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

Armin Drozg, Jakob Rogelj, Gregor Čepon*, Miha Boltežar

Faculty of Mechanical Engineering, University of Ljubljana, Slovenia

A R T I C L E I N F O

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A B S T R A C T

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.

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 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

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* Corresponding author.
E-mail address: gregor.cepon@fs.uni-lj.si (G. Čepon).

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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 electro-dynamics 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] (see Fig. 1).

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 (Fig. 2a). Reconstruction of rotational DoFs is schematically presented in Fig. 2b. The parameters of T-element are shown in Fig. 3 and given in Table 2.

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

3. Experimental setup

Experimental setup is schematically presented in Fig. 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 transferred 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 Fig. 5a.

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 (Fig. 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 $\mathrm{kg/m^3}$. Preliminary analysis of 23 kg steel plate shows that the mass of additionally mounted sensors has a negligible 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]:

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

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 (Fig. 6).

Indirectly obtained rotational responses using T-element poorly define anti-resonance regions. Those are local characteristics of a tested system 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 Fig. 7a are in average equal to 0.7. On the