and energy approach seem a more useful tool for practical applications.

As previously shown experimentally, the following parameters have a predominant impact on subspan oscillation amplitudes: bundle tilt, the ratio of vertical to the horizontal frequency in each subspan, tensile load, the ratio of bundle separation over conductor diameter and subspan length. Moreover, the flow on the conductors can vary from sub-critical, critical and super-critical depending on the Reynolds number thus on the conductor diameter, wind speed and surface roughness (conventional vs. trapezoidal) and it has a paramount influence on the energy introduced by the wind.

There was only one experimental benchmark and more results are required to validate the models, however, modelling has shown that one way of controlling subspan oscillations is to increase the subspan oscillation frequency decreasing the subspan length.

This brochure has reported the state of the art regarding aeolian vibrations and subspan oscillations modelling. Of course, this field of expertise is not static and research, as much numerical than experimental, is still going on in order to improve our knowledge of the phenomenon and translate it into improved numerical models.

References

Afanasyeva, O., Ryzhov, S., Feldshteyn, V.: Dynamic models for the study of vibration Power Line conductors and communication cables in the air flow, Problems of Mechanical Engineering and Automation (1) 50–57 (1998a)

Afanasyeva, O., Feldshteyn, V., Ryzhov, S.: Calculation of rational geometry of the helical support clamp under the terms of vibration. Electricheskie Stantsii (Power Plants) (1), 12–17 (1998b)

Anderson, K., Hagedorn, P.: On the energy dissipation in spacer-dampers in bundled conductor of overhead transmission lines. J. Sound Vib. **180**(4), 539–556 (1995)

Bate, E.: The vibration of transmission line conductors. Transaction of the Institution of Engineers (Australia), vol. X, pp. 277–290 (1930)

Belloli, M., Resta, F., Rocchi, D., Zasso A.: Wind tunnel investigation on aeroelastic behaviour of rigidly coupled cylinders. In: Proceeding 5th International Symposium on Cable Dynamics, Santa Margarita Liguria (Italy), 15–18 Sept 2003 (2003)

Brika, D., Laneville, A.: Laboratory investigation of the power imparted by wind to a conductor using a flexible model. In: IEEE (P.E.S.) Winter Meeting (1995)

Brika, D., Laneville, A.: The power imparted by wind to a flexible conductor in the wake of another. IEEE Power Eng. Rev. **17**(1) (1997)

Carrol, J.S.: Laboratory studies of conductor vibration. Electr. Eng. Trans. AIEE Power Apparatus Syst. **55** (1956)

Cigada, A., Manenti, A.: Sulla misura dello smorzamento proprio dei conduttori con il metodo dell'onda stazionaria. Rapporta Interna del Dipartimento di Meccanica del Politecnico di Milano 8–96 (1996)

CIGRE SC 22: WG on Mechanical Oscillations Guide on Conductor Self-Damping Measurements. Guide pour les mesures d'auto-amortissement des conducteurs. Electra no. 62, pp. 79–90 (1979)

CIGRE SC 22 WG 01: Report on aeolian vibration (Rapport sur les vibrations éoliennes). Electra no. 124, pp. 41–77 (1989)

CIGRE SC 22, WG 11, TF 2: Guide to vibration measurement on overhead lines (Guide des mesures des vibrations sur les lignes aériennes). Electra no. 163

CIGRE TF 22.11.01: Modelling of aeolian vibration of single conductors: assessment of the technology. Electra no. 181, pp. 52–69 (1998)

CIGRE TF B2.11.04: Overhead conductor safe design tension with respect to aeolian vibrations. Technical Brochure 273 (2005)

CIGRE TF B2.11.01: Modelling of aeolian vibrations of a single conductor plus damper: assessment of technology. Electra no. 223, pp. 28–36 (2005)

CIGRE WG B2.31: Modelling of aeolian vibration of single conductors strung at relatively high tensile load. Application to HV & UHV lines. Electra no. 256, pp. 34–40 (2011)

CIGRE WG B2.46: Wind induced motion on bundled conductors (excluding ice galloping) Part A —Aeolian vibrations (To be published in 2015)

G. Diana (ed.), *Modelling of Vibrations of Overhead Line Conductors*,
CIGRE Green Books, https://doi.org/10.1007/978-3-319-72808-7

CIGRE WG B2.46: Wind induced motion on bundled conductors (excluding ice galloping) Part B —Subspan oscillations (To be published in 2015)
Claren, R., Diana, G.: Mathematical analysis of transmission line vibration. IEEE Trans. Power Apparatus Syst. **PAS-88**(12) (1969)
Claren, R., Diana, G.: Mathematical analysis of transmission line vibration–IEEE Trans 31C83 '67
Claren, R., Diana, G., Giordana, F., Massa, E.: The vibrations of transmission line conductor bundles. In: 71 TP 158 PWR, IEEE Winter Meeting (1971)
Diana, G., Cheli, F., Fossati, F., Manenti, A.: Aeolian vibrations of overhead transmission lines: computations in turbulence conditions. J. Wind Eng. lndustrial Aerodyn. **46** & **47**, 639–648 (1993)
Diana, G., Di Giacomo, G., Claren, R.: An approach to vortex shedding under turbulent air flow on a single vibrating cylinder. In: IEEE 1979 Summer Meeting, New York, 15 July (1979)
Diana, G., Falco, M.: On the forces transmitted to a vibrating cylinder by a blowing fluid (experimental study and analysis of the phenomenon). Meccanica **VII** (1) (1971)
Diana, G., Falco, M., Gasparetto, M.: On vibrations due to vortex shedding induced on two cylinders with one in the wake of the other. Meccanica (3) (1976)
Diana, G., Falco, M., Cigada, A., Manenti, A.: On the measurement of overhead transmission lines conductor self-damping. IEEE Trans. Power Delivery **15**(1), 285–292 (2000)
Diana, G., Giordana, F.: Sulle vibrazioni di un cilindro in scia di un altro – Analisi del fenomeno con modello analitico. L'Energia Elettrica (7) pp. 448–457 (1972)
Diana, G., Gasparetto, M.: Energy method for computing the amplitude of vibration of conductor bundles due to wake effect. L'Energia Elettrica (1972)
Diana, G., Gasparetto, M., Di Giacomo, G., Nicolini, P.: Analytical method for computing subspan oscillation Analytical and Experimental results. In: C 74 493-3, IEEE Summer Meeting, Anaheim California, USA, 14–19 July 1974 (1974)
Diana, G., Gasparetto, M., Tavano, F., Cosmai, U.: Field measurement and field data processing on conductor vibration (comparison between experimental and analytical results). In: CIGRE' International Conference on Large High Voltage Electric Systems, 1982 Session (1982)
Diana, G., Manenti, A., Cigada, A., Belloli, M., Vanali, M., Pirotta, C., Zuin, A.: Stockbridge type damper effectiveness evaluation: parts I and II. IEEE Trans. Power Delivery **18**(4), 1462–1477, Oct 2003 (2003)
Diana, G., Manenti, A., Belloli, M., Muggiasca, S., Bousseau, P., Peyrard, C., Relun, N.: Modeling of Aeolian vibration of overhead line conductors with wind speed variations along and across the span. In: 8th International Symposium on Cable Dynamics, Clamart (France), 20–23 Sept 2009 (2009)
Diana, G., Belloli, M., Manenti, A., Muggiasca, S., Guglielmini, S., Bousseau, P.: Impact of turbulence on vortex induced vibrations and fatigue of conductors: modelling and real span experimentation. In: CIGRE General Session, Paris 2010, Paper B2-303 (2010)
Diana, G., Belloli, M., Giappino, S., Manenti, A., Mazzola, L., Muggiasca, S., Zuin, A.: Wind Tunnel testing developments in the last 50 years. In: 2013 European and African Conference on Wind Engineering, Robinson College, Cambridge, UK, 7–11 July 2013 (2013)
EPRI: Transmission line reference book—wind-induced conductor motion, 2nd. edn, pp. 3–25. Electric Power Research Institute, Palo Alto, Ca 2009 1018554, USA (2009)
Falco, M., Gasparetto, M., Nicolini, N., Di Giacomo, G.: Comportamento vibratorio di lunghe campate di attraversamento, equipaggiate con conduttore singolo e con dispositivi smorzanti. L'Energia Elettrica (5) 311–324 (1973)
Farquharson, F.B., McHugh, R.E.: Wind tunnel investigation of conductor vibration using rigid models. Trans. AIEE Power Apparatus Syst. **75** (part III) (1956)
Foata, M., Noiseux, D.: Computer analysis of asymmetries of a two-conductor bundle upon its aeolian vibration. IEEE Trans. Power Delivery **6**(3) (1991)
Hadulla, T.: Vortex-induced vibrations in overhead line conductor bundles. Doctoral Thesis, Technische Universität Darmstadt (2000)
Hagedorn, P.: On the computation of damped wind-excited vibrations of overhead transmission lines. J. Sound. Vib. **83**(2), 263–271(1982)

Hagedorn, P., Schmidt, J.: The effect of a damper on a vibrating conductor calculated by use of the complex mechanical impedance of the damper, Annals Cigre 22-86 (WG01) 05, Nov 1985 (1985)

Hardy, C.: Comparison of theoretical calculations and field measurements on single conductors. CIGRE 22-91 (WG11-TF1) 9 (1991)

Hardy, C., Leblond, A.: Comparison of conductor self-damping measurements. CIGRE SC 22-93 (WG 11) 88 (1993)

Hardy, C., Van Dyke, P.: Field observations on wind-induced conductor motions. J. Fluids Struct. 43–60 (1995)

IEC 61897: Requirements and tests for stockbridge type aeolian vibration dampers. (1998)

IEEE Std. 563-1978: Guide on conductor self-damping measurements (1978)

IEEE Std. 664-1993: Guide on the measurement of the performance of Aeolian vibration dampers for single conductors (1993)

Ikegami, R., et al.: Structural analysis. High Voltage Power Transmission Systems—Boeing Co. Seattle BPA Ctr 14-03-1362N (1971)

Ko, R.G.: Theoretical investigation for Hydro-Quebec into the aerodynamic stability of bundled power line conductors, Part I: two dimensional stability analysis of a conductor in the wake of a fixed conductor. Lan Tech Rep LA-122, NRC (Canada) (1973)

Kraus, M., Hagedorn, P.: Aeolian vibrations: wind energy input evaluated from measurements on an energized transmission line. IEEE Trans. Power Delivery **6**, 1264–1270 (1991)

Leblond, A., Hardy, C.: Aeolian vibration calculations of conductor-damper systems, 22-00 (WG11-TF1) 09, Kolding, May 2000 (2000)

Leblond, A., Hardy, C.: On the computation of safe design tension with regard to aeolian vibration of damped single conductors. In: Proceeding of the 4th International Symposium on Cable Dynamics, pp. 137–144, Montréal, 28–30 May 2001 (2001)

Leblond, A., Hardy, C.: On the estimation of a 2x2 complex stiffness matrix of symmetric stockbridge-type dampers. 3rd International Symposium on Cable Dynamics, Trondheim, Norway, Aug 1999 (1999)

Möcks, L., Schmidt, J.: Survey of measurements of mechanical self-damping of ACSR conductors. CIGRE SC 22-89 (WG 11) TFI-2 (1989)

Noiseux, D.U.: Similarity laws of the internal damping of stranded cables in transverse vibrations. IEEE Trans. Power Delivery **7**(3), 1574–1581 (1992)

Noiseux, D.U., Houle, S., Beauchemin, R.: Transformation of wind tunnel data on aeolian vibration for application to random conductor vibrations in a turbulent wind. IEEE Trans. Power Delivery **83**(2), 263–271 (1988)

Palazuelos, E., Izquierdo, J., Fernandez, A.: Control of conductors to prevent construction problems. In: 1989 International Conference on Overhead Line Design and Construction: Theory and Practice, 84–88 (1988)

Papailiou, K.O.: On the bending stiffness of transmission line conductors. IEEE Trans. Power Delivery 12(4) Oct 1997 (1997)

Pon, C.J., Havard, D.G., et al.: Aeolan vibrations of bundle conductors. Canadian Electrical Association, Report No. 177 T 510 (1989)

Price, S.J., Païdoussis, M.P.: The aerodynamic forces acting on groups of two and three circular cylinders when subject to a cross-flow. J. Wind Eng. Ind. Aerodyn. **17,** 329–347 (1984)

Rawlins, C.B.: Recent developments in conductor vibration research. Technical Paper No. 13, ALCOA Lab (1958)

Rawlins, C.B.: Effect of wind turbulence in wake–induced oscillations of bundled conductors. In: Conference Paper C74 444–6, IEEE PES Summer Meeting, Anaheim, CA, 14–19 July 1974 (1974)

Rawlins, C.B.: Fundamental concepts in the analysis of wake-induced oscillation of bundled conductors. IEEE Trans. Power Apparatus Syst. **PAS–95**(4), 1377–1393 (1976)

Rawlins, C.B.: Extended analysis of wake-induced oscillation of bundled conductors. IEEE Trans. Power Apparatus Syst. **PAS–96**(5), 1681–1689 (1977)

Rawlins, C.B.: Power imparted by wind to a model of a vibrating conductor. Technical Report No. 93-82-1 EL Prod. Div, ALCOA Lab., Massena, N.Y. (1982)

Rawlins, C.B.: Model of power imparted by turbulent wind to vibrating conductor. Report No. 93-83-3, Alcoa Conductor Products Co., Spartanburg, South Carolina (1983a)

Rawlins, C.B.: Notes on the measurements of conductor self-damping. Report W 93-83-4, Alcoa Lab., Alcoa Conductor Products Co. (1983b)

Rawlins, C.B.: Wind tunnel measurements of the power imparted to a model of vibrating conductor. IEEE Trans. Power Apparatus Syst. **PAS-102**(4) (1983c)

Rawlins, C.B.: An efficient method for measuring dissipation by dampers in laboratory spans. IEEE Trans. Power Delivery **3**(3) (1988)

Rawlins, C.: Conductor self-damping data and comparison between theoretical and experimental data on aeolian vibration on single conductor. CIGRE 22-92 (WG11-TF1) 12 (1992)

Rawlins, C.B.: Calculation of damping efficiency of dampers from damper impedance. 22-97 (WG11-TF1) 31, Sendai. Oct 1997 (1997)

Rawlins, C.B.: The long span problem in the analysis of conductor vibration damping. IEEE Trans. Power Deliv. **15**(2) (2000)

Seppa, T.: Self-damping measurements and energy balance of ACSR drake. IEEE WPM, Paper No. 71 CP-161 (1971)

Sergey, I., Vinogradov, A.: Mathematical simulation and calculation experiment for different forms of conductors dynamics. In: Proceeding 5th International Symposium on Cable dynamics, pp. 93–100, Santa Margherita, Italy, 15–18 Sept 2003 (2003)

Seveso, A.: Politecnico di Milano, Dipartimento di Meccanica Valutazione sperimentale dello smorzamento strutturale del conduttori e proposta di una metodologia di misura da applicare al metodo dell'onda stazionaria. Tesi Laurea di G. De Nardis, A. Seveso, AA. 95–96 (1996)

Simpson, A.: On the flutter of a smooth circular cylinder in a wake. Aeronaut. Q (1971)

Slethei, T. O., & Huse, J.: Conductor vibration—theoretical and experimental investigations on a laboratory test span. In: Proceedings of the Institution of Electrical Engineers, IET Journals & Magazinese, 112(6), 1173–1179 (1965)

Snegovskiy, D.: Wake-induced oscillations in cable structures: finite element approach. Available on http://bictel.ulg.ac.be/ETD-db/collection/available/ULgetd-07142010-102207/ (2010)

Snegovskiy, D., Lilien, J.L.: Nonlinear finite element approach to simulate wake-induced oscillation in transmission system. In: Proceedings of ASME 2010 3rd Joint US-european Fluids Engineering (FEDSM2010). Available on http://hdl.handle.net/2268/102157 (2010)

Streliuk, M.I., Serguey, I.I. Vinogradov, A.A., Krasnov, V.A.: Dynamic loads on spacers at subspan oscillations of the EHV T/L conductors. Energ. Stroit. (1), 67–71 (in Russian) (1986)

Tavano, F.: Results of self-damping measurements on conductors for overhead lines and on earth wires with optical fibres. Cigre SC 22-88 (WG 11) 18 (1988)

Tavano, F.: Collection of experimental data on aeolian vibration on single conductors. CIGRE 22-91 (WG11 TF1) 6 (1991)

Tompkins, J.S., Merrill, L.L., Jones, B.L.: Quantitative relationships in conductor vibration damping. IEEE Trans. PES **75**, 879–894 (1956)

Tsui, Y.T.: Two dimensional stability analysis of a circular conductor in the wake of another. IEEE Paper A75 576-9 (1975)

Wardlaw, R.L., Cooper, K.R.: A wind tunnel investigation of the steady aerodynamic forces on smooth and stranded twin bundled power conductors for the Aluminum Company of America. Lab Tech Rep LA-117, NRC (Canada) (1973)