



# Comparative analysis of the structural solutions of bearing vibration test equipment used in quality control procedures

Mateusz Wrzochal<sup>1</sup>

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## Abstract

The paper provides a comprehensive and detailed description of design solutions of industrial rolling bearing vibration measurement systems used in quality control. The aim of the proposed article was to recognise what design solutions are used among such stands, to make a theoretical analysis of the advantages and disadvantages of each type of solution, as well as an attempt to identify such solutions, the application of which will allow high metrological properties to be achieved. The article is a starting point for the design of new equipment intended for the bearing industry. A theoretical analysis has been made of the most important components of the devices, such as the spindle assembly, drive assembly, clamp assembly, sensor assembly, and data transmission assembly. In the analysis, pictures showing the devices manufactured by various companies from all over the world were included. With the analysis carried out, further experimental work is possible. The analysis presented in the paper allows criteria to be established for the selection of test stands for comparative tests (tests of systems of different design, evaluation, and comparison of indications). It is also possible to relate the measurement result to the design of the device in use. The result of the analysis is the establishment of a design base, which will provide guidance for the construction of improved vibration measurement devices for the bearing industry.

**Keywords** Rolling bearings · Quality control · Industrial measurements · Vibration · Industrial devices

## 1 Introduction

Quality control in the bearing industry is a very important process affecting the further operation of machines and mechanical devices. Quality control in production plants is a very complex and complicated process, which includes both static measurements, such as those of rings [1], raceways [2], balls [3] or clearance [4], as well as measurements that have a dynamic character — measurements of friction torque [5], vibrations [6], or bearing durability [7].

Although the individual components of the bearing are measured several times during the manufacturing process and the manufacturing accuracy is kept within very narrow tolerance limits, manufacturing errors mean that only after the bearing is assembled is it possible to fully assess its quality [1–5, 7]. The most important are systems for

controlling the vibration of manufactured bearings. The entire population of manufactured bearings is subjected to vibration monitoring and it is the vibration level that determines the final quality of the bearing [6].

Authors from all over the world are very interested in rolling bearings. This is due to the fact that the rolling bearing is a very common component of machinery and relatively often fails, causing downtime, which in turn has an economic impact.

There are thousands of publications in scientific article databases that address the issue of bearings and the vibrations they generate. This large number of publications makes it possible for extensive review papers to appear. Most of the review papers that appear are concerned with the diagnosis of rolling element bearings as well as the diagnosis of machines containing rolling element bearings [8–10]. A review [11] clearly shows that vibration analysis is a very effective way to assess a rolling bearing. As the authors of a very comprehensive review [12] note, the latest methods should focus on being able to detect not only the fault and even its type, but above all to assess its magnitude or level of degradation. The authors of the review [13] prove the

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✉ Mateusz Wrzochal  
mwrzochal@tu.kielce.pl

<sup>1</sup> Faculty of Mechatronics and Mechanical Engineering,  
Kielce University of Technology, al. Tysiąclecia Państwa  
Polskiego 7, 25-314 Kielce, Poland

advantage of modern methods such as neural networks over other less effective methods. The authors of the review paper [14], on the other hand, demonstrate the need to develop further more advanced methods.

However, the hundreds of papers cited in the above-mentioned review refer to typically diagnostic issues, i.e., bearings that have not only left the production plant, but in most cases have already been in operation for a long time and contain a significant defect, are considered. Work on vibration measurement of bearings in the production aspect, i.e., up to the point when the bearing has left the production plant, is undertaken much less frequently. A very valuable contribution to the assessment of bearing quality using industrial vibration measurement equipment is made by works [15–19]. However, the measurement results obtained in these works are considered to be fully reliable. When analysing the design of industrial rolling bearing vibration systems, however, differences in the construction of their key components are noticeable, and any difference can and probably does affect the measurement result. It therefore seems justified to address the issue of not only quality control itself, but also the complex equipment used for it. There is another additional aspect that justifies addressing this topic; that is, the increase in requirements for rolling bearings, as well as the continuous improvement of production techniques, generates the need to improve measuring instruments and methods for assessing the quality of rolling bearings in production plants.

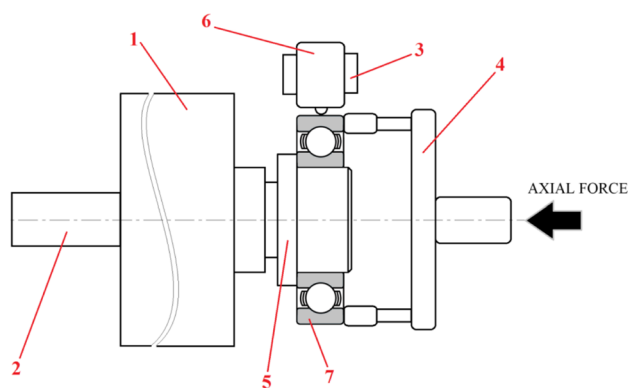
Long-term work must commence to improve the quality control process in bearing manufacturing plants. The first stage of this work is the theoretical recognition of the structures of industrial rolling bearing vibration measurement systems.

The methodology of industrial rolling bearing vibration measurements is based on procedures compliant with the current standards, used in bearing manufacturing plants [20–22].

The procedures contained in ISO 15242 describe the method, conditions, and parameters under which industrial measurement of rolling bearing vibration is carried out. They also describe the method of measurement data acquisition. On the other hand, the standard does not define the vibration level limits that the tested bearing types should not exceed, nor does it define the specific design of the functional components. A sketch showing the industrial method of measuring bearing vibration is shown in Figure 1.

The measuring procedure is as follows:

- the rolling bearing is placed with the inner ring on a shaft which is allowed to rotate in a spindle (the spindle has a universal shaft seat suitable for different bearing types),
- an axial load is applied to the bearing outer ring by means of a pusher (the force depends on the dimension



**Fig. 1** Sketch of an industrial rolling bearing vibration measurement. 1, spindle; 2, end of shaft connected to the drive; 3, sensor holder; 4, pusher setting the axial force; 5, end of shaft adapted to seat the bearing; 6, electrodynamic vibration velocity sensor; 7, tested bearing

of the bearing type, and the pusher head itself is usually adjustable, interchangeable or to some extent universal, which makes it possible to adapt it to the outer ring of the tested bearing),

- the shaft speed reaches 1800 rpm,
- radial vibrations of the running and loaded bearing are recorded by an electrodynamic vibration velocity sensor, which is in direct contact with the fixed outer ring (the sensor is installed in the holder and allows measurement of relative vibrations),
- once the measurement has been taken, the pressure load is deactivated and the pusher is released, allowing the bearing to be removed/replaced.

There are two types of systems when it comes to setting the reference speed — systems adapted to manual measurements and systems adapted to automatic measurements. In the case of systems for manual measurement, the 1800-rpm reference speed is adjusted by the operator (usually by means of a spindle speed adjustment knob). In these systems, it is also the operator who decides when the measurement is taken. In contrast, in systems adapted to automatic measurement, once the bearing has been mounted and the operator has started the measurement cycle, the spindle automatically spins up to the programmed 1800 rpm, and the system automatically takes the measurement after a set amount of time.

The standard includes exceptions regarding the speed of the inner ring at which the measurement is taken. These mainly apply to bearings smaller than those included in the standard. In this case, a speed twice as high, i.e., 3600 rpm, is suggested. Similarly, the standard allows a lower speed of 900 rpm to be used for bearings larger than those included in the standard. However, the standard specifies that a change in the reference speed should be justified and agreed in advance between the manufacturer and the customer.

The value of the axial force and the design of the load-setting assembly are key to the precision of the measurement. Axial force is defined by standards but not in a very strict way. For example, for single-row bearings in the 50–100-mm outer diameter range, a load of 135–165 N is specified. Therefore, the difference in permissible load is 300 N. Whether 135 N or 165 N is applied will affect the result of the vibration measurement. However, for bearings in the lower range (50 mm), the impact will be greater, while for larger bearings (100 mm), the impact of applying an allowable axial force will be less.

A much more significant influence on the precision of the measurement will be the method of applying pressure (the design of the pressure application unit). When designing and constructing such a device, it is necessary, above all, to eliminate the error of misalignment of the clamp and the spindle and the mutual displacement of the axes. It is also necessary to protect against uncontrolled changes in these two geometrical parameters of the system. Any imperfection in this respect can lead to a tilting of the bearing (change of rings concentricity), which significantly overestimates the obtained vibration measurement result.

The vibration's RMS value in three filtered frequency bands is calculated based on the signal received: low frequencies 50–300 Hz, medium frequencies 300–1800 Hz, and high frequencies 1800–10,000 Hz (when using exceptions to the shaft's rotational speeds, the ranges' limit frequencies are obviously subject to change).

A special industrial unit, strictly related to the applied rotational speed, referred to as Anderon, was introduced to evaluate the vibration level. Anderon is a special unit found only in the bearing industry. This unit is closely related to the rotational speed of the inner ring of the rolling bearing under test, which is 1800 rpm (if the rotational speed of the shaft is other than 1800 rpm, then there is no basis for expressing the vibration level in the Anderon unit). The basis for calculating the vibration level in the Anderon units is to calculate the RMS value of the vibrating velocity of the bearing in the given band in units of ( $\mu\text{m}$ )/s, and then convert the vibration level into Anderons according to the formula:

$$1 \text{ Anderon} = 2\pi \cdot 30 \sqrt{\log_2 \frac{f_h}{f_l} \frac{\mu\text{m}}{\text{s}}}$$

where  $f_h$  is the highest frequency in the band and  $f_l$  is the lowest frequency in the band.

This means (by substituting the limits of the designated three analysed bands 50–300 Hz, 300–1800 Hz, and 1800–10,000 Hz into the formula) that one 1 Anderon in the low and medium frequency bands is equal to 7.7  $\mu\text{m}/\text{s}$ , while in the high frequency band, 1 Anderon is equal to 7.51  $\mu\text{m}/\text{s}$ . Relating each measured vibration level in Anderon units to a specific inner ring speed is a kind of standardisation that

makes it easier to compare the vibration results of bearings even of different types. In addition, the 'weight' of one Anderon is similar in each band, even though the bands vary considerably in width. Bearing manufacturers specify Anderons limits (for selected frequency ranges) in company standards. If the tested bearing is under the limit, then it is operating correctly. The adopted evaluation method has been used for decades in production plants. It is so ingrained that the devices that are the subject of this article are called Anderometers by some manufacturers, and analogue devices of the older type allow vibration levels to be expressed only in Anderons. The measurement time should not be lower than 0.5 s, while the measurement itself should be conducted when the readings stabilise (the result's variability should be caused by fluctuations instead of the bearing's unstable dynamic state related to the commencement of the rollers' and race's interoperability or the insufficiently distributed grease). This is defined as the transient period.

Finally, it is worth adding that each manufacturer has its own maintenance rules as to specific operations and verification period. Examples of activities performed for this class of equipment are verification of sensor characteristics (standard 15242:1 specifies tolerances for the deviation of readings relative to a reference sensor as a function of frequency), verification of spindle and pusher concentricity, verification of radial deviation between the pusher axis and spindle axis, geometric measurements of the shafts elements on which bearings are mounted (to assess wear).

The aim of the article is to identify which design solutions are used among these types of stands, to make a theoretical analysis of the advantages and disadvantages of each type of solution, and to try to identify those solutions whose application will allow high metrological properties to be achieved. The article is a starting point for work on the design of new equipment intended for the bearing industry. Thanks to the analysis, further experimental work is possible, as the analysis presented in the article makes it possible to establish criteria for the selection of test stands for comparative tests (tests of systems of different design, evaluation, and comparison of indications). The comparative studies will be able to identify the stations with the best solutions, as well as the reference station. The experimental work carried out will, in turn, allow design work to be carried out, consisting of the development of a concept and model for a new stand and virtual theoretical simulations of the proposed solutions. This work has been carried out because none of the available publications allowed this type of analysis to be performed.

It should also be made clear that the article is part of an extensive study on the evaluation of the metrological properties of industrial rolling bearing vibration measurement systems. The analyses have been carried out on many levels and are extensive, for which reason it is

not possible to antedate all the material in one article. The main objective of the analyses in general is to improve the metrological properties of bearing vibration measurement systems in production plants (parameters such as the accuracy, fidelity, repeatability, and reproducibility of the measurement result are considered). The work carried out is a response to the latest trends appearing in the bearing industry. The evolution of manufacturing techniques and the ever-higher demands of bearing users mean that rolling bearings leaving the production line have increasingly better operating properties (lower vibration and noise levels, longer life, lower thrust torque, etc.). Therefore, for the quality assessment process to take place correctly, measuring instruments and techniques must be adapted simultaneously to the emerging trends (change in the level of characteristics determining rolling bearing quality).

In summary, the most important effect of the analyses carried out in this paper is the creation of a design base that will provide guidance for the construction of improved devices. In turn, the effect of all the work carried out, of which this article is a part, is to be the implementation of new devices for industrial vibration measurement, with greater accuracy, fidelity, as well as repeatability and reproducibility.

## 2 Overall design of an industrial rolling bearing vibration measurement system

Industrial rolling bearing vibration measurement systems are one of the most important devices intended for quality control of bearings manufactured in manufacturing plants. All manufactured bearings undergo vibration control. Bigger manufacturing plants have as many as several dozen of such devices. There are usually three vibration measurement

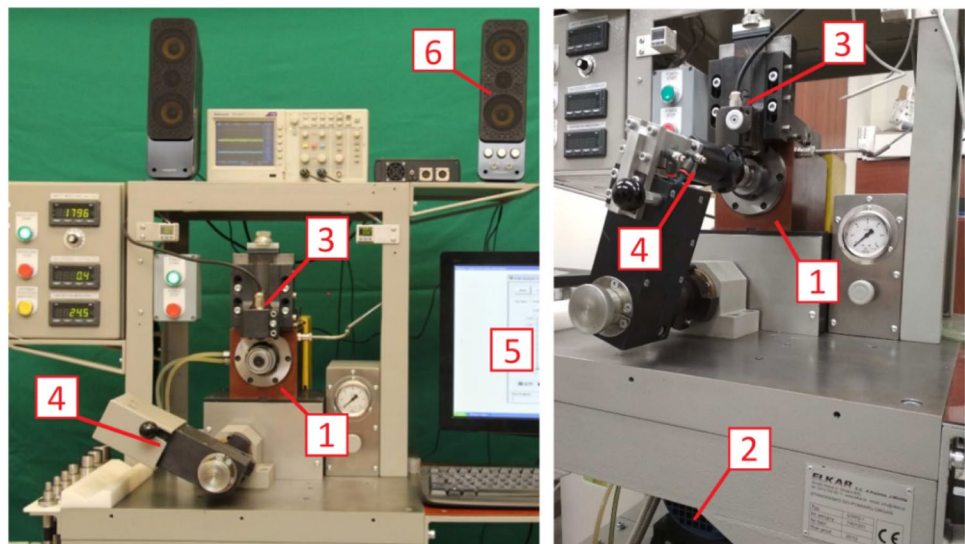
stations located at the end of each manufacturing line. Two of them are intended for continuous control of ready-to-use products to be shipped from the plant. The third device at the end of the line is intended for repeated (manual) control of items rejected during automatic control. Furthermore, the laboratories of industrial companies have additional manual devices intended for in-depth bearing control, verification of new solutions, and statistical testing.

Companies usually have sufficient manufacturing facilities, developed based on decades of experience, to be able to create devices intended for controlling the vibration of their own devices. World-leading bearing manufacturing companies, such as SKF, ZYS, and LDI, not only have their own measurement equipment but also sell it to other companies by providing them with a specific offer [23–25]. There are also suppliers of precision measuring equipment for the bearing industry. These include companies such as SUGAWARA, PDI, and BALTECH [26–28]. Regardless of who manufactures industrial rolling bearing vibration measurement systems, it is possible to highlight the subassemblies included in each of these devices, i.e., the spindle assembly, drive unit, clamp assembly, sensor assembly, and measurement data transmission assembly.

The overall design of an industrial rolling bearing vibration measurement system is presented in Figure 2. The system is located in the Rolling Bearing Testing Laboratory, belonging to the Faculty of Mechatronics and Mechanical Engineering of the Kielce University of Technology. The device is intended for testing purposes, like other such devices located in laboratories of rolling bearing manufacturers. The practical application of such a system can be found in papers [29–32].

The central point of such a device is the spindle (1) driven by the electric motor (2). The positioning assembly, including a vibration sensor, (3) is located above the spindle.

**Fig. 2** Industrial test device intended for measuring rolling bearing vibration. 1, spindle; 2, electric motor; 3, positioning assembly including a vibration sensor; 4, clamp; 5, monitor; 6, speaker



The bearing's axial load is applied by the clamp (4). Aside from the panel or monitor (5) intended for displaying the result, the system also features a speaker (6) that enables the obtained measurement signal to be heard. Very experienced plant workers can often diagnose a bearing's defect by solely listening to the signal.

Further subchapters of the presented review concern other subassemblies/factors that may affect the measurement's accuracy.

### 3 Spindle assembly of a rolling bearing vibration measurement system

The vibration measurement system's spindle is the central subassembly of any device and ensures precise rotation that enables the tested bearing's inner ring to be put into motion. One side of the spindle is equipped with a socket adapted for interchangeable shafts, whereas the other side is adapted for drive force application. The shaft's cylindrical surface, on which the bearing is fitted, should have an accuracy grade of f5 and be characterised by minimum geometrical errors. Theoretically, the standard [20] allows for measurement solutions in which the inner ring is stationary; however, none of the known devices uses such a solution (the reason for this is the more complex testing instruments, issues with vibration sensor positioning as well as longer bearing assembly and disassembly on/from the measuring device).

It can be noted that all solutions presented in this paper have their spindle positioned so that the measurement axis is horizontal. Theoretically, positioning the bearing so that its axis is horizontal results in additional gravitational forces acting on the rolling elements in the bearing, thus generating additional vibration. However, this is the way rolling bearings are fitted most often, so this method represents their actual operating condition of the bearing.

Two types of spindles are used: hydrodynamic and air bearing spindles. The measurement station presented in Figure 2 features a hydrodynamic spindle. The biggest advantages of such a solution include a relatively low price and easier repairs in case of seizure. The weaknesses of hydrodynamic spindles include the limit range of rotational speeds at which they can operate and grease contamination sensitivity (even a temporary lack of which can cause permanent damage).

Figure 3 presents the measurement station of the Japanese company SUGAWARA. It features an original solution in the form of a fully air bearing spindle. These bearings ensure higher rotational precision and operation at greater speed ranges than hydrodynamic bearings. Air spindles are ready for operation directly following the application of pressure and do not require a special lubrication system. Their limited



Fig. 3 SUGAWARA test device equipped with an air bearing spindle

application derives from their high price, greater overall dimensions (than competitive spindles of similar parameters) and lower impact resistance.

### 4 Drive unit of a rolling bearing vibration measurement system

In the case of the discussed devices, the spindle's drive unit is subject to two important requirements. Firstly, the location, type and quality of the transmission, and the drive unit's fitting method must prevent the transfer of vibration caused by its operation to the device's spindle and secondly, the drive unit must maintain stable rotations during the measurements.

Some manufacturers position the motor directly behind the spindle and combine them with a coupling. The available solutions feature two variants: in one of them, the motor is positioned on a separate slab, isolated from the rest of the measurement system (BALTECH device presented in Figure 4), (Fig 5 and 6) whereas in the other, the motor is rigidly combined with the measuring slab (such structure is used in SUGAWARA's station with a

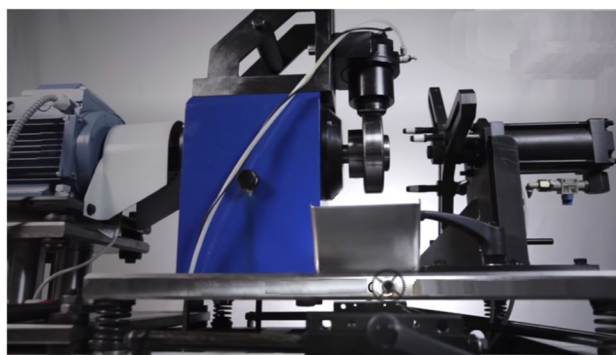


Fig. 4 BALTECH rolling bearing vibration measurement system [28]



**Fig. 5** SKF rolling bearing vibration measurement system [23]

spring clamp shown in Figure 7). The motor requirements can be slightly lower in the first case; however, in the second case, it is necessary to use a high-quality silent motor with a special design.

Other manufacturers prefer shifting the motor below the spindle. Such a solution requires the use of a belt transmission that sometimes transmits the drive force long distances. This design is used, among others, in the station presented in Figure 2 and SKF's station presented in Figure 5.

SKF positioned the motor at the bottom of the control cabinet, thereby requiring the use of a much longer V-belt than in the station presented in Figure 2, where the motor is positioned right below the measuring slab. The longer the distance between the motor and spindle, the better the quality of the transmission belt and pulleys should be.

## 5 Clamp assembly of a rolling bearing vibration measurement system

To achieve the proper kinematic conditions of the tested bearing, the bearing must be loaded axially during each vibration measurement. The applied load should be large enough to avoid inner play and prevent rolling element sliding against the ring races, as well as small enough to prevent the bearing from seizing or causing plastic strains in the bearing elements. The load extent depends on the bearing's type and size, and is specifically determined by standards [21, 22].

The applied force prevents the outer ring from rotating, but the applied load arrangement must enable the ring to

vibrate freely. The free motion of the loaded bearing is ensured by the flexible (most often rubber) elements that combine the clamp's working parts (visible in both cases in Figure 6). The flexible elements embedded into the clamp's head have another very important role. They offset small inaccuracies formed during the clamp's manufacturing or fitting.

The structure of the entire load arrangement must ensure that the axial force is distributed evenly across the bearing's entire circumference. The point and direction of the applied outer load must correspond to the spindle's rotation axis at specific limits. For small bearings (outside diameter between 10 and 25 mm), the distance between the spindle's axis and the clamp's axis must not exceed 0.2 mm, whereas for very large outside diameters (170–200 mm), radial deviation between pusher and spindle axes cannot be more than 2.5 mm. On the other hand, the angle between these axes cannot exceed  $0.5^\circ$  [20]. The clamp's and spindle's misalignment must be limited to a minimum, as a bearing's skewing during measurement drastically affects the result obtained. An additional head position adjustment attempt was proposed in the Polish patent designated as PL 221624 B1. The clamp's design assumes placing the head on a pendulum on the ball joint, thereby preventing the head from stiffening when in contact with the bearing's outer ring. This solution enables the coaxial positioning of the connector and housing, including thrust elements with the tested bearing.

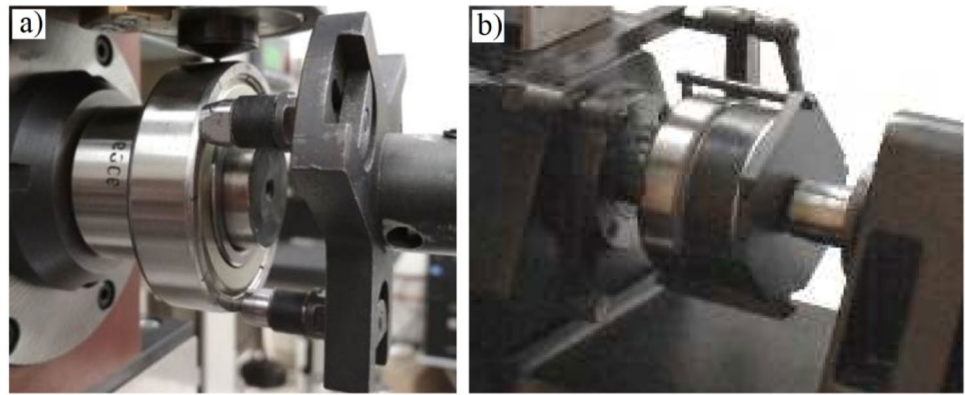
Clamp designs in industrial measurement systems can differ in many aspects. A very popular variant assumes that the clamp head can interoperate with the bearing's stationary outer ring at three points (Figure 6a). There are also solutions in which the force can be distributed across the outer ring's entire circumference (as shown in Figure 6b).

The first solution of the ones presented in Figure 6 allows for very efficient adjustment of the distances between the three working arms and the clamp axis while changing the bearing size. This variant enables offsetting the spindle's and clamp's axial symmetry errors to some extent but requires a very rigid structure of the entire load assembly. Insufficient rigidity and craftsmanship precision errors or wear can cause easy skewing of the tested bearing, thereby resulting in measurement errors.

A clamp remaining in contact with the bearing's outer ring along its entire circumference ensures that the force is distributed evenly. This eliminates the risk of the bearing becoming skewed due to craftsmanship imperfections and lower rigidity, as well as ensuring repeatable loading. However, this solution requires the spindle's and clamp's misalignment errors to be as small as possible and the use of substantially more testing instrumentation in the form of interchangeable heads.

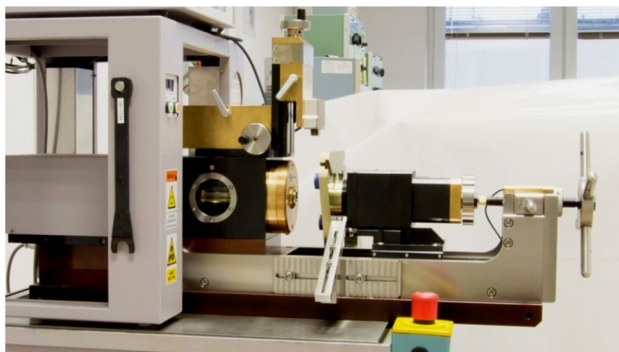
The head's motion and assurance of required force can be implemented in three ways. The available solutions include pneumatic, mechanical, and hybrid clamping.

**Fig. 6** Head of a bearing axial load assembly: (a) three-point clamp, (b) peripheral clamp [23]



Fully pneumatic clamps are most common and feature the clamp's head positioned directly on the end of the pneumatic actuator's piston rod. Due to the pneumatic actuator's own resistance, this clamp design (shown in Figures 2 and 4, among others) can have difficulties in maintaining the required load for small force ranges (in the case of larger loads for bearings with larger dimensions, these resistances become less significant).

This can result in a low repeatability of measuring vibration of smaller rolling bearings. If the device is solely intended for measuring the vibration of smaller rolling bearings, it is better to use a hybrid clamp. Hybrid clamps are characterised by the fact that the pneumatic actuator displaces the head to a specific position, whereas the specific force is adjusted by a mechanism that contains a spring or a spring set. This mechanism is fitted to the actuator's piston rod, while its other side, along the spring(s) axis, features the clamp's head. Mechanical force application (using springs) ensures higher repeatability by applying even small loads. The fully mechanical clamp does not feature a pneumatic actuator, and the spring set is displaced manually by the operator using a lever. This design is shown in Figure 7. However, the entire device is mostly affected by whether the clamp and spindle are permanently positioned coaxially



**Fig. 7** SUGAWARA rolling bearing vibration measurement system equipped with a fully mechanical (spring) clamp system [26]

in a single, rigid structure (devices in Figures 7 and 14) or whether the clamp's head is fitted to a swivel arm and is only applied to the spindle during the measurement. The clamp's swivel arm design allows for substantial space savings in the room or hall in which the measurement system is positioned and is substantially more ergonomic. However, using the swivel arm increases the risk of permanent misalignment between the two most important subassemblies of the rolling bearing vibration measurement device, i.e., the spindle and clamp (especially after prolonged use). This solution also requires more frequent technical inspection of such devices. Another weakness of the clamp's swivel design is the substantially lower rigidity, which fails when greater loading of larger bearings is required. The clamp assembly is equipped with a swivel arm in the system presented in Figure 2, and in the FAG device shown in Figure 8.



**Fig. 8** FAG rolling bearing vibration measurement system equipped a clamp assembly that enables lifting for bearing replacement [33].

## 6 Sensor assembly of a rolling bearing vibration measurement system

Even though the standard [20] allows for the use of any type of sensors (displacement, velocity, acceleration, and force sensors), all available industrial devices feature electro-dynamic vibration velocity sensors for measuring rolling bearing vibration. These are the reasons for using solely electrodynamic vibration velocity sensors:

1. A rolling bearing emits a very wide spectrum of frequencies. It is therefore necessary to apply a measurement compromise in the form of vibration velocity signal evaluation (using the vibration displacement signal would make it more difficult to evaluate the higher frequency amplitudes, whereas using the vibration acceleration signal would hinder the evaluation of lower frequency amplitudes).
2. Due to the high sensitivity of differentiating elements in measurements using sensors adapted to measure high frequencies (considering the high-frequency noise), the trend of using acceleration sensors is retained, thereby reducing all calculations to integration. There are therefore two possibilities: use an electrodynamic sensor and evaluate the rolling bearings' vibration based on the direct velocity signal or use an acceleration sensor and obtain the velocity signal through integration.
3. The relative vibration measurement method (when the sensor fitting assembly is the reference point) filters vibration deriving from the spindle, motor, pumps, or pneumatic systems, among others, because the sensor grip and the spindle's shaft vibrate similarly, and the sensor mainly records vibration deriving from the working bearing.
4. Vibration acceleration sensors are only manufactured as seismic sensors that measure the object's absolute vibration. Even if the placement of an acceleration sensor on the tested bearing did not generate an issue on each measurement (and it is a rather large issue in the case of serial measurements of many manufactured bearings), the sensor would not only record the bearing's vibration, but also the vibration of the entire device and maybe even other signals, e.g., vibration of the building in which the device is placed.

The sensor fitting assembly is a mechanism that enables precise fitting of the electromagnetic vibration sensor

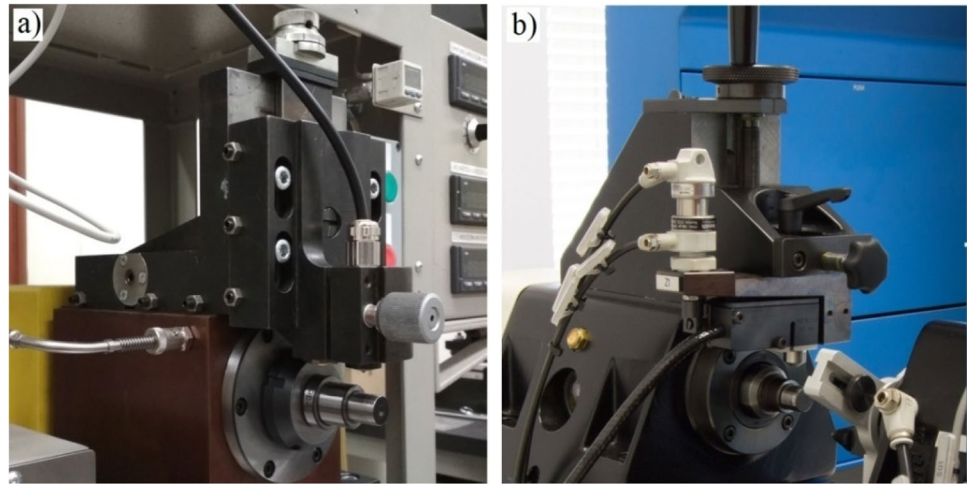
and its positioning only in two directions relative to the spindle: radial vertical (when the tested bearings' diameter is subject to change) and radial (when the tested bearings' width is subject to change). After applying each setting adapted to the given bearing, it is necessary to prevent the sensor from moving. Usually, the sensor's feed, relative to the spindle's axis, is not very precise, and the operator is tasked with making a subjective evaluation of whether the sensor's measuring pin is positioned near the outer ring's half-width. On the other hand, the radial vertical feed must be controlled either by an additional displacement sensor or through a knob scale determining the displacement in each unit. The sensor's positioning in the radial vertical direction substantially affects the measurement's result, as it is decisive in terms of the sensor tip's pressure on the bearing's outer ring. The displacement that presses the sensor's pin against the bearing affects the tension of the springs that retain the coil that moves within the permanent magnet's field. The sensor's initial tension is given by the manufacturer and failure to comply with the manufacturer's recommendations may cause substantial deterioration in the sensor's parameters. The sensor fitting assembly must ensure the greatest possible perpendicularity of the sensor pin's axis in relation to the spindle's axis (the max. non-perpendicularity can amount to  $5^\circ$ ), and the radial horizontal motion must be prevented (the max. deviation can amount to 0.5 mm for bearings with an outer diameter smaller than or equal to 70 mm, and to 1 mm for bearings with an outer diameter greater than 70 mm) [20].

The feed designs are not much different at particular stations, and the ability to use strong displacement locks makes them have minor impact on the measurement (provided that the operator positioned the sensor's pin correctly). The greatest difference in the design of sensor assemblies is that some enable additional sensor movement. It is possible to distinguish solutions in which a sensor remains in position (permanently clamped in the grip) during a measurement, bearing replacement, and between measurements. Such a design is presented in Figure 9a. Further bearings are pushed under the sensor's pin, which slides on the outer ring until the bearing is completely fixed and pressed.

Other solutions allow for the sensor's additional movement (most often oscillating or rectilinear), thereby enabling its shift from the working position during a bearing replacement. The sensor's additional movement is usually implemented by using a small pneumatic actuator shown in Figure 9b.



**Fig. 9** Different design solution for a vibration sensor fitting assembly: (a) stationary sensor, (b) sensor applied for the measurement by a pneumatic actuator



## 7 Data transmission assembly of a rolling bearing vibration measurement system

A measurement data transmission assembly encompasses not only all elements responsible for signal transfer from the sensor to the results panel, but mainly the manner of the results' presentation. All deliberations presented in this subchapter will come down to a single basic difference between the discussed systems. The difference is whether the signal that reaches the results panel is solely analogue or

whether it is changed into a digital signal during the transfer. Systems featuring two different types of result presentation are shown in Figure 10.

Because the first devices intended for industrial rolling bearing vibration evaluation were created as early as the 1960s, the prototype system is an analogous device. Electrodynamic sensors are generic sensors. This means that they generate voltage that can be further processed to obtain the desired information. In analogue systems, the signal obtained from the sensor undergoes a series of

**Fig. 10** Various solutions for presenting the results of rolling bearing vibration measurement systems: (a) ZYS station with an analogue panel [24], (b) PDI station with a digital display [27]



operations, such as amplification (the signal from the sensor is weak, it therefore must be initially amplified), filtration (using analogue band-pass; low-pass and high-pass filters enables distribution of the obtained signal to three separate channels related to three frequency bands), or processing (e.g., using an RMS value transducer). The processed signal that reaches the meter (on a specific channel) tilts the indicator proportionally to the vibration generated by the rolling bearing. The three channels are related to a specific frequency band. It is possible to additionally amplify the signal using the knobs responsible for a specific setting that must be adapted to the vibration level. Each setting determines the total number of Anderons generated by the tested rolling bearing, whereas the indicator corresponding to the given setting indicates the set value's percentage. The panel that indicates the vibration level result in the analogue system is shown in Figure 11.

The analogue solution is much simpler and cheaper, but aside from the desired RMS value in three bands, expressed in Anderons, it does not provide any other information. It is also possible to connect an oscilloscope to enable viewing a temporary signal waveform. In the case of measuring bearings without substantial defects, the indicator precisely indicates the determined value; however, the reading for more damaged bearings is not as definite, and it is necessary to determine the range in which the indicator is tilting. Bearings with a damaged ball are most problematic as the result can change radically during the measurement. It is not problematic to use such devices at the end of the manufacturing line.

Systems utilising a digital result analysis are much more functional in laboratories. In such case, the electric signal generated by the sensor's operation

is amplified (up to 1000 times) in an amplifier integrated with a micro-processor module containing an analogue-digital converter and communication port that enables the module to be connected to a computer. The communication port's type (RS 422/485 or USB) affects the sampling frequency capabilities. A digital measurement signal offers many analysis opportunities. The most important functions of rolling bearing vibration measurement system software include the following:

- entering data concerning the type of tested bearing, its geometrical parameters, and the measurement conditions. It is also important to be able to declare (or generate, based on the entered data) the bearing's characteristic frequencies,
- determination of frequency band ranges and acceptable vibration levels,
- measurement chain calibration option,
- observation of the current bearing vibration signal in terms of time and frequency, continuous RMS value averaging in the set period for each band, signalling when the set limit values are exceeded (these limits are an individual matter for each company and are defined by internal documents. They are determined based on the intended use of the bearing and the individual agreement between the manufacturer and the customer),
- option to save a waveform over a specific time interval in a file,
- plotting the saved time signal and its spectrum,
- statistical analysis of the obtained result series,
- measurement reports' printing.

**Fig. 11** Panel of the analogue rolling bearing vibration measurement system, indicating the measurement result of the vibration's RMS value in three frequency bands, expressed in Anderons



**Fig. 12** Digital screen displaying the current rolling bearing vibration measurement result

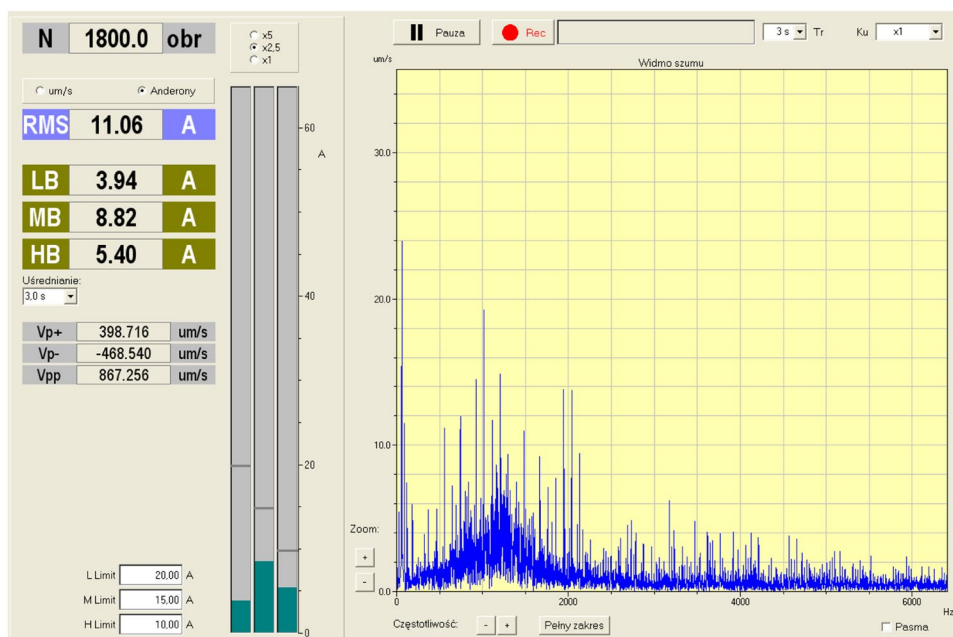


Figure 12 shows a station screen with the current vibration spectrum and the instantaneous RMS value displayed. The additional functions provided by the digital technique are very useful for in-depth rolling bearing analyses and tests; however, when the systems are compared as measurement instruments, it is sufficient to be able to merely observe the RMS value in the specific frequency band.

### 8 Modifications of standard systems

When reviewing industrial rolling bearing vibration measurement systems, it is possible to take notice of other subassemblies that provide other functions, as well as modifications that involve replacing a subassembly’s key part to slightly alter the nature of the measurements.

It is possible to use the example of the rolling bearing radial load system which contains a device made by the Ningbo Yirong Electromechanical Technology (Figure 13) and a modern model of the SKF device which, instead of a standard sensor, contains a laser Doppler vibrometer (shown in Figure 14). The standards do not principally specify any additional radial load, which obviously affects the measurement result. These type of devices are intended as laboratory stations instead of manufacturing line elements. They measure the vibration in specific-purpose bearing tests to test their behaviour under a substantial radial load. The additional load system is used at the recipient’s special request when the application requires such information. As shown in Figures 13 and 14, the radial load is applied by an assembly of two coupled actuators acting on the bearing’s outer ring at a specific angle.

An innovative solution was used by SKF, which replaced the standard electrodynamic sensor with a contactless laser vibrometer, thereby facilitating its integration with existing measurement systems. The use of a laser vibrometer simplifies the sensor positioning system to a degree and substantially extends the measurement equipment’s lifetime. The laser vibrometer calibration procedure is also much simpler than in the case of an electrodynamic sensor. On the other hand, lack of experience in applying contactless vibration measurements can lead to substantial measurement errors. It must be noted that each misalignment between the beam and the bearing’s radius can prevent the light beam from reflecting completely off the bearing’s outer ring. The bearing’s surface, with a metallic gloss, can also turn out



**Fig. 13** BTV-6 rolling bearing vibration measurement device containing an additional radial load assembly [15]



**Fig. 14** SKF rolling bearing vibration measurement station head equipped with a laser Doppler vibrometer and containing an additional radial load assembly [23]

to be problematic. Detecting the measurement point can be an issue when using some types of contactless devices. In such cases, it may be helpful (especially for in-depth testing) to apply an additional substance to the outer ring. It is also necessary to remember that the vibrometer must be rigidly fixed to the measurement system and be able to only detect the bearing's vibration and not the vibration of the entire device. The laser vibrometer, aside from being a commensurate substitute for a standard electrodynamic sensor, can also function as an additional non-invasive sensor, acting as a common control element for comparative tests of different systems.

## 9 Comparative measurement of one bearing on three different systems

In order to investigate the quantitative differences between the systems, an experiment was carried out by taking a series of 50 vibration measurements of the 6205ZZ bearing on three different systems. The systems are indicated by

the numbers of the drawings on which they are located. A bearing characterised by similar Anderson values in each of the three bands was selected for the study. For each system and band, the arithmetic mean, the root mean square deviation of a single measurement and the maximum and minimum values are given.

It should be noted that the review does not present all known devices, but only those that allowed characteristic design differences to be presented. Presenting other devices of similar design to those presented would have made the analysis less clear. In the 'Discussion' section, reference is made to the most recent publications in which a similar class of devices was used and evaluated through the prism of the analysis presented.

The chapter 'Comparative measurement of one bearing on three different systems' shows that the results for the same bearing measured in the same way can differ from each other and as much as possible depend on the stand structure. However, the biggest difficulty in analysing these results is two basic problems. Firstly, the measurement result is three numbers associated with three frequency bands. In the event of a discrepancy, it is unclear which band to use, as the bands are equivalent. From the measurements carried out, it is impossible to say which position gives the smaller variation, as the devices give different variation in different bands. System 2 has the smallest scatter and variation of results in the medium band, system 3 in the low band, and system 5 in the high band. Secondly, it is also not possible to directly compare the values obtained in the different bands, as the correct value of the measured vibrations is unknown. From the table presented in Chapter 9, it is not possible to say which system shows the highest and which the lowest results on average, as this also depends on the band. In the case of the results obtained in the mid-frequency range, more similar arithmetic averages of the vibration level are obtained for systems 3 and 5, while in the case of the high frequency band, the results of systems 2 and 3 are closer together. It is also noticeable that there is a lack of consistency for the maximum and minimum values indicated by the systems. It is also likely that if another bearing is measured, the result may change in relation to the scale and the nature of the difference. If we include a larger number of systems in the study, comparing them with each other will be even more difficult.

It should also be mentioned the bearing itself does not generate highly repeatable and reproducible dynamic behaviour. It is quite natural for the balls and raceways to spontaneously change the deviations and geometric structure of the mating surfaces during tests performed on different devices. The bearing balls may align differently and on a different device may rotate in altered planes. Tasking a minimally different load on the next measurement may

**Table 1** Statistical parameters for a series of 6205 bearing vibration measurements in different frequency bands for three different measurement systems

		System 2	System 3	System 5
<b>50–300 Hz</b>	<b>Arithmetic mean, And</b>	<b>6.02</b>	<b>4.6</b>	<b>5.26</b>
	Mean squared deviation of single measurement, And	0.3	0.22	0.23
	Minimum value, And	5.6	4.3	4.9
	Maximum value, And	6.9	5	5.7
	<b>300–1800 Hz</b>	<b>Arithmetic mean, And</b>	<b>6.27</b>	<b>5.66</b>
<b>300–1800 Hz</b>	Mean squared deviation of single measurement, And	0.28	0.35	0.42
	Minimum value, And	5.8	5.1	4.7
	Maximum value, And	6.8	6.3	6.1
	<b>1800–10,000 Hz</b>	<b>Arithmetic mean, And</b>	<b>6.98</b>	<b>6.84</b>
<b>1800–10,000 Hz</b>	Mean squared deviation of single measurement, And	0.29	0.24	0.21
	Minimum value, And	6.4	6.2	7.1
	Maximum value, And	7.6	7.3	8.1

cause the balls to operate at a slightly different point on the raceway. The bearing can also become damaged in between, or if the defect is pre-existing, it can transfer to other bearing components. When taking multiple measurements on a single system, the vibration level can also change on its own, due to the temperature increase caused by friction inside the bearing. Thus, to some extent, the dimensions of the bearing components may change, as well as the properties of the applied lubricant. Any even minor of the above-mentioned factors can have a significant impact on the difference in the results obtained.

From the simple tests presented in the article, it can be seen that some differences already occur for the measurement of the same bearing on equipment of the same class. In this case, it is assumed that the difference is mainly influenced by the design solutions used. If the vibration measurement is transferred to the plane of the recipient, then changes in even the smallest details, i.e., the use of a different sensor, a different method, different processing of the raw signal (e.g., the shape of filters), signal conversion (integration, differentiation), initial housing of the bearing, etc., will cause even greater discrepancies.

In other words, the discrepancy of indications on different devices for the same bearing or bearing series, even with the best efforts on the part of the manufacturer and the customer, will still occur for completely natural and explainable reasons. The most important thing, therefore, is for both the manufacturer and the customer to be aware of the reasons for these differences, trying to establish common ground for measurements by conducting joint comparative tests.

It is difficult to relate the values obtained in Table 1 to specific limits or recommendations. The ISO 15242 standards cited in the paper do not define the acceptable levels of vibration generated by the bearings tested. This is an individual matter for each manufacturing plant. In turn, each manufacturer has its own internal standards (limits) depending on the type and size of bearings. This results in

different limits at each company, even if they produce the same type of bearing for similar applications. In addition, in some cases, the acceptable vibration limit for a specific bearing batch produced is the result of an agreement between the manufacturer and the customer. This means that individual customers also have a say in vibration level limits and can further tighten internal requirements for various reasons. However, the employees of the production plants do not provide any information, as the limits in question are part of the company's wide-ranging secrecy.

The tolerance field of vibration levels is about the range from 0 And to the imposed limit. It is mostly the case that each band has a different limit value. In the low band, the limits reach the highest values (the largest tolerance field), while in the high band, the limits reach the lowest values (the smallest tolerance field). Exceeding the limit value results in the rejection of the bearing from the production line. The rejected bearing goes to a semi-automatic station and is subject to additional verification by the operator. There may be additional provisions in plant standards. For example, those stating that exceeding the limit value by 3 or 5% is additionally tolerated. However, as I have already mentioned, unfortunately, it is not possible to generalize this in any way.

## 10 Discussion

As already mentioned in the ‘Introduction’, whenever a publication deals with the assessment of rolling bearing vibrations for quality control, every time the results of such measurements are considered reliable and no systematic or random errors or errors caused by an inappropriate measurement method are taken into account. Taking into account the experience of the constructors of the devices presented in this review, it is possible to evaluate the measurement solutions used by other authors who measure bearing vibrations on a similar class of devices.

In the paper [15], the BVT-6 device in Figure 13 was used, and the vibrations of 30 tapered roller bearings were measured in the study. Each bearing was measured once. However, as can be seen from the comparative studies carried out in this paper (Chapter 9), some spreads are obtained when measuring bearing vibrations. In order to obtain accurate analyses, it is necessary to perform several measurements and also to take into account the uncertainty of the measurements.

In the work [16], the BVT-5 (an older version of the BVT-6) was used, but the mounting assembly of the original sensor was removed. Instead, a measurement solution was proposed that involved gluing the accelerometers to the bearing outer ring. However, such a method is rather problematic for testing a larger bearing population, as the sensors need to be glued in place after each measurement. In addition, inappropriate attachment of the sensor can cause distortion of the measurement result. Besides, seismic sensors such as accelerometers can record not only the vibrations of the bearing, but also of the entire device and possibly even other signals. The advantage of the solution in the cited work is that three sensors distributed around the circumference of the outer ring are used, increasing the amount of information coming from the bearing.

The paper [17] uses a measurement system that has a pressing mechanism of the S0910-III A device from Ningbo Yirong Electromechanical Technology; however, this device has a memberally different sensor mounting system as well as a different spindle. In addition to a contact sensor (accelerometer), the authors also use a non-contact measurement using a laser Doppler vibrometer. For both bearing vibration measurements taken at the same time, two completely different results were obtained. The authors explain this by the excessive influence of other parts of the system on the accelerometer measurement. However, no information was given as to whether the vibrometer was associated with the position on which the bearing was operated and how rigid the vibrometer mounting was. These are two key issues. In order to obtain reliable vibration measurement results with the vibrometer, the measuring system should look like that of the SKF stand shown in Figure 14. In order to obtain good agreement between contact and non-contact measurements, the vibrometer must not be on a stand outside the stand. Unfortunately, even if the vibrometer is rigidly mounted on the stand, the agreement will never be very good. Analyses in the paper [34] show that the relative error in the measurement of the RMS value with a standard sensor and a laser can be as high as 53.40% for the low band, 41% for the medium band, and 49% for the high band, depending on the device (tests were performed on three different systems). It should be noted that the measurements are taken by the electrodynamic sensor and

the laser vibrometer at the same point on the outer ring and not at the same time at two different points.

In the paper [11], a bearing quality assessment rig was used for the tests, which has a less common longitudinal design similar to that seen in Figure 4. This design causes the operator to have to stand next to the spindle and not in front of it. This may slightly affect the ergonomics of the operator but is not relevant to the measurements. However, the device has another unique solution. The vibration sensor is fused to the radial load element of the bearing. Without comparative tests on this type of bench, however, it is difficult to say how such a design affects the measurement result. However, there may be a risk of vibration damping and inadequate results if too high a radial load is applied. A major advantage is that the bench has two additional accelerometers bolted to the spindle housing, which supplement the analyses by recording signals from the drive system.

The conducted analysis allows for the following theoretical conclusions concerning each of the discussed subassemblies:

- (a) Despite numerous strengths offered by air bearing spindles, the manufacturers of rolling bearing vibration measurement systems are more inclined to use hydrodynamic bearings. Putting aside the technical and operational factors, the rotation accuracy [35] and natural vibration generated by the spindle's operation [36] are most important for the spindle's selection in terms of the measurement's accuracy. The share of the harmonic related to the shaft's rotational frequency is eliminated with a mid-block filter; however, the spindle's natural vibration constitutes one of the uncertainty components when measuring rolling bearing vibration.
- (b) It is difficult to evaluate the impact of the motor's positioning on the measurement's result without in-depth testing. Regardless of the drive unit positioning option chosen by the builder, the motor should be characterised by the highest noiselessness possible and minimum natural vibration, aside from adequate power. Wear of the drive belt and technical deterioration of the spindle unequivocally negatively affect the operation of the device, and most importantly, the accuracy and uncertainty of bearing vibration measurements. This can result in the appearance of additional harmonics in the measured spectrum, which will mix with the bearing vibration, artificially inflating the measurement results. The condition of the drive system, belt, and spindle should be inspected in proportion to the frequency of use of the station. Belt degradation is assessed visually, and if wear is suspected, the belt is replaced. It is also recommended

to periodically check the dynamic state of the spindle, in order to detect deterioration, using other vibration sensors. A good solution is to use permanent accelerometers bolted to the spindle housing as in the case of the stand presented in the work [11]. This solution allows continuous monitoring and early diagnosis of problems with the drive system.

- (c) The reconnaissance carried out regarding the design of the loading system makes it possible to obtain some detailed indications (it is possible to identify the loading system that allows the most precise results to be obtained, as well as the system that will potentially pose the greatest problems in terms of precision of the results).

As an example of a solution with potential precision problems, the system in Figure 2 can be mentioned. It contains a ball joint inside the pusher assembly, in theory, to further compensate for uneven loading. However, the additional connection to the swing arm may result in variable positioning of the load head. An analysis of the solutions suggests that the best solutions for the loading system are the systems in Figures 3 and 5. A good solution is to use a mechanical loading system (the force is set by springs), with which the system in Figure 7 is equipped. In summary, to achieve high measurement accuracy, pusher components should be designed with the highest precision. The pusher design should be as rigid as possible (preferably permanently coaxial) and free of joints and redundant connections, and compensation for manufacturing imperfections should only be made through the rubber parts of the pushing head.

- (d) Assemblies that prevent additional sensor motion ensure high structure rigidity but expose the vibration sensor to substantial wear and even damage due to the bending forces and impacts acting on the sensor's pin. These forces are caused by subsequent bearings that slide onto the shaft and which must be in direct contact with the pin located in the same position. The sensor's amplitude characteristics may change over time (quicker than in the second variant).

An assembly with a mobile vibration sensor substantially prolongs the sensor's lifetime, but the system's moving elements may become maladjusted and cause additional sensor displacement or twisting in the future. An additional pneumatic actuator in the device's entire system also increases the probability of system failure.

- (e) The type of measurement data processing assembly can contribute to gross errors, i.e., operator mistakes. If the person operating the analogue device does not have much experience, he or she can make measurement errors related not only to the use of improper settings, but also to mistakes caused by the need to make

multiple conversions to percentages. The digital technique substantially lowers the risk of mistakes, and the additional save option substantially facilitates measurement data collection and analysis.

- (f) Additional resonances caused by some component of the measuring device reaching frequencies that coincide with the rolling bearing's own vibrations can be a problem. This may result in an undesirable and uncontrolled increase in the vibration level of the tested bearing, which will not be in accordance with the actual condition. The most exposed part of the system to resonance can be triggered by both the drive unit and the running bearing, which is also a trigger. Great care must therefore be taken in the design of the entire measurement system and, above all, the sensor mounting assembly. It is advisable to build various prototype sensor holders and test them for resonances on the triggers, as well as to run virtual computer simulations.

## 11 Conclusions

The analysis of the available rolling bearing vibration measurement systems is an important guideline for builders of measurement equipment intended for the bearing industry. Firstly, the demonstrated design variations can help explain the differences between measurement results obtained for two different devices and secondly, the review of the commonly used subassembly designs will be a valuable guideline for builders that design new devices (new bearing types) if the test parameters of the currently used devices turn out to be insufficient.

The general nature of the standards' entries allows the design of devices presented in this paper to differ substantially, despite the same measurement principle and evaluation method. Even the smallest technical difference affects the measurement's result, considerably at times, and the applied design type can decide what the result is.

The analysis performed is a first step towards building new devices of this type with higher metrological properties. Further research should focus on finding methods and test procedures that can evaluate and compare different systems. Reliable evaluation and comparison studies will allow the best solutions for this type of system to be identified. There are, however, certain difficulties that make direct comparisons of industrial rolling bearing vibration measurement systems difficult. Firstly, the system's operation influences the measurement result (e.g., the above-mentioned bearing overshoot caused by an improper (faulty or misaligned) clamping structure). Secondly, the result of a bearing vibration can vary spontaneously, independently of the measuring system or operator. This variability relates,

for example, to the reproducibility of measurement results, interpreted as the degree of agreement between successive vibration measurements. Difficulties with measurement reproducibility arise from the fact that after removing and refitting the bearing, the balls may roll to slightly different positions in the inner and outer raceways, and the rotation axes of the balls can change. In addition, when testing the same bearing on different equipment, there is a risk that the balls and raceways may change the existing deviation and geometric structure of the matting surfaces. The bearing may also become damaged in the meantime or, if the defect was pre-existing, may be transferred to other bearing components. When carrying out multiple measurements on a single system, the vibration level can also change spontaneously, e.g., due to temperature increases caused by friction inside the bearing (change in the dimensions of the bearing components due to thermal expansion and change in the properties of the lubricant used). In addition, the result of vibration measurement is an unknown value, which is very difficult to determine precisely. There are no reference bearings whose vibrations are known, and which can provide a basis for determining the efficiency of the device under test.

Reliable comparative tests of these systems are very much needed from the point of view of the bearing industry and include, among other things, the testing of various new developments, as well as the selection of the most reliable systems that can serve as reference systems. For this reason, both universities supporting the bearing industry and industrial companies should further develop procedures which, among other things, make it possible to evaluate a given system or compare it with another in a reliable manner, i.e., by separating the natural tendency for a bearing's vibration level to differ from the variability caused by the system.

**Availability of data and material** All posted data is available and verifiable.

**Code availability** Not applicable.

## Declarations

**Ethics approval** Not applicable.

**Consent to participate** Not applicable.

**Consent for publication** Affiliation agree to publish the manuscript.

**Conflict of interest** The author declares no competing interests.

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