On the performance of direct piezoelectric rotational accelerometers in experimental structural dynamics

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Abstract

Rotational responses are comparing to the translational responses less frequently used in the experimental structural dynamics. Even though they represent half of all the existing degrees of freedom they are often omitted, since they are difficult to measure. Nevertheless, they have an important contribution in structural dynamic modifications, model validation, substructuring etc. Therefore in this paper a performance evaluation of two direct piezoelectric rotational accelerometers is made in order to show the possibilities of their usage in the structural dynamic applications. Additionally, the results are compared to a commonly used method of approximated rotational responses obtained from two offset translational accelerometers. Sensors were tested with impact and sine-sweep excitations. Data is analyzed in the form of frequency response functions and compared to a numerical reference with a coherence criterion. The quality of directly obtained rotations are expected to have great potential in structural dynamics.

Keywords: Rotational degrees of freedom, direct piezoelectric rotational accelerometer, indirect rotational reconstruction, frequency response function, coherence criterion

1. Introduction

System's moment inertia is defined by rotational degrees of freedom (DoFs). The latter represents half of all the existing DoFs and can be expressed in the form of time series, frequency response functions (FRFs) or modal shape

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slopes. Their implementation in a numerical model is a common procedure, however several issues appear whenever they are obtained experimentally due to the data contamination [1–3]. Consequently, this represents some limitations in the applications such as structural dynamic modifications [4], model updating and validation [5], acoustics [6] as well as dynamic substructuring [7, 8]. Nevertheless, since the quality experimental rotational DoFs influence the accuracy of structural dynamic characteristics, the methods to efficiently measure the rotations are still the subject of ongoing research.

A lot of effort has been invested so far in sensors development to obtain rotational motion as well as procedures to apply a pure moment excitation. A general overview of some original methods including T-block element, mass additive techniques, finite differences, estimation techniques, simple transducers and usage of laser setup are summarized in papers [9, 10]. Those methods set standards upon which newer procedures were proposed in recent years in order to improve their deficiencies. Procedure of finite differences theory, together with two offset translational accelerometers can be found in [11, 12]. Methods to apply pure moment excitation for mass normalized FRFs has been proposed in [5, 13, 14]. A new type of sensors based on bimorph materials [15, 16], micro electro mechanical systems (MEMS) [17, 18], strain gages [19] and piezoelectric materials [20] has been also developed in recent years. However, extensive research in this field still does not provide reliable procedure that would gain much popularity in the real applications. Therefore, researcher have also tried to combine experimental and numerical results [21] or even completely replace the rotational responses based on the translational approximations [7].

Omitting or replacing rotational responses with approximation may be sufficient whenever analytical or numerical data are used. However, any approximation normally relays on predetermined assumptions, which may be very difficult to be satisfied in the practice. Further, taking into account typical data contamination [22–24], consequently leads to the erroneous final result. Thus, in this paper, performance evaluation of force-excited rotational responses is made with two commercially available direct quartz based piezoelectric rotational accelerometers and indirect reconstruction of rotational responses based on T-element with two offset translational responses. In contrast to classical translational accelerometers, direct rotational accelerometers are rarely used in the field of experimental structural dynamic. This is related with their high cost, additional experimental work and expansion of DoFs in the numerical model. Moreover, difficulties with pure moment excitations prevents to obtain mass normalized modal shape slopes. Therefore, direct rotational sensors are more frequently used for active control of oscillating shafts and car crash testings [25]. The latter are more typical for active control of oscillating shafts and car crash testings [25]. However, lightweight and robust construction as well as wide dynamic and frequency range seems to be suitable also for structural dynamics applications. Therefore, a comprehensive analysis is performed in order to assess the adequacy of direct rotational sensors for experimental structural dynamics analyses. A comparison of FRFs associated with rotational DoFs is performed on a steel plate with several combinations between excitation and measuring points. The most frequently used reconstructed rotational responses obtained using T-element are compared with an old and new generation of Kistler Type 8840 direct rotational accelerometers. The analysis is captured by proposing impact and sine sweep excitations applied with modal hammer and electrodynamics shaker. The quality of the measured FRFs is assessed based on a comparison with numerical reference using visual inspection and coherence criterion.

The following section briefly presents a quartz based piezo-electric rotational accelerometer and T-element for indirect approximation of rotational DoFs, in third section an experimental setup is explained, followed by testing results and coherence criterion.

2. Rotational sensors

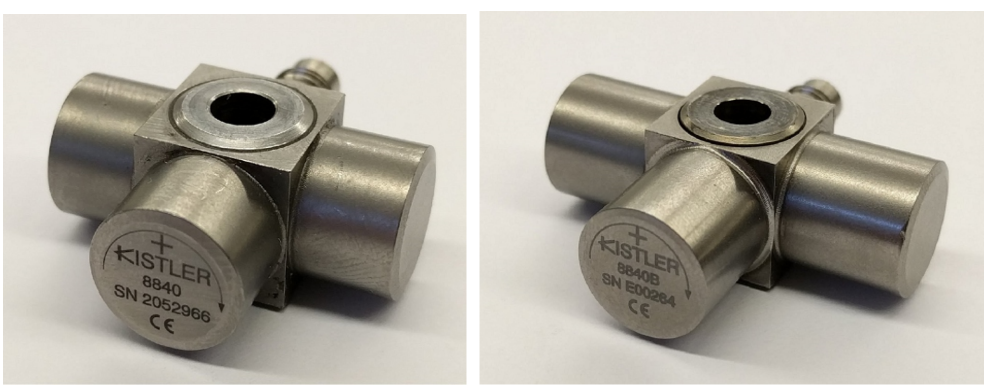
A brief presentation and technical specifications of direct piezoelectric rotational accelerometers and indirect T-element are given in this section as they are used in a performance evaluation test.

2.1. Direct rotational accelerometer

Piezoelectric rotational accelerometers are direct sensors for obtaining angular motion of a structure. They are based on a very stable quartz crystal and do not use standard voltage mode piezoelectric sensor couplers (IEPE types), but are powered by any commercially available 20-30 VDC power supply. In this paper an older generation Kistler Type 8840 and a newer generation Kistler Type 8840B are analyzed. Both of them have two spatially separated quartz shear-mode-element assemblies [25]. Direct sensing of rotational DoFs has several benefits comparing to the indirect options. One of the most important quality is a sensitivity-matching of each quartz element, where an error of 0.25 % in sensitivity-matching can contribute 12.3 % error to the final result [25]. Further, local flexibility is not an issue due to the small size and one point attachment. Moreover, lightweight, compact and robust construction as well as wide dynamic and frequency range meet all the typical experimental modal analysis (EMA) conditions. Technical specifications are presented in Table 1. For additional information a reader is referred to [25].

Table 1: Technical specifications of quartz-based piezoelectric rotational accelerometer, Kistler Type 8840 and 8840B.

Technical data	Units	Type 8840	Type 8840B
Acceleration range	$\mathrm{k\,rad/s^2}$	±150	±8
Sensitivity	$\mu\mathrm{V/rad/s^2}$	35.5	600
Freq. response	Hz	1...2000	0.5...3000
Resonant frequency	kHz	23	23
Transverse sensitivity	%	<1.5	<2
Mass	g	18.5	23

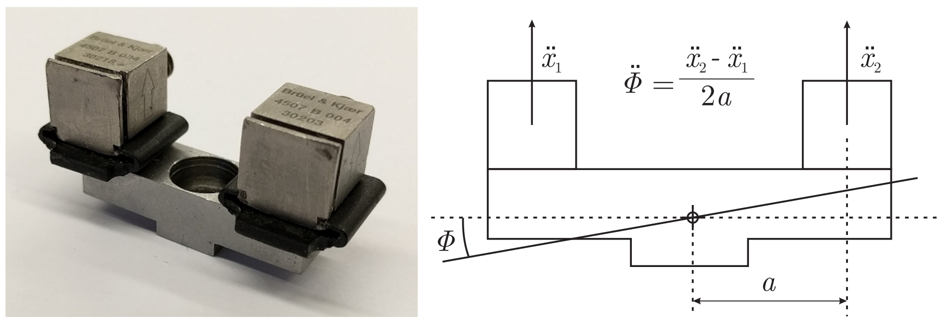


(a) (b)

Figure 1: Direct rotational accelerometers: a) Kistler Type 8840, b) Kistler Type 8840B.

2.2. Indirect measurement of rotations using T-element

T-element was used for indirect reconstruction of rotational motion as proposed by Ewins et al. [26]. This method presents one of the most commonly used procedure to experimentally obtain rotations. It consist of two precisely positioned translational accelerometers attached on a steel T shape element with adhesive mounting base (Figure 2a). Reconstruction of rotational DoFs is schematically presented in Figure 2b. The parameters of T-element are shown in Figure 3 and given in Table 2.



(a) (b)

Figure 2: T-element: a) Assembly of T-element, b) Reconstruction of rotational DoFs.

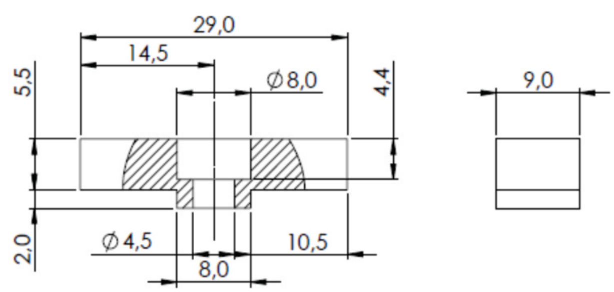


Figure 3: Technical documentation of T-element [mm].

Table 2: Technical specifications of translational accelerometers and T-element.

Technical data	Units	Brüel & Kjær Type 4507-B-004	T-element (with sensors)
Acceleration range	ms^{-2}	700	/
Sensitivity	mV/ms^{-2}	10	/
Freq. response	Hz	0.3...6000	/
Resonant frequency	kHz	19	∼4.2 (FEM[1])
Transverse sensitivity	%	<5	/
Mass	g	4.6	12

[1] Finite Element Method

3. Experimental setup

Experimental setup is schematically presented in Figure 4. Impact excitation was performed with a modal hammer and a sine sweep excitation with an electrodynamic shaker powered by power amplifier. Excitation signals were transfered through NI DAQ output module. On the other side signals were acquired with NI DAQ input module and analyzed with Python script. Two direct piezoelectric rotational sensors as well as indirect T-element were mounted with a M5 screw and tightened with a 2 Nm of torque on a free-free supported steel plate. Dimensions of plate as well as experimental point locations and directions are shown in Figure 5a.

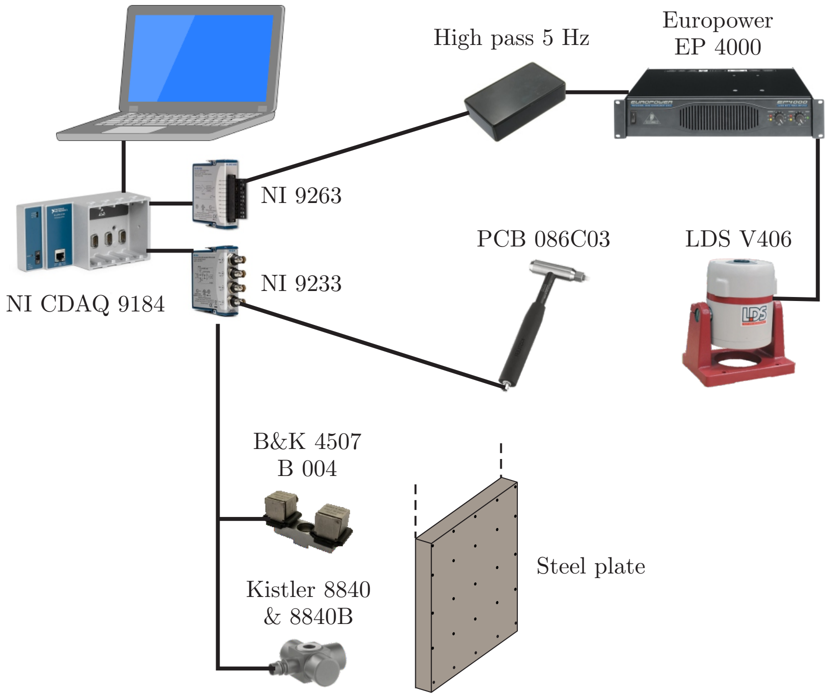
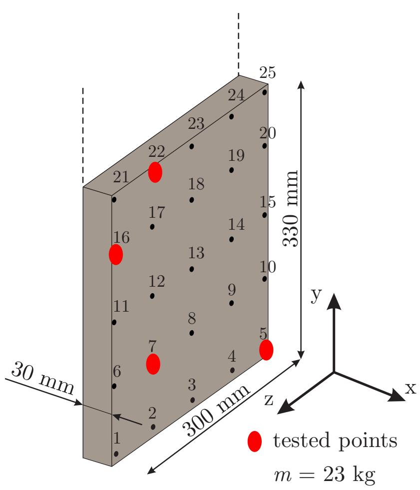


Figure 4: Experimental setup.



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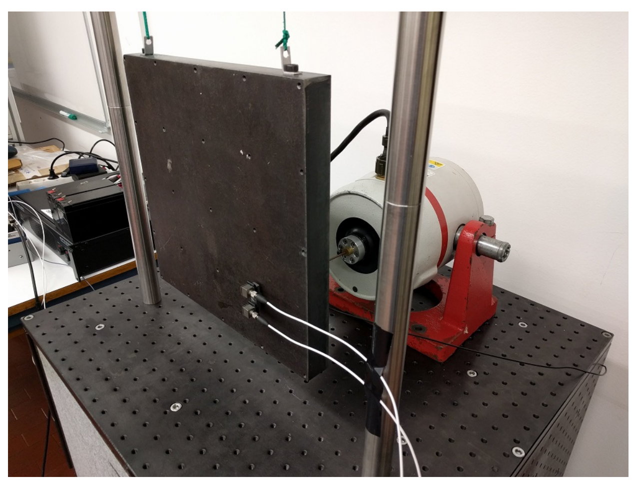


(b)

Figure 5: Experimental setup: a) Dimensions and measuring points on a steel plate, b) T-element measurement setup.

4. Testing and results

Experimental investigation was performed in order to evaluate performance capabilities of direct and indirect piezoelectric rotational accelerometers in the experimental structural dynamics. Sensors were tested using two excitation types. The first one is impact excitation applied by a modal hammer and the second one a sine sweep excitation performed with an electrodynamic shaker. Measurements were obtained in all mutual combinations between four input and output experimental points (Figure 5a). All together 16 FRFs for each sensor. The results were compared with FRFs from an equivalent numerical model up to 3 kHz. Numerical model is made of 2D mesh with around 1800 four node shell elements and six DoFs in each node (around 11 k DoFs altogether). Elastic modulus was 210 GPa, Poisson's ratio 0.3 and density of 7849 kg/m^3. Preliminary analysis of 23 kg steel plate shows that the mass of additionally mounted sensors has a neglegible effect on the dynamic properties of the system. Therefore sensor's mass was not included in the numerical model. The first pair of FRF indexes marks output or response and the second pair input or excitation position and direction. Beside graphical presentation, an additional correlation with a numerical reference is made using coherence criterion. This is unity scaling criterion that compares two different FRFs for the same input-output position and direction. Values closer to one represent perfect correlation and on the other side values closer to zero no correlation at all. Coherence criterion is expressed as [27]:

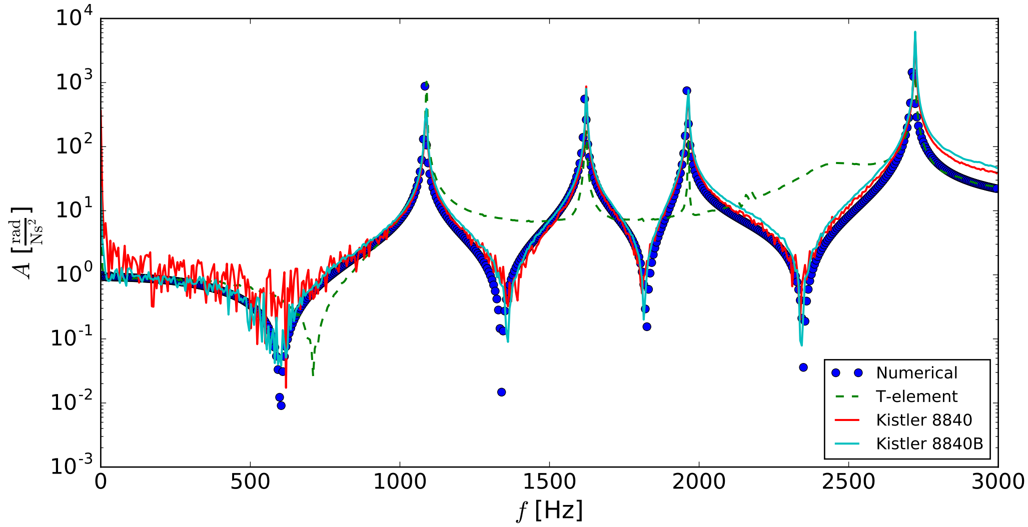
$$\mathrm{coh}_{ij} = \frac{(\mathrm{H}_{ij}^{\mathrm{num}} + \mathrm{H}_{ij}^{\mathrm{exp}})(\mathrm{H}_{ij}^{\mathrm{num}*} + \mathrm{H}_{ij}^{\mathrm{exp}*})}{2\,(\mathrm{H}_{ij}^{\mathrm{num}*}\,\mathrm{H}_{ij}^{\mathrm{num}} + \mathrm{H}_{ij}^{\mathrm{exp}*}\,\mathrm{H}_{ij}^{\mathrm{exp}})}; \quad i = 1,2,3,4; \quad j = 1,2,3,4, \quad (1)$$

where $\mathrm{H}_{ij}^{\mathrm{num}}$ and $\mathrm{H}_{ij}^{\mathrm{exp}}$ stand for numerical and experimental FRF for particular output i and input j location and $\mathrm{H}_{ij}^{\mathrm{num}^*}$ as well as $\mathrm{H}_{ij}^{\mathrm{exp}^*}$ for their complex conjugation.

4.1. Impact excitation

Impact excitation was performed using a modal hammer and aluminum tip within frequency band of excitation up to 4.2 kHz. Two transfer point FRFs for all three sensors are compared with a numerical FRFs (Figure 6).

Indirectly obtained rotational responses using T-element poorly define anti-resonance regions. Those are local characteristics of a tested system



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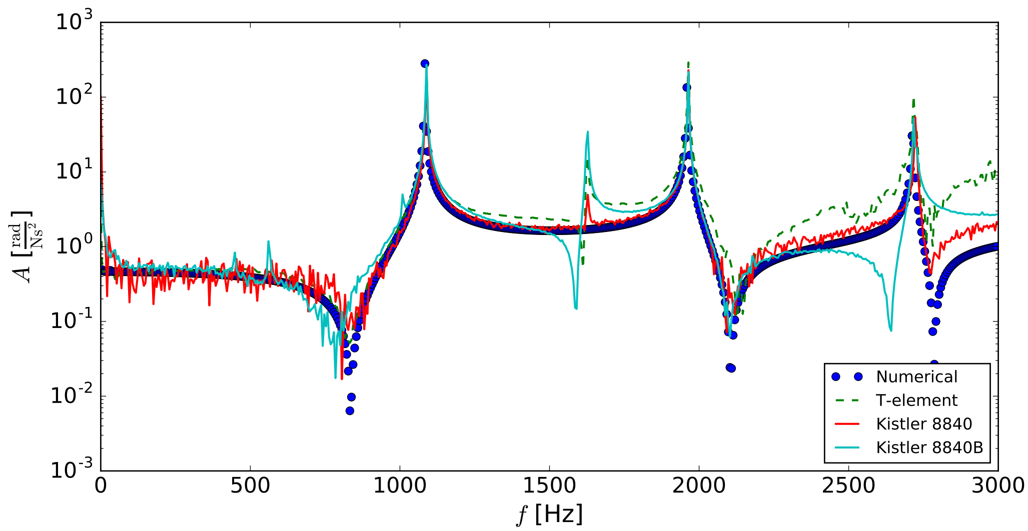


(b)

Figure 6: FRFs induced by impact excitation: a) FRF_{7rz7x}, b) $\mathrm{FRF}_{16rz22x}$.

mostly influenced by sensor's position and cross sensitivity effect. The latter is related by geometrical imperfections of T-element and mismatch of translational accelerometer's sensitivity factor. Moreover the position is also affected due to the big size and misalignment caused by test operator. Nevertheless, natural frequencies are well aligned with a numerical FRFs but their amplitudes and corresponding damping factor are quite inaccurate. Noise level is fairly low through entire frequency range but overall quality of the signal is not suitable for further use in applications such as dynamic substructuring, where even small misalignment of anti-resonances leads to erroneous final results [22–24]. Coherence values in Figure 7a are in average equal to 0.7. On the other side a directly obtained rotational responses seem to provide more accurate results in terms of natural frequencies, their amplitudes and also anti-resonance regions within entire 3 kHz frequency range. Despite calibration limit at 2 kHz for Type 8840 accelerometer the results match with a numerical reference within entire frequency range. Noise level for that particular sensor is higher comparing to the newer Type 8840B accelerometer especially at lower frequencies below 500 Hz. Amplitudes and damping factors are in both cases quite well aligned with a numerical FRFs. Coherence values in Figures 7b and 7c are around 0.9 with slightly higher values for a newer Type 8840B. In the case of same node and different DoFs measurement a spurious peak appears around 1.6 kHz for of all three sensors. Reason for this is probably related with misalignment of sensors position deviating from exact location. However, small and robust construction of direct rotational sensors as well as optimal position of well matched quartz-lattices ensures satisfied results that are comparing to indirect option more suitable for structural dynamic application. Beside lower level of noise of the newer Type 8840 the obtained results are practically the same for both sensors.

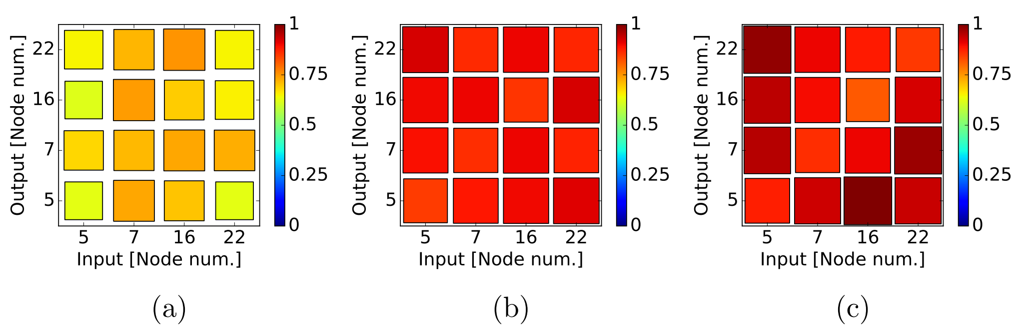
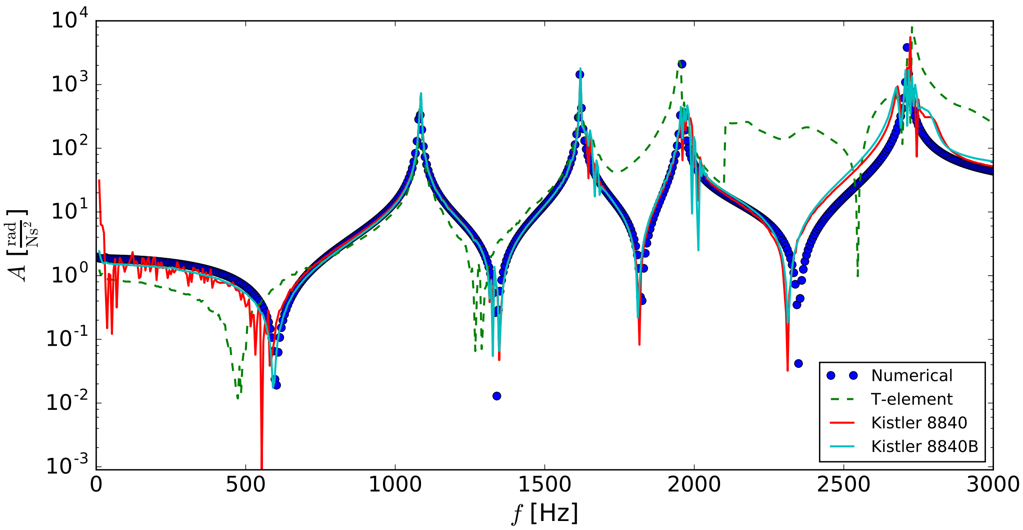


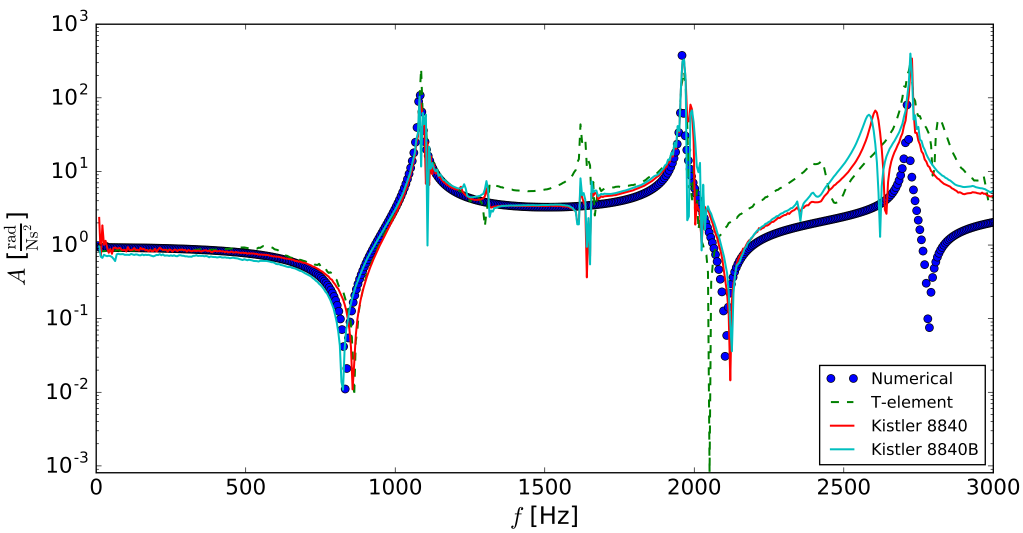
Figure 7: Coherence values between numerical and experimental FRFs: a) T-element (coh. avg. 0.69), b) Kistler Type 8840 (coh. avg. 0.88), c) Kistler Type 8840B (coh. avg. 0.91).

4.2. Sine sweep excitation

Sine sweep excitation was applied using electrodynamic shaker in a frequency band between 10 Hz and 3 kHz. Two typical transfer point FRFs are presented in Figure 8. Probably due to the more controlled input of energy at each frequency, low level of noise is present for all three sensors. Similar to impact excitation, a T-element provide less accurate results comparing to direct sensors especially above 1.5 kHz. Although the natural frequencies are well correlated with the numerical reference, overall shape of the FRF is completely erroneous. Due to this, the values of coherence criterion in Figure 9a are in average 0.6. With both direct sensors better definition of static response and lower frequency responses are achieved. However, multiple spurious peaks appears around natural frequencies. Analogous to the hammer impact, mode around 1.6 kHz appears probably due to offset of sensor position. The latter, slightly decrease a coherence values on the diagonal in Figures 9b and 9c but an average still remains around 0.87. In general a responses below 2 kHz are more correlated with a numerical FRFs comparing with a higher frequency responses. This is true for both resonance and anti-resonance regions for all three sensors.



(a)



(b)

Figure 8: FRFs induced by sine sweep excitation: a) FRF_{7rz7x}, b) $\mathrm{FRF}_{16rz22x}$.

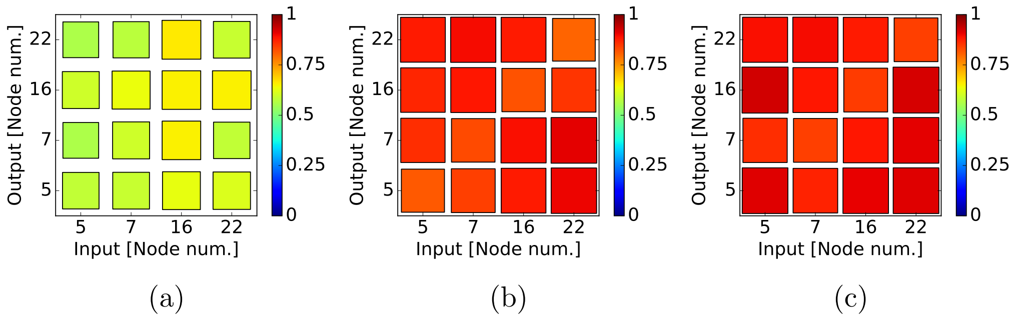


Figure 9: Coherence values between numerical and experimental FRFs: a) T-element (coh. avg. 0.61), b) Kistler Type 8840 (coh. avg. 0.86), c) Kistler Type 8840B (coh. avg. 0.89).

5. Conclusions

The objective of this paper was to access the performance capabilities of commercially available direct rotational accelerometers for identification of rotational DoFs in the field of structural dynamics. Comparison consisted of two direct rotational sensors and commonly used indirect rotational sensor based on a reconstructed translational responses. Test was performed on a simple steel plate for different input and output locations. Plate was excited with impact and sine-sweep excitations and responses obtained in the form of FRFs. The results from both direct rotational accelerometers are in general more accurate comparing to the reconstructed rotational responses from T-element. This is true for global systems characteristics such as natural frequencies, the height of their amplitudes and damping factors as well as local characteristics; positions of anti-resonances. The latter are very sensitive to sensors position which is in the case of T-element difficult to control due to its size and inevitable minor dislocations of two accelerometers. Cross sensitivity is the next influential feature more effectively canceled out within direct sensors based on completely controlled construction environment, which is difficult to achieve by construction of the T-element. T-element produces lower level of noise for both excitation types in entire frequency range. Rotational responses obtained using direct accelerometers are relatively good aligned with numerical reference within 3 kHz frequency range, which is not the case for indirect rotational responses, where the increasing deviation is observed above 2 kHz.

Overall, compact and robust construction of direct rotational sensors, simplicity of use and nevertheless the quality of the FRF responses seems to have great potential in the variety of structural dynamic applications. Comparing to indirect options, they are far more accurate and reliable despite the slightly higher levels of noise in signals. However, there is a drawback with a direct rotational sensors, since their price is noticeable higher comparing to classical translational accelerometers. Cost of individual sensor is in the range of a few thousand dollars.

References

[1] K. Tomczyk, E. Layer, Accelerometer errors in the measurement of dynamic signals, Measurement 60 (2015) 292–298.

[2] G. D'Emilia, A. Gaspari, E. Natale, Evaluation of aspects affecting measurement of three-axis accelerometers, Measurement 77 (2016) 95–104.

[3] K. Tomczyk, Impact of uncertainties in accelerometer modeling on the maximum values of absolute dynamic error, Measurement 80 (2016) 71–78.

[4] T. L. Schmitz, G. S. Duncan, Three-Component Receptance Coupling Substructure Analysis for Tool Point Dynamics Prediction, Journal of Manufacturing Science and Engineering 127 (4) (2005) 781–790.

[5] A. S. Elliott, A. T. Moorhouse, G. Pavić, Moment excitation and the measurement of moment mobilities, Journal of Sound and Vibration 331 (11) (2012) 2499–2519.

[6] A. T. Moorhouse, A. S. Elliott, T. A. Evans, In situ measurement of the blocked force of structure-borne sound sources, Journal of Sound and Vibration 325 (4) (2009) 679–685.

[7] D. de Klerk, D. J. Rixen, S. N. Voormeeren, F. Pasteuning, Solving the RDoF Problem in Experimental Dynamic Substructuring, in: Proceedings of the XXVI International Modal Analysis Conference, Orlando, FL, Society for Experimental Mechanics, Bethel, CT, 2008.

[8] A. Drozg, G. Čepon, M. Boltežar, Full-degrees-of-freedom frequency based substructuring, Mechanical Systems and Signal Processing 98 (2018) 570–579.

[9] M. L. M. Duarte, D. J. Ewins, Rotational degrees of freedom for structural coupling analysis via finite-difference technique with residual compensation, Mechanical Systems and Signal Processing 14 (2) (2000) 205–227.

[10] A. S. Morris, R. Langari, Chapter 20 - Rotational Motion Transducers, in: Measurement and Instrumentation (Second Edition), Academic Press, Boston, 2016, pp. 599–632.

[11] S. S. Sattinger, A Method for Experimentally Determining Rotational Mobilities, The Journal of the Acoustical Society of America 64 (6) (1978) 1734–1734.

[12] T. J. Gibbons, E. Öztürk, N. D. Sims, Rotational degree-of-freedom synthesis: An optimised finite difference method for non-exact data, Journal of Sound and Vibration 412 (2018) 207–221.

[13] P. Varoto, M. Lofrano, T. Cicogna, L. Oliveira, Moment Mobility FRF Measurement Techniques, in: Proceedings of the XXIV International Modal Analysis Conference, St. Louis, MO, Society for Experimental Mechanics, Bethel, CT, 2006.

[14] Y. Champoux, V. Cotoni, B. Paillard, O. Beslin, Moment excitation of structures using two synchronized impact hammers, Journal of Sound and Vibration 263 (3) (2003) 515–533.

[15] M. Bello, A. Sestieri, W. D'Ambrogio, F. La Gala, Development of a rotation transducer based on bimorph PZTS, Mechanical Systems and Signal Processing 17 (5) (2003) 1069–1081.

[16] H. Xiaoyan, S.-F. Ling, K. H. Heng, A New Transducer for Rotational and Translational Impedance Measurement, Journal of Intelligent Material Systems and Structures 19 (10) (2008) 1207–1215.

[17] A. Gola, E. Chiesa, E. Lasalandra, F. Pasolini, M. Tronconi, T. Ungaretti, A. Baschirotto, Interface for MEMS-based rotational accelerometer for HDD applications with 2.5 rad/s2 Resolution and digital output, Sensors Journal, IEEE 3 (2003) 383–392.

[18] A. Jacquelyn, M. Hakhamaneshi, D. Wilson, B. L. Kutter, Advances in Measuring Rotation with MEMS Accelerometers, in: 10th International Conference on Physical Modeling in Geotechnics, Perth, Australia, 2014.

[19] C. Yuan, L. P. Luo, Q. Yuan, J. Wu, R. J. Yan, H. Kim, K.-S. Shin, C.-S. Han, Development and evaluation of a compact 6-axis force/moment sensor with a serial structure for the humanoid robot foot, Measurement 70 (2015) 110–122.

[20] H. Lv, L. Qin, J. Liu, Principle Research on a Single Mass Six-Degree-of-Freedom Accelerometer With Six Groups of Piezoelectric Sensing Elements, IEEE Sensors Journal 15 (6) (2015) 3301–3310.

[21] L. Thibault, A. Butland, P. Avitabile, Variability Improvement of Key Inaccurate Node Groups – VIKING, in: Topics in Modal Analysis II,

Volume 6, Conference Proceedings of the Society for Experimental Mechanics Series, Springer New York, 2012, pp. 603–624.

[22] D. de Klerk, D. J. Rixen, S. N. Voormeeren, General framework for dynamic substructuring: History, review, and classification of techniques, AIAA Journal 46 (5) (2008) 1169–1181.

[23] D. de Klerk, How Bias Errors Affect Experimental Dynamic Substructuring, in: Proceedings of the 28th International Modal Analysis Conference (IMAC XXVIII) Jacksonville, FL, Springer New York, 2011, pp. 1101–1112.

[24] D. de Klerk, S. N. Voormeeren, Uncertainty Propagation in Experimental Dynamic Substructuring, in: Proceedings of the Twenty Sixth International Modal Analysis Conference, Orlando, FL, Society for Experimental Mechanics, Bethel, CT, 2008.

[25] M. Dumont, N. Kinsley, Rotational Accelerometers and Their Usage in Investigating Shaker Head Rotations, in: Sensors and Instrumentation, Volume 5, Conference Proceedings of the Society for Experimental Mechanics Series, Springer, Cham, 2015, pp. 85–92.

[26] D. J. Ewins, M. G. Sainsbury, Mobility Measurement for the Vibration Analysis of Connected Structures, The Shock and Vibration Bulletin (42) (1972) 105–113.

[27] M. V. van der Seijs, D. van den Bosch, D. J. Rixen, D. de Klerk, An improved methodology for the virtual point transformation of measured frequency response functions in dynamic substructuring, in: 4th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, Kos Island, Greece, 2013.