Available online at www.sciencedirect.com
SCIENCE DIRECT
ELSEVIER
Journal of Sound and Vibration 286 (2005) 417–427
JOURNAL OF SOUND AND VIBRATION
www.elsevier.com/locate/jsvi

Short Communication

On standardisation of calibration procedure for accelerometer

Jyoti K. Sinha*

Vibration Laboratory, Reactor Engineering Division, Bhabha Atomic Research Centre, Mumbai 400 085, India

Received 12 March 2004; received in revised form 23 November 2004; accepted 9 December 2004
Available online 25 January 2005

Abstract

In structural dynamics and vibration diagnosis, accelerometer is mainly used in measuring the acceleration of vibrating structures. There are several well-known manufacturers making different kinds of accelerometers which are commercially available, and widely used in practice. It was experienced that the measured responses using Integrated Circuit Piezoelectric (ICP) type accelerometers were not reliable in many cases. Hence to verify such observations, few ICP type accelerometers of three well-known manufacturers were tested in the Laboratory and their signals were compared. Based on the test results of four different accelerometers, a calibration procedure has been suggested.

1. Introduction

In structural dynamics and vibration, vibration measurement is a matured area of research in identifying and solving the vibration-related problems of structural components. In fact, now-a-days vibration measurement plays a significant role in the dynamic qualification of newly designed structural components [1–4], prediction of faults and structural aging-related problems [5–7], condition monitoring of machines [8–11], and several other structural dynamics studies and diagnosis [12–17]. To meet these requirements, accelerometers are mainly used to measure the acceleration responses of the vibrating components. Commercially, several types of accelerometers manufactured by many well-known manufacturers are available all over the world. Obviously, the quality of the vibration-based diagnosis and/or identification of vibration-related problems mainly depend on the

*Tel.: +91 22 2559 15 01/02; fax: +91 22 2550 51 51.
E-mail address: vilred@magnum.barc.ernet.in (J.K. Sinha).

doi:10.1016/j.jsv.2004.12.004

measured responses using accelerometers. So, reliability of the commercially available accelerometers is very important. It has been experienced during field vibration measurements, accelerometers mainly *Integrated Circuit Piezoelectric* (ICP) type, are not found to measure the non-stationary impulsive responses of structures accurately in many cases. However, confidence in measuring impulsive signals using the charge-type piezoelectric accelerometers is very good [6,10]. But now-a-days, the ICP-type accelerometers are widely used in practice. Considering the importance of such ICP-type accelerometer, few tests were conducted in the Laboratory on four different ICP-type accelerometers of three different world-renowned manufacturers, and their test results compared. Unfortunately, a unique test result was far from reality in most of the tests. The paper presents the details of the tests carried out on the four different accelerometers in the laboratory and their results. A typical comparison of field data was also discussed. Based on the experiences and the test results, a calibration procedure for the accelerometer has also been suggested that would avoid such discrepancies seen in the test results, and improve the performance of the accelerometers.

Moreover, it may be noted that the model number and the manufacturers name of the ICP-type accelerometers used in the experiments are deliberately not mentioned, as the intention is to share the experiences among several engineers and researchers involved in the area of vibration measurements and diagnosis. It is expected that such experiences and observations presented in the paper will be instrumental in enhancing the confidence level in calibration and the reliability of the measured signal in future.

2. Usages of accelerometer

Following are the main technical specifications that decide the use of accelerometers.

(a) *Sensitivity* which relates the electrical signal (often in Voltage (V)) to the amplitude of vibration in acceleration.
(b) *Frequency range* in which vibration measurement is useful.
(c) *Amplitude limit* that specifies the maximum range of acceleration that can be measured accurately.
(d) *Shock limit* is maximum level of acceleration that the accelerometer can withstand without any damage.
(e) *Linearity* is the accuracy of the measured acceleration amplitude in the measuring *Frequency range*.
(f) *Natural frequency* which is indirectly indicative of the measuring *Frequency range* . Higher the natural frequency of an accelerometer, larger the measuring frequency range in general.

In general, the selection of accelerometers is based on their technical specifications and the measurement requirements like frequency range to be measured, amplitude of vibration, etc. Accelerometers are in general used for following types of signal measurements.

(a) Periodic signal—Sinusoidal or/and swept-sine,
(b) Random,
(c) Impulsive.

Hence the accuracy in all the above measurements is important. Few laboratory experiments were conducted on few number of ICP-type accelerometers to confirm the same fact.

3. Laboratory experiments

Four ICP-type accelerometers having different technical specifications from three different world-renowned manufactures were chosen for the Laboratory experiments. The technical specifications of accelerometers are listed in Table 1 and they have been named as Accelerometers A–D. Out of these four accelerometers, three were uniaxial and one was triaxial (Accelerometer C).

A long stroke shaker was used for the Laboratory experiments. The schematic of the shaker is shown in Fig. 1. All the four accelerometers were mounted on the front of the shaker armature which is also shown in Fig. 1. Front width of the armature is 150 mm and the side arms are guided through four ball bearings with four soft springs such that it can reciprocate in only one direction without any relative motion across the armature width. The armature is very stiff to cause any deformation across the armature width for the kind of tests conducted. In fact, the complete system resembles as a single degree of freedom system of a rigid mass (armature) supported on a spring. Moreover, simultaneous responses were measured from all the four accelerometers during

Table 1
Technical specification of the accelerometers

	Accel. A	Accel. B	Accel. C	Accel. D
Sensitivity (mV/g)	500	100	500	1000
Frequency range (Hz)	1–10,000	1–14,000	1–5000	1–5000
Amplitude limit (g)	10	75	10	5
Linearity (%)	$< \pm 5$	± 4	± 3	± 1
Shock limit (g)	5000	1000	5000	1000

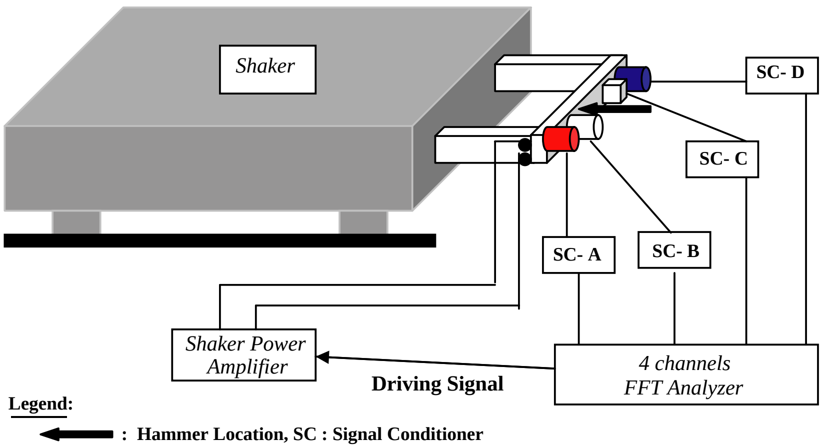

Fig. 1. Schematic of the shaker and the testing setup for the accelerometers.

different tests conducted and the possibility of any error was ruled out. Accelerometers A, B and D were mounted on the armature with stud, and Accelerometer C was mounted with adhesive. The vibration signals from each accelerometer were conditioned through their own compatible signal conditioners, i.e., accelerometer together with compatible signal conditioner from the same manufacturer. This was done to eliminate any possibility of error due to unknown incompatibility in electronics, if any, from other manufacturer. Finally, the voltage signals were processed through a four-channel FFT analyser. The following tests were conducted.

3.1. Sinusoidal excitation

An in-built signal generator in the four-channels FFT analyser was used to drive the shaker through its power amplifier. Sinusoidal signals were given to the shaker at several frequencies at different amplitude levels and simultaneously responses were measured from all accelerometers mounted on the shaker armature. The amplitude of excitation was controlled through the power amplifier of the shaker, and the signal from Accelerometer A was used as a reference for quantifying level of excitation given. The maximum level of excitation used was 4 g. It was observed that the measured signals from all accelerometers were in phase with amplitude within an error of 2% for all kind of sinusoidal tests conducted. A typical comparison of the measured

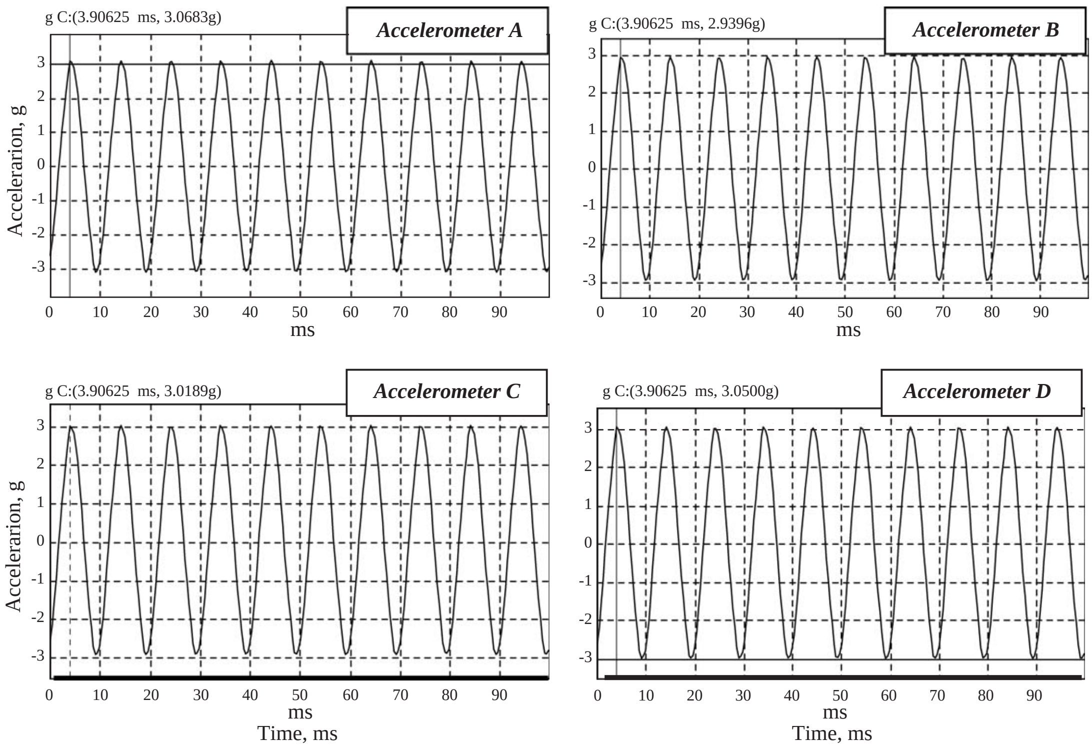

Fig. 2. A comparison of measured responses by the four accelerometers when shaker is excited by the sinusoidal signal at 100 Hz.

responses by all the four accelerometers is shown in Fig. 2 when the shaker was oscillating at 100 Hz with maximum amplitude of 3.0 g.

3.2. Random excitation

Similar to the above test, several random excitations in different frequency bands within the frequency limit of Accelerometer D with different maximum amplitudes upto 5 g measured from the reference Accelerometer A were used to excite the shaker and the responses were measured from all the four accelerometers. Though the nature/pattern of the measured signals were nearly identical, but the amplitudes were never found to be same for all the four accelerometers. The error of amplitude with respect to the reference Accelerometer A was observed to be of the order of 30% and more in many cases. A typical case is shown in Fig. 3 when the shaker was excited with a random excitation in a frequency band of 400 Hz–3 kHz.

3.3. Impulsive excitation

Several impulsive excitations were given to the centre of the armature (marked in Fig. 1) by a small hammer with different types of impacting heads from soft to hard (very stiff). The amplitude of excitations given was very small and the responses were measured from all the four

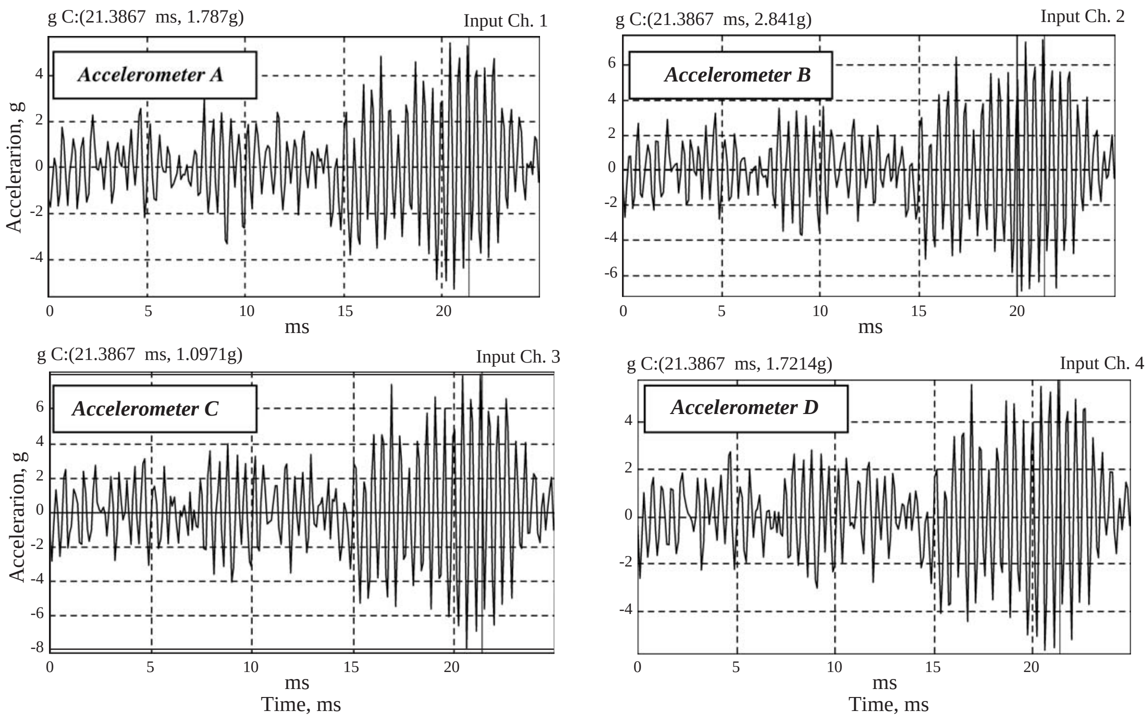

Fig. 3. A comparison of measured responses by the four accelerometers when shaker is excited by the random signal.

accelerometers. An impulsive signal generates a broadband of excitation depending upon the level of excitation amplitude and the impulsive head. A typical impulse and its PSD are shown in Fig. 4 when the hammer with a much harder tip was used. Even with this hammer head the frequency band of excitation is upto approximately 1.4 kHz which is well below the measuring frequency range of all the accelerometers. For other hammer tips, the frequency band of excitation was even lower. The measured amplitude and phase were found to be almost identical for all the four accelerometers when a soft tip hammer was used. It is compared in Fig. 5. However, with increased hardness in the hammer tip, the measured responses (both amplitude and phase) by all the four accelerometers were found to be totally different. Few such typical responses are shown in Figs. 6 and 7. The measured responses by the Accelerometers A–C, shown in Figs. 6 and 7, at least appear to be the responses due to an impulsive load though the phase and amplitudes are significantly different, but the measured response by Accelerometer D seems strange in nature. Moreover, it can be seen that the signal from Accelerometer B was consistently found to be in phase with the armature movement. The same fact was not observed for other accelerometers.

Fig. 4. A typical PSD of the impulse with hard tip.

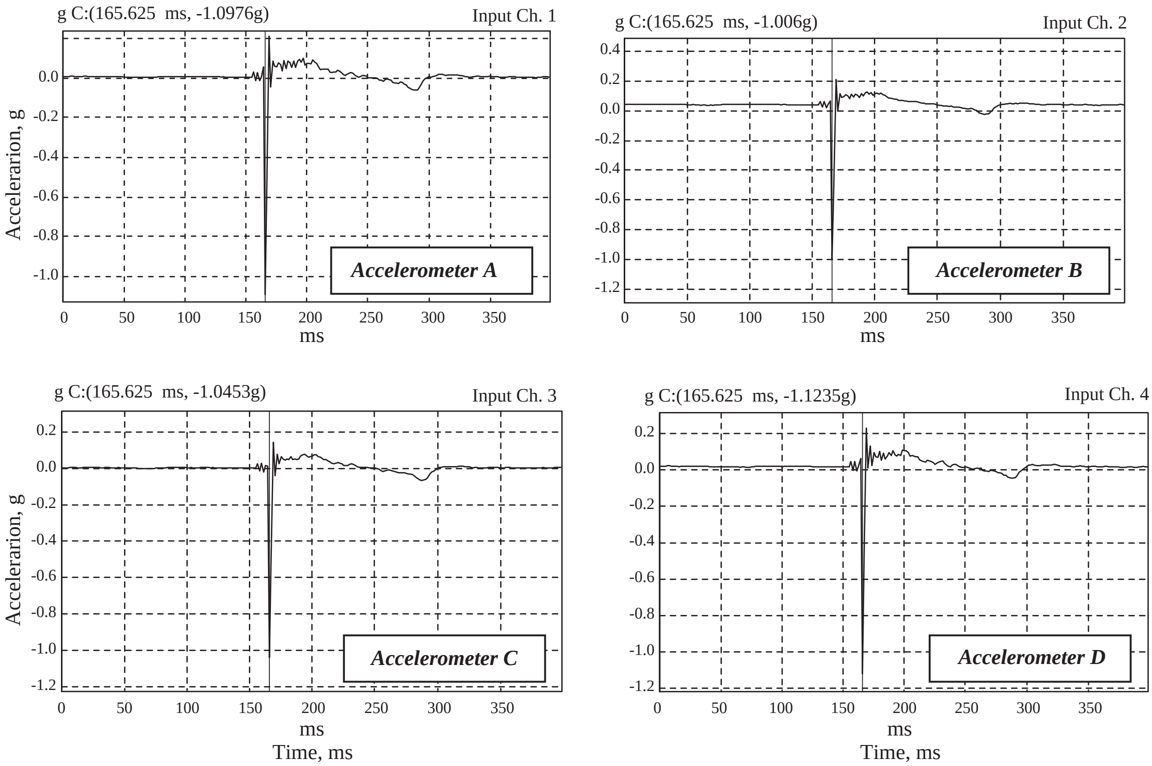

Fig. 5. A comparison of measured responses by the four accelerometers when shaker armature is excited by a soft tip hammer.

4. Field measurements

Centrifugal pumps are used to circulate moderator to the reactor vessel in nuclear power plants through a long pipe. The pump operating speed is 3000 rpm for the case discussed here. Vibration measurements were carried out all along the length of the pipe conveying fluid using Accelerometers B and C during four such pumps being operational. A typical comparison between the two measured responses at a location using Accelerometers B and C is shown in Fig. 8. It can be seen from the figure that both the time history patterns and their spectra are totally different. The appearance of peaks at the pump rpm and the vane passing frequency show some credible signal measured by Accelerometer B.

5. Discussion

As observed from the field observations and the three different tests conducted on four accelerometers in the Laboratory within the range of their technical specifications, it is difficult to rely on the quality of measured responses especially when measuring a random and an impulse

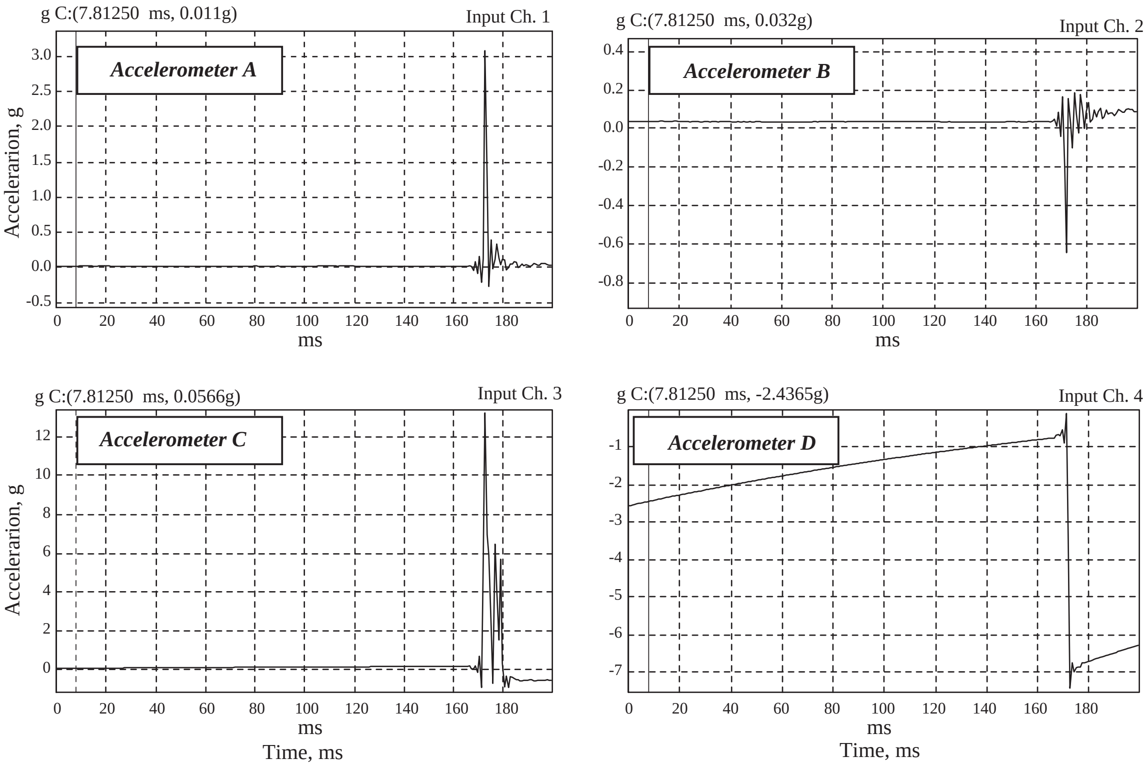

Fig. 6. A comparison of measured responses by the four accelerometers when shaker armature is excited by a hard tip hammer.

kind of response. Typically, all the accelerometers have shown a creditable response measurement when measuring sinusoidal behaviour. As per the theory the accelerometer should accurately measure other kind of responses once it is measuring the sinusoidal response accurately. In fact, even if it is assumed that the impulsive signal given may excite the accelerometer natural frequency, the measured responses should not be like the one observed in the experiments. One such observation has been made during measurement on a pump with a charge-type piezoelectric accelerometer, where impulsive suction jet on the blades and casing exciting the accelerometer natural frequency mounted on the casing, and it was measured confidently with it [10]. Hence, the error seen in the measured signals especially for transient/non-stationary signals (random and impulsive responses) is raising a suspicion towards the associated electronics used in the ICP-type accelerometers.

6. Calibration

The International code ISO 5347-0 [18] gave the guidelines for the calibration of vibration pick-ups, which is generally followed by the manufacturers. The calibration procedure adopted generally uses the sinusoidal vibration generator (shaker) with varying frequency and amplitude

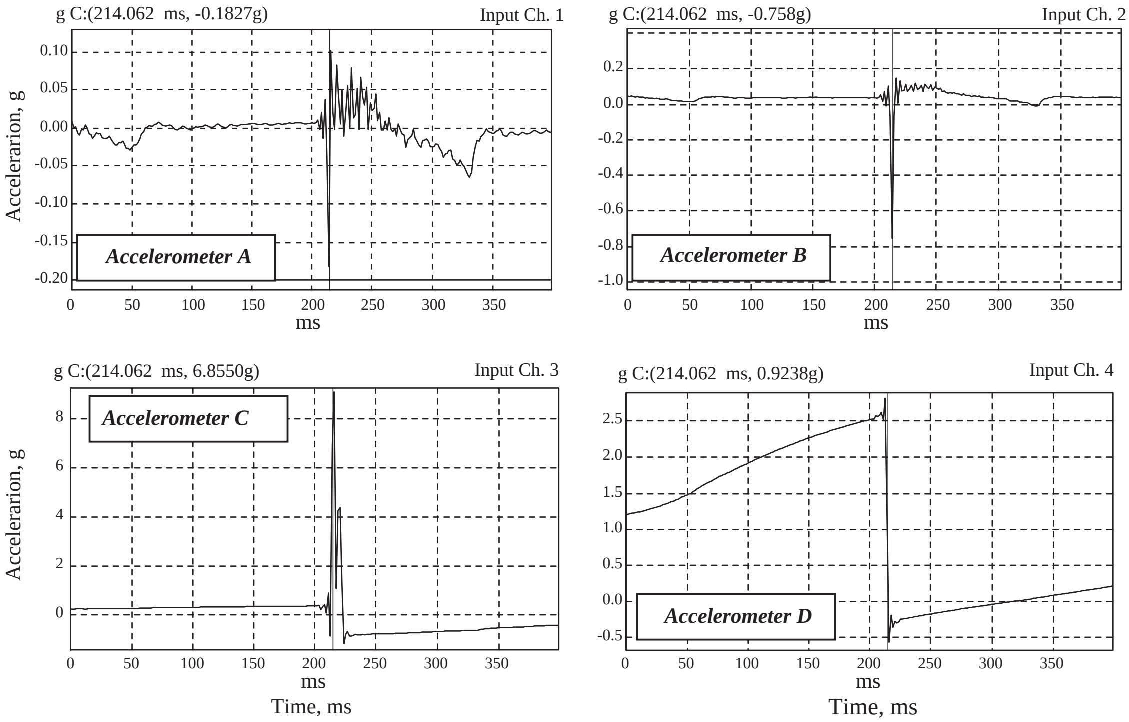

Fig. 7. A comparison of measured responses by the four accelerometers when shaker armature is excited by a harder tip hammer (hammer swing almost same as given for Fig. 6).

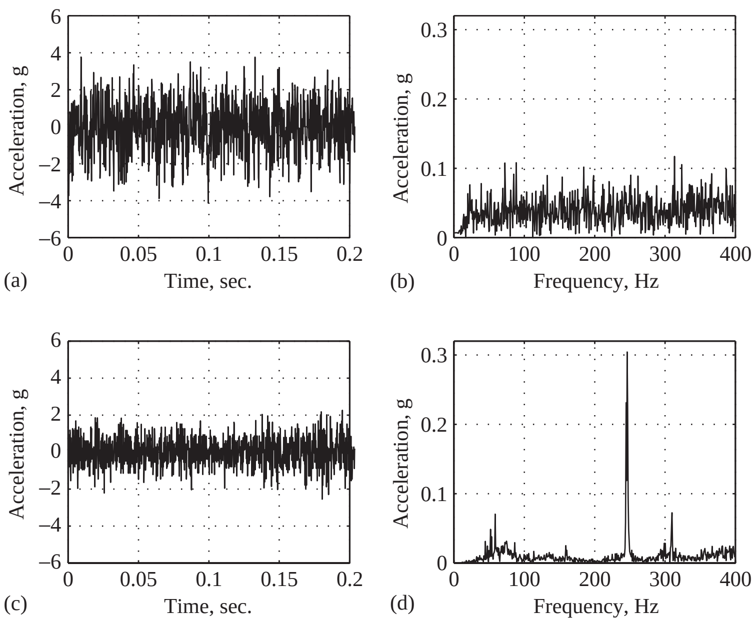

Fig. 8. A comparison of measured responses of a pipe conveying fluid during four pumps operation ((a,b) Accelerometer C, and (c,d) Accelerometer B).

to characterise the accelerometer to be calibrated by comparing its measured responses with other well-calibrated accelerometer. Accuracy in sinusoidal response measurement satisfies the calibration procedure adopted. However, it has been observed that the performance of such calibrated accelerometer may not be useful for measuring the random and impulsive behaviour of structures. Hence the random and the impulsive loading test should also be included in the calibration along with the standard calibration procedure for the accelerometer.

7. Concluding remarks

The simple tests carried out in the Laboratory on four different ICP-type accelerometers within the range of their technical specification reveal the limitations of the accelerometers. Considering the wide application of the ICP-type accelerometers in industries as well as in research studies, it is important to enhance the confidence level in the measured responses. It is only possible if the ICP-type accelerometer is calibrated for different kinds of structural responses expected in real-life scenario and produces the responses efficaciously. Few additional tests need to be included in the calibration procedures that have already been brought out in the paper.

Acknowledgements

The author acknowledges Mr. B.C.B.N. Suryam, Scientific Officer, and Mr. Anil K. Narayan, Vibration Laboratory, RED, BARC, Mumbai for their assistance during measurements.

References

[1] R.I.K. Moorthy, A.R. Rao, Jyoti K. Sinha, A. Kakodkar, Use of an unconventional technique for seismic qualification of equipments, *Nuclear Engineering and Design* 165 (1996) 15–23.
[2] J.K. Sinha, Simplified method for the seismic qualification using measured modal data, *Nuclear Engineering and Design* 224 (1) (2003) 125–129.
[3] J.K. Sinha, R.I.K. Moorthy, Combined experimental and analytical method for a realistic seismic qualification of equipment, *Nuclear Engineering and Design* 195 (2000) 331–338.
[4] J.K. Sinha, R.I.K. Moorthy, Dynamic qualification of complex structural components of nuclear power plants, *Nuclear Engineering and Design* 180 (1998) 147–154.
[5] R.I.K. Moorthy, J.K. Sinha, A.R. Rao, S.K. Sinha, A. Kakodkar, Diagnostics of direct CT-PT contact of coolant channels of PHWRs, *Nuclear Engineering and Design* 155 (1995) 591–596.
[6] J.K. Sinha, S.K. Sinha, R.I.K. Moorthy, Diagnosis of the bearing failure in a Pillger Mill, *Shock and Vibration Digest* 28 (2) (1996) 11–14.
[7] R.I.K. Moorthy, A.R. Rao, J.K. Sinha, S.C. Mahajan, A. Kakodkar, Development studies for degradation diagnostics of PHWRs, *IAEA Technical Committee Meeting on Utilization of Condition Monitoring and Degradation Diagnostic System to Improve Nuclear Safety*, IAEA, Vienna, Austria, 1991.
[8] J.K. Sinha, Health Monitoring Techniques for Rotating Machinery, Ph.D. Thesis, University of Wales Swansea, 2002.
[9] J.K. Sinha, M.I. Friswell, A.W. Lees, The identification of the unbalance and the foundation model of a flexible rotating machine from a single run down, *Mechanical Systems and Signal Processing* 16 (2002) 255–271.

[10] A.R. Rao, J.K. Sinha, R.I.K. Moorthy, Vibration problems in vertical pumps—need for integrated approach in design and testing, *Shock and Vibration Digest* 29 (2) (1997) 8–15.
[11] J.K. Sinha, A.W. Lees, M.I. Friswell, Estimating unbalance and misalignment of a flexible rotating machine from a single run-down, *Journal of Sound and Vibration* 272 (2004) 967–989.
[12] J.K. Sinha, M.I. Friswell, Model updating: a tool for reliable modelling, design modification and diagnosis, *Shock and Vibration Digest* 34 (2002) 13–35.
[13] J.K. Sinha, M.I. Friswell, The use of model updating for reliable finite element modelling and fault diagnosis of structural components used in nuclear plants, *Nuclear Engineering and Design* 223 (1) (2003) 11–23.
[14] J.K. Sinha, A.R. Rao, R.I.K. Moorthy, Significance of analytical modelling for interpretation of experimental modal data: a case study, *Nuclear Engineering and Design* 220 (2003) 91–97.
[15] J.K. Sinha, P.M. Mujumdar, Transmissibility of strain produced in PVDF actuator to elastic beam, *Journal of Sound and Vibration* 265 (3) (2003) 681–688.
[16] J.K. Sinha, S. Singh, A.R. Rao, Added mass and damping of submerged perforated plates, *Journal of Sound and Vibration* 160 (3) (2003) 549–564.
[17] J.K. Sinha, R.I.K. Moorthy, Added mass of submerged perforated tubes, *Nuclear Engineering and Design* 193 (1999) 23–31.
[18] ISO 5347, Methods for the calibration of vibration and shock pick-ups—Part 0: Basic concepts, 1987.