24th INTERNATIONAL CONGRESS ON SOUND AND VIBRATION
23–27 July 2017, London
ICSV24 23-27JULY 2017 LONDON CALLING

NEW EFFECTS OF ONE-POINT MECHANICAL METAL-TO-METAL CONTACT ALLOWING THE MEASUREMENT OF HIGH FREQUENCY VIBRATION USING HANDHELD PROBES AND HEAVY VIBRATION SENSORS

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Two new independent methods of extending vibration frequency measurement ranges up to 20 kHz were designed in the areas where it had previously been limited to 1–3 kHz.

The first method is helpful when measuring with a stick sensor or handheld portable instruments, and the second is useful for heavy (massive) sensors. When applied, both methods provide new diagnostic capabilities especially for rolling/ball bearings and gearboxes.

Keywords: vibration, sensors, frequency range, vibrodiagnostics

1. Introduction

The first method is related to discovering the previously unknown behavior of one-point metal-to-metal contacts. It is found that the traditional transfer function incorrectly describes situations at frequencies higher than the resonance frequency of the contact. Theoretically and through experiments it is shown that the frequency response of such contact (minus resonance) is linear on a logarithmic axis and linearly dependent on the force applied to that contact. The measurement range of stick sensors is traditionally supposed to range from several Hz to 1 kHz, and its resonance usually ranges from 2–3 kHz. Thus, such sensors are widely recommended for use up to approximately 1 kHz. Discovered linearity provide the possibility of electronically compensating for the decreasing frequency response after resonance and measuring vibration accurately after resonance in a range over 10 times wider (i.e., about 4 to 20 kHz). The new extended frequency response of the stick sensor requires two things to be implemented to work properly: electronic compensation which raises the signal approximately 15 dB/octave in a range of 5–20 kHz and forces the sensor to measure the applied forces all the time. Then the new stick sensor responses present as the ratio of the compensated vibration frequency signal and the forces signaled in real time. Such a stick sensor may work in two ranges: in the traditional 10 Hz – 1 kHz and in the extended 4–20 kHz, which allows one to measure regular vibration as well as monitoring the bearing and gearboxes with handheld devices w/o surface preparation.

The second method discovered is to measure high frequency vibrations using heavy (massive) sensors. It was previously known that heavy sensors have a limited frequency response because of low resonance. For instance, a one pound mass sensor has a resonance frequency about 3–5 kHz even though the resonance of the sensitive element itself of such a sensor could be tens of kHz. A special mechanical filter was placed between the sensor's sensitive element and the sensor body, which raised the heavy sensor's frequency resonance up to 30 kHz and the measurement range up to 15–20 kHz. The mechanical filter's natural resonance ranges from 700–1300 Hz, and its Q-factor does not really affect the sensor's frequency response curve—only a small change (about +/-1%) on the curve may be seen at the point of mechanical filter resonance frequency and only if the sensor's mass is very large (over 2 lbs.). Such a method of extending the frequency response allows for the use of a heavy sensor (for example, a wireless sensor with batteries) or bulky vibration switch for the effective monitoring of bearings and gearboxes.

2. Measurement of vibration with the use of hand-held stick sensors or portable instruments

In practice, the collection of data for vibradiagnostics systems is often performed by route measurements of vibration with the help of a portable device, while a magnet, stick, or probe is used for installation of the gauge. It is well known that the probe limits the measurement by a frequency of 1–2 kHz, and the magnet by a frequency of 4–6 kHz. Such frequency limitation certainly reduces the possibilities and the accuracy of the diagnostics. In Fig. 1, there are presented, for comparison, frequency responses for various versions of fixing of the same vibration gauge with its own resonance of 50 kHz.

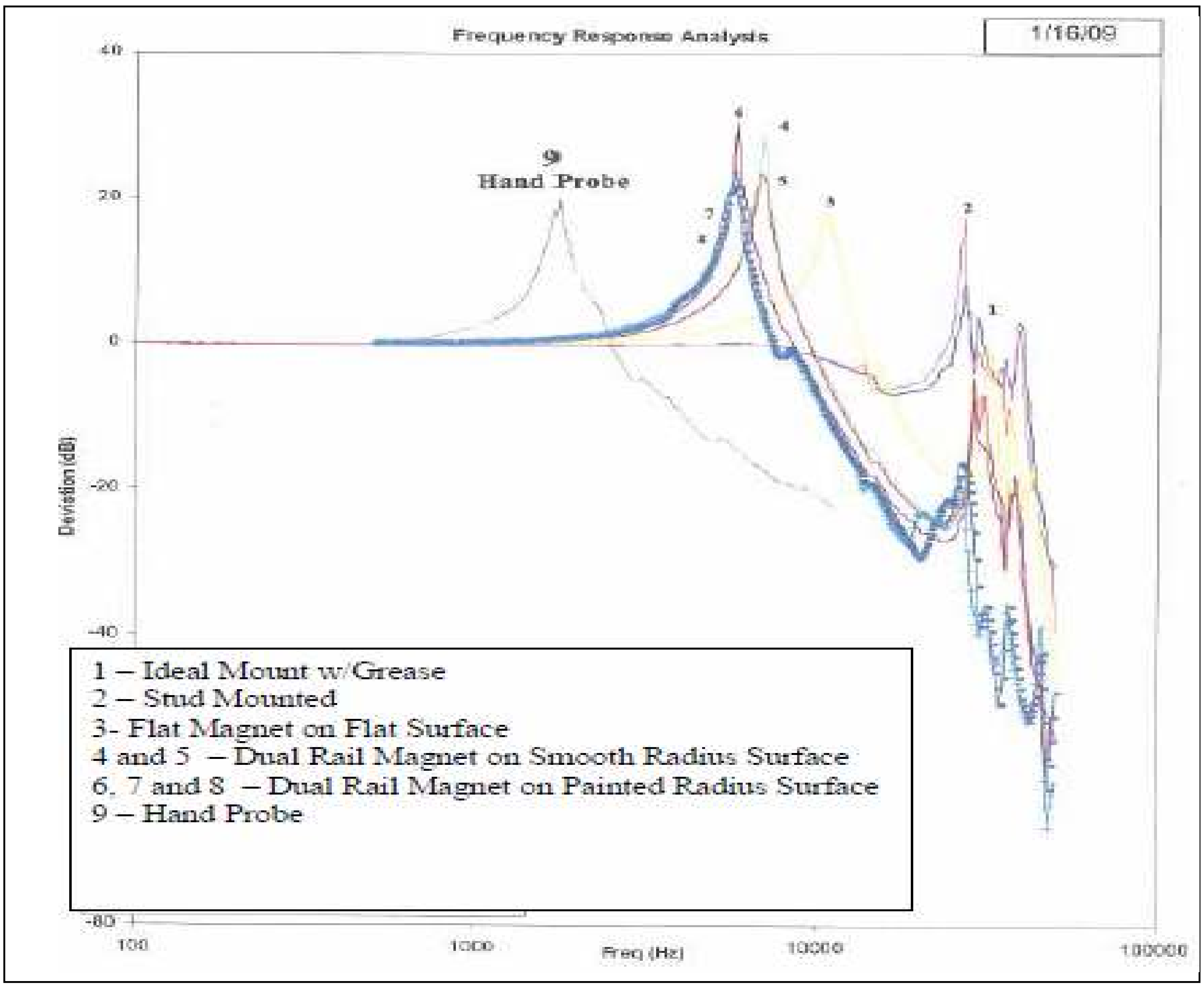
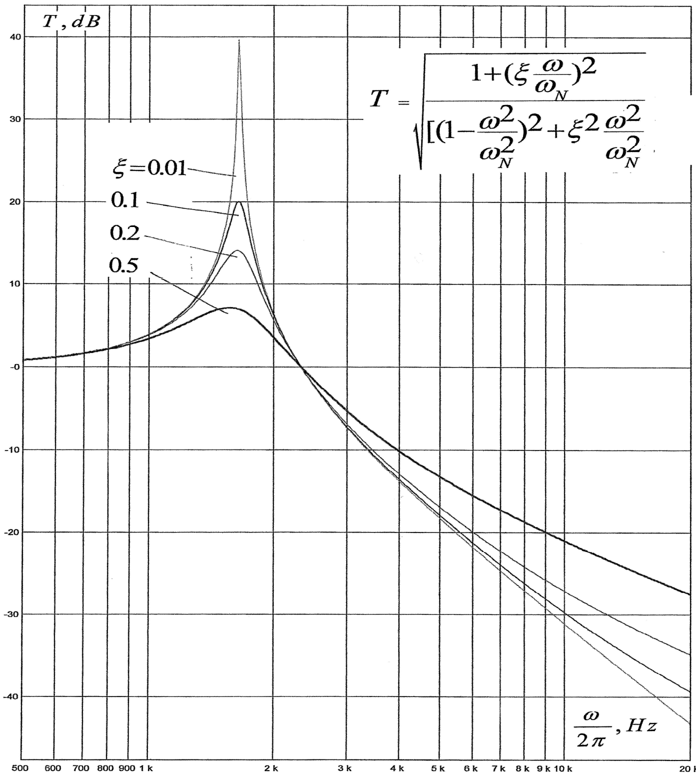
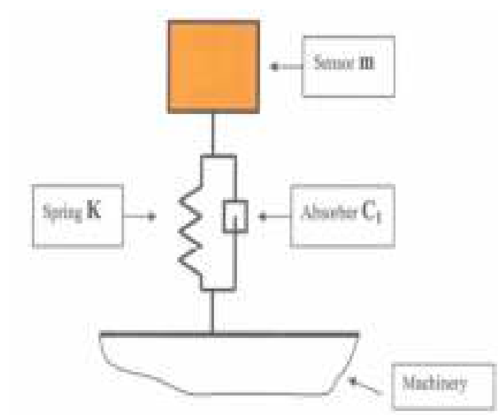


Figure 1: Frequency responses for various versions of fixing of the same gauge with its own resonance of 50 kHz.

The sensor with a probe is often more convenient for nonmagnetic and rough surfaces, and practically speaking, in route measurements it may be used only for measuring at low frequencies. At the same time, the high-frequency measurements with the probe might considerably improve the quality of vibrodiagnostics, for instance, in case of rolling bearings.



$$T = \sqrt{\frac{1+(\xi\frac{\omega}{\omega_N})^2}{[(1-\frac{\omega^2}{\omega_N^2})^2+\xi^2\frac{\omega^2}{\omega_N^2}}} \quad (2.1)$$



$$T = \frac{\frac{c_1}{k}p+1}{p^2\frac{m}{k}+p\frac{c_1}{k}+1}, \text{ where } \frac{c_1}{k}=\xi \quad (2.2)$$

a) b)

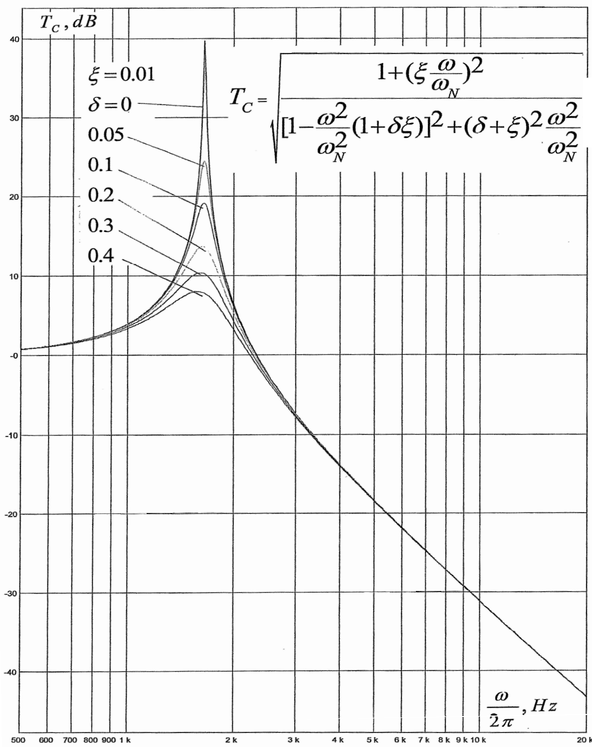
Figure 2: a) - Classical design transfer characteristic of the gauge with the probe and b) mechanical contact model

T-transfer function, ω -input frequency, ω_N - natural frequency, ξ – mechanical contact damping coefficient, p – Laplace-Karson operator, m – sensor mass, k – stiffness of mechanical contact, c_1 – absorber damper coefficient

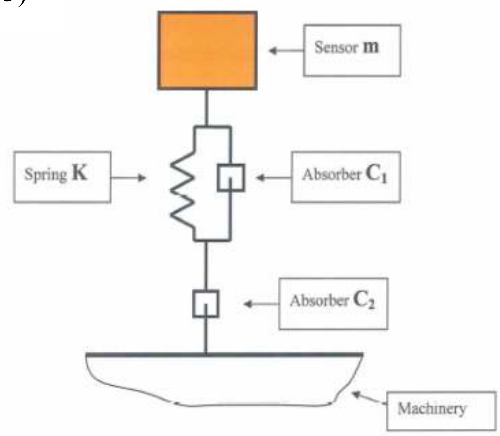
Let us start with the model of the transfer of oscillations through the contact connection of the probe and the surface.

In Fig. 2 a), there is presented the classical design transfer characteristic (2.1) and (2.2) of the gauge with the probe and in Fig. 2 b) – mechanical contact model. In this characteristic, no possibilities are seen for the reliable measurement of vibration at high frequencies. Nevertheless, attentive consideration of the mechanical model of the "probe-metal surface" contact has shown that the classical model is not accurate exactly in the above-resonance region. The clarified mechanical model of the contact is actually described by the function (2.3) and (2.4) presented in Fig. 3. The transfer characteristic in the above-resonance frequency region is firstly linear in the logarithmic coordinates and secondly stable and practically does not depend on the degree of damping of the contact connection.

The experimental frequency characteristic of the gauge with the probe taken off in the logarithmic coordinates fully confirms this fact (Fig. 4 a). Having compensated for the linear sensitivity dependence of the frequency characteristic with the help of electronics and with the use of the tightness force adjustment sensor (Fig 4 b and 5 b), we have managed to obtain a stable and flat frequency characteristic (see Fig. 5 a) permitting one to reliably measure the vibration in the range of 4–20 kHz on any metal surface without any special preparation thereof [1].



$$T_C = \sqrt{\frac{1+(\xi\frac{\omega}{\omega_N})^2}{[1-\frac{\omega^2}{\omega_N^2}(1+\delta\xi)]^2+(\delta+\xi)^2\frac{\omega^2}{\omega_N^2}}} \quad (2.3)$$

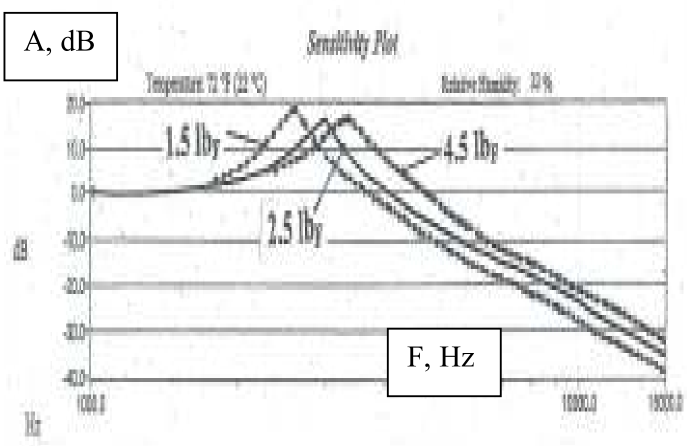


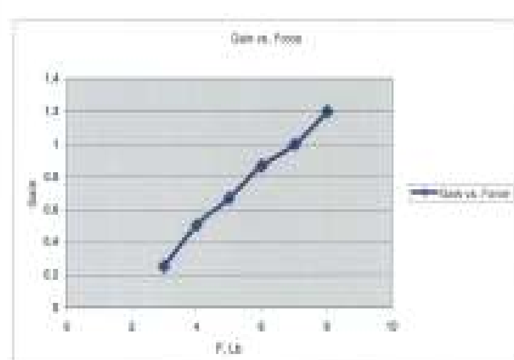
$$T = \frac{\frac{c_1}{k}p+1}{p^2(\frac{c_1}{c_2}+1)\frac{m}{k}+p(\frac{m}{c_2}+\frac{c_1}{k})+1}, \ where\ \frac{c_1}{k}=\xi, \frac{m}{c_2}=\delta \quad (2.4)$$

a) b)

Figure 3: a) - Design transfer characteristic of the clarified mechanical model of the gauge with the probe and b) Offered model of mechanical contact

T-transfer function, ω -input frequency, ω_N - natural frequency, ξ – mechanical contact damping coefficient, δ - mass damping coefficient, p – Laplace-Karson operator, m – sensor mass, k – stiffness of mechanical contact, c_1 – first absorber damper coefficient, c_2 - second absorber damper coefficient





a) b)

Figure 4: Experimental a) -frequency characteristic of the gauge with the probe and b) gain vs applied forces

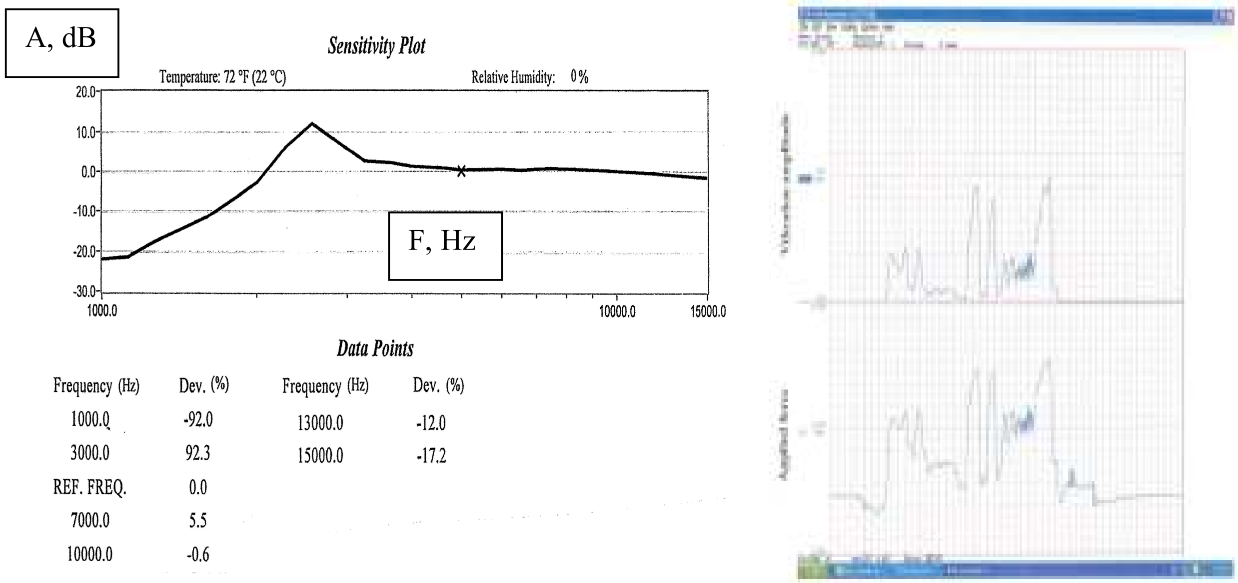
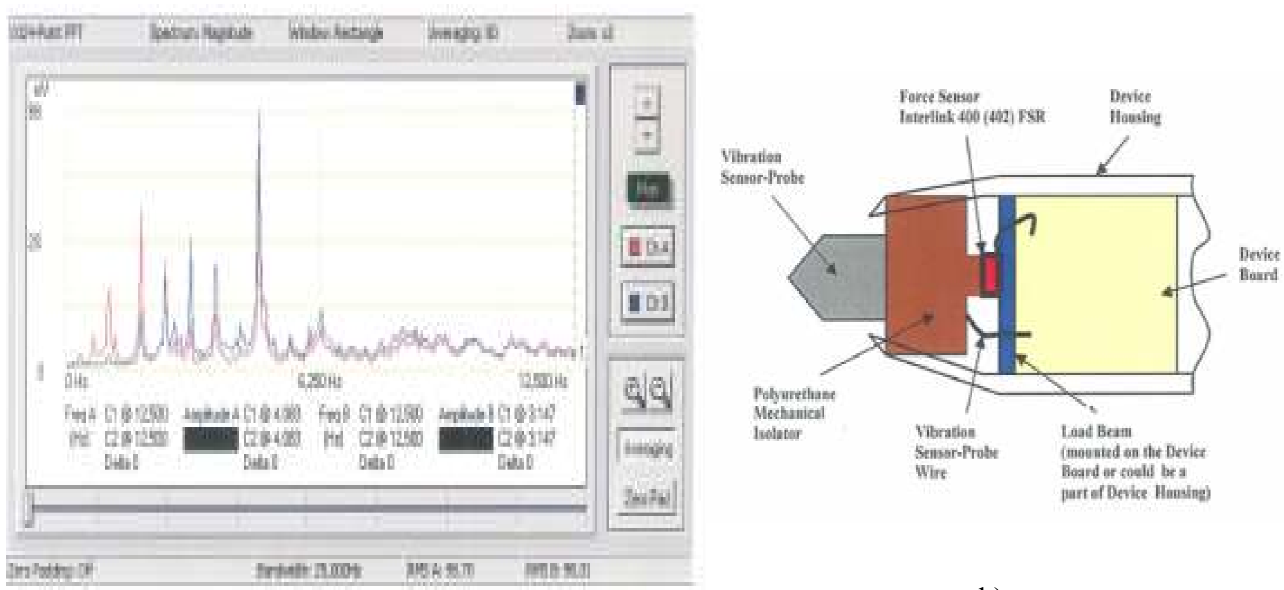


Figure 5: a) Frequency characteristic of the gauge with the probe compensated with the help of electronics and a tightness force adjustment sensor and b) illustration of gain linear dependence to the dynamically applied forces

As an example, Fig. 6 a) presents two spectra: one is taken with the help of a gauge rigidly fixed on the casing of the bearing, and the other by a gauge with a high-frequency probe without preparation of the surface. As clearly seen, the spectra in the high-frequency region (over 4 kHz) are identical. Fig 6 b) illustrated a construction of offered sensor.



a) b)

Figure 6: a) Comparison of spectra of signals taken off by a gauge rigidly fixed on the casing of the bearing (red), and by a gauge with a high-frequency probe without preparation of the surface (blue) and b) illustration of sensor construction

The possibility of reliable measurement of high-frequency vibration with the help of a gauge with a probe and without any preparation of the surface has made it possible to develop portable devices [2] which increase the reliability of diagnostics of bearings and gearboxes.

3. Measurement of vibration by the sensors with increased mass

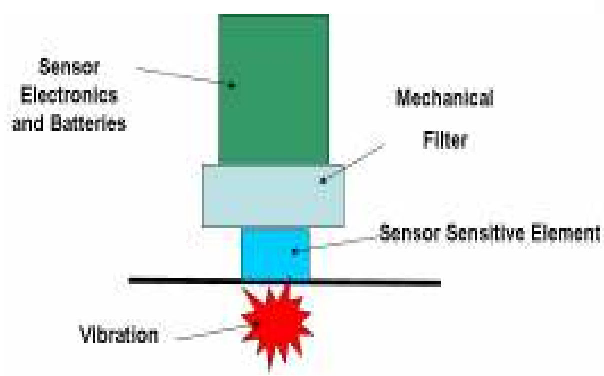
The research of vibration measurement with the gauges of increased mass has gained particular priority with the appearance and wide use of wireless transducers with built-in power packs.

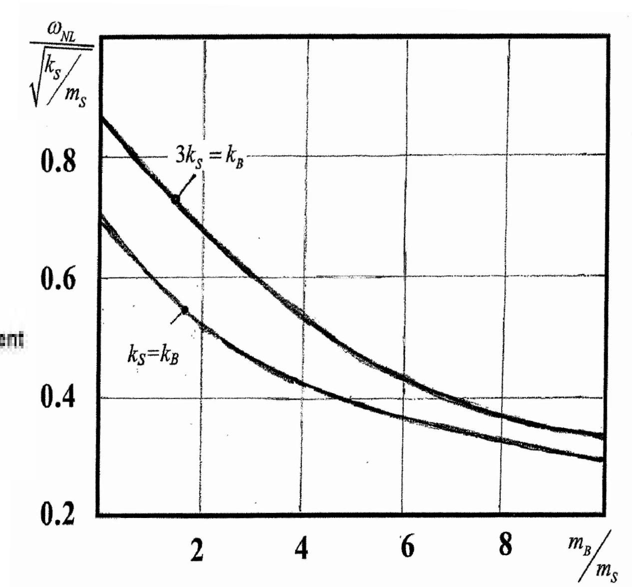
It is known that sensors with increased mass have a lower setting resonance which can be determined approximately by the following formula:

$$\omega_{NL} = \sqrt{0.5[w - \sqrt{w^2 - \frac{4K_S K_B}{m_S m_B}}]}, \qquad (3.1)$$

where $w = \frac{K_B}{m_B} + \frac{K_S}{m_S}(1 + \frac{m_S}{m_B})$ and ω_{NL} is the frequency of the setting resonance, m_S is the mass of the sensing element proper, m_B is the mass of the base and body of the gauge, K_B and K_S are coefficients of elasticity associated with the rigidness of fixing of the sensing element and of the whole gauge.

The Fig. 7 b) illustrates of the idea of using the mechanical filter. The calculations show that the average frequency of the setting resonance is reduced 2–3 times with a 6–8-fold excess of the mass of the gauge over the mass of the sensing element (see Fig. 7 b). Such a ratio of masses is typical for wireless sensors and sensors with the body of increased strength for explosion-hazardous applications.





a) b)

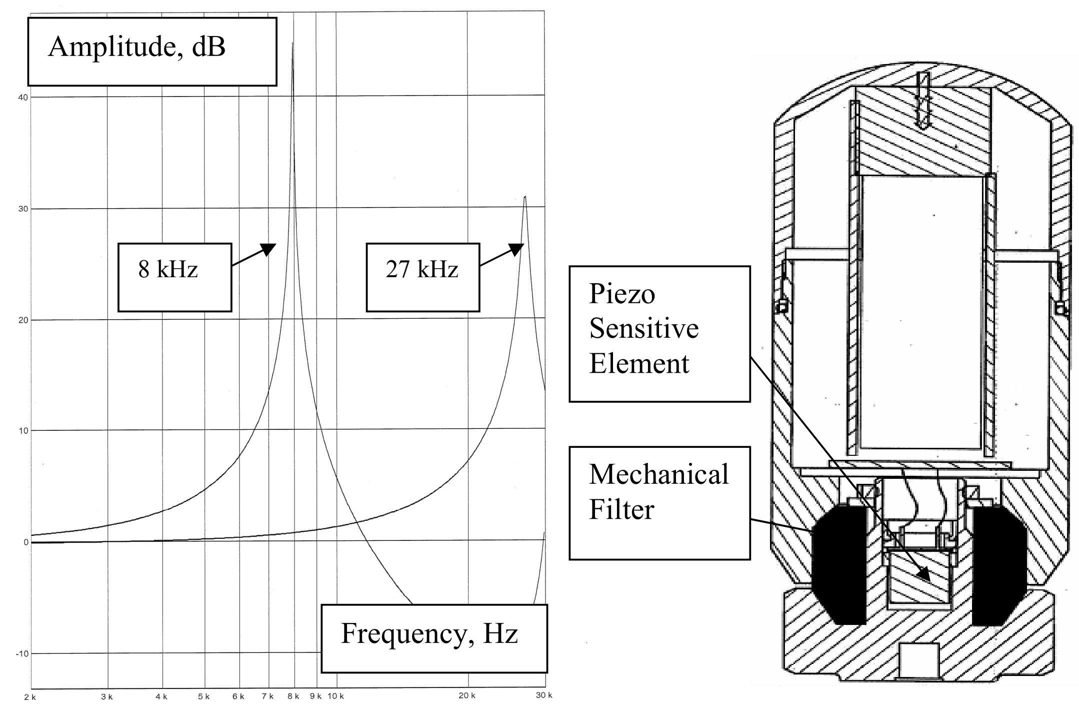
Figure 7: a) Illustration of the idea of using mechanical filter and b) plot of dependence of the setting resonance frequency on the ratio of the mass of the gauge to the mass of the sensing element

We have managed to show that a specially manufactured mechanical filter [3] installed between the sensing element secured on the facility and the remaining part of the structure of the gauge essentially increases the setting resonance and permits one to reliably measure the vibration up to 20 kHz and over.

The formula of the setting resonance for this case has the following form:

$$\omega_{NL} = \sqrt{0.5[w - \sqrt{w^2 - \frac{4K_S K_B}{m_S(m_{B1} + \frac{m_{B2}}{\gamma})}}]}, \qquad (3.2)$$

where $m_B = m_{B1} + m_{B2}$, $w = \frac{K_B}{m_{B1} + \frac{m_{B2}}{\gamma}} + \frac{K_S}{m_S}(1 + \frac{m_S}{m_{B1} + \frac{m_{B2}}{\gamma}})$ and m_{B1}, m_{B2} are the masses of the parts of the gauge constructively located before and after the mechanical filter; correspondingly, a γ is the coefficient of damping of the mechanical filter.



a) b)

Figure 8: a)-Comparison of frequency characteristics of a wireless gauge with the mass of 0.5 kg manufactured according to the traditional technology (resonance at 8 kHz) and new technology (resonance at 27 kHz) and b)-Cut drawing of the sensor with mechanical isolation filter.

For example, Fig. 8 a) presents frequency characteristics of a wireless gauge with the mass of 0.5 kg manufactured as per the traditional and new technologies. As shown, the sensor manufactured as per the new technology allows the measurement of vibration up to 20 kHz and is already used for both monitoring of low-frequency vibration and for monitoring the condition of the rolling bearings. The Fig. 8 b) illustrated the example of mechanical isolation filter construction.

4. Conclusion

Two new independent methods of extending vibration frequency measurement ranges up to 20 kHz were designed in the areas where it had previously been limited to 1–3 kHz.

The first method based on the new effect of metal to metal contact which frequency response after resonance appears to be linear in logarithmic axis and possible then to be accurately compensated. Based on that effect the new extended frequency response stick sensor offered. It is two things implemented to the stick sensor: electronic compensation which raises the signal approximately 15 dB/octave in a range of 5–20 kHz and force sensor to measure the applied forces constantly and adjust the gain accordingly. Such a stick sensor may work in two ranges: in the traditional 10 Hz – 1 kHz and in the extended 4–20 kHz, which allows one to measure regular vibration as well as monitoring the bearing and gearboxes with handheld devices w/o surface preparation.

The second method discovered is to measure high frequency vibrations using heavy (massive) sensors. It was previously known that heavy sensors have a limited frequency response because of low resonance. For instance, a one pound mass sensor has a resonance frequency about 3–5 kHz even though the resonance of the sensitive element itself of such a sensor could be tens of kHz. A special mechanical filter was placed between the sensor's sensitive element and the sensor body, which raised the heavy sensor's frequency resonance up to 30 kHz and the measurement range up to 15–20 kHz. The mechanical filter's natural resonance ranges from 700–1300 Hz, and its Q-factor does not really affect the sensor's frequency response curve—only a small change (about +/-1%) on the curve may be seen at the point of mechanical filter resonance frequency and only if the sensor's mass is very large (over 2 lbs.). Such a method of extending the frequency response allows for the use of a heavy sensor (for example, a wireless sensor with batteries) or bulky vibration switch for the effective monitoring of bearings and gearboxes.

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