XXI IMEKO World Congress "Measurement in Research and Industry"
August 30 – September 4, 2015, Prague, Czech Republic

MAGNETIC EFFECTS IN THE CALIBRATION OF SENSORS UNDER SINUSOIDAL EXCITATIONS

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Abstract– This paper describes the magnetic effects studied at CEM in their realization of a primary standard for dynamic force calibration using sinusoidal excitations of force transducers, although they can also affect any sensor with an electrical output mounted on an electrodynamic shaker. In this study the electromagnetic behaviour for the interaction between sensor and shaker or a similar source of magnetic fields is explained and a solution to minimise this interaction is also included.

Keywords: magnetic effects, shaker, dynamic sensor.

1. INTRODUCTION

This paper describes the magnetic effects studied at CEM in their realization of a primary standard for dynamic force calibration using sinusoidal excitations of force transducers.

This work was part of a project called "Traceable dynamic measurement of mechanical quantities" financed by the European Union under the European Research Metrology Program [1].

This standard is based on the direct definition of force as mass times acceleration. The transducer is loaded with different calibrated masses and different accelerations are generated by a vibration shaker system. The acceleration is measured by a laser vibrometer traceable to the unit of length (laser wavelength).

The laser vibrometer (Polytec CLV 2534) is placed over the shaker (LDS 726 with power amplifier PA 2000, which can work from 5 Hz up to 2400 Hz) by means of a special table designed for this purpose.

Being a fully dynamic measurement it requires a multichannel data acquisition system in real time. A NI PXI 1033 module with a 4462 card (24 bits, 204.8 kS/s) has been used. The implemented software, which is programmed in Labview, samples the signals separately with a speed of 40 kS/s and applies the sine approximation method in order to determine the signals amplitudes and phases in real time.

The sensor is characterised by its dynamic sensitivity, which is the ratio of its electrical output signal of the force transducer and the acting dynamic force. The sensitivity phase is determined as the phase difference between the sensor output and the laser vibrometer output.

The required masses for generating the forces on the sensors have been manufactured and calibrated to determine their mass and their corresponding uncertainty. The masses have nominal values 347 g, 1 kg, 2 kg, 7.3 kg and 12.3 kg. The three smaller masses are screwed to the sensor under calibration, the bigger ones are connected under pressure by means of a special adaptor. Depending on the sensor to be calibrated, special adaptors may be required in order to screw the masses to the sensor or the sensor to the shaker. Different corrections and influence factors have to be taken into account for this standard. References [2] and [3] provide complete information about this development.

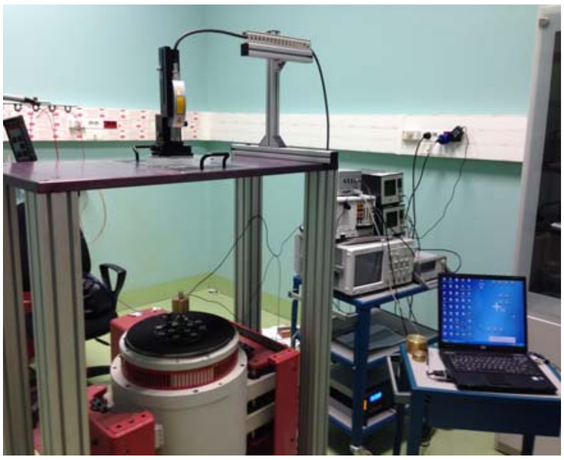

Fig. 1. Overview of the standard for dynamic force calibration using sinusoidal excitations.

2. DESCRIPTION

This work arises from the study of the behaviour of the sensor sensitivity at low frequencies. In principle, the lower the frequency the behaviour should be increasingly closer to the static behaviour, that is, the sensor sensitivity must remain constant. This sensitivity behaviour is as expected for heavy loads, but not for small loads. In fact, the smaller the load the sensitivity variation is increased.

In this work the sensitivity behaviour has been studied in the range from 5 Hz to 200 Hz. This study was conducted for different excitation accelerations according to the possibilities of the vibration shaker and for several sensors with different size and working principle, resistive or piezoelectric. Fig. 2. to Fig. 4. are examples of this kind of behaviour for two different sensors with different working principles. There is no effect on the phase for the piezoelectric sensor, so no plot is shown.

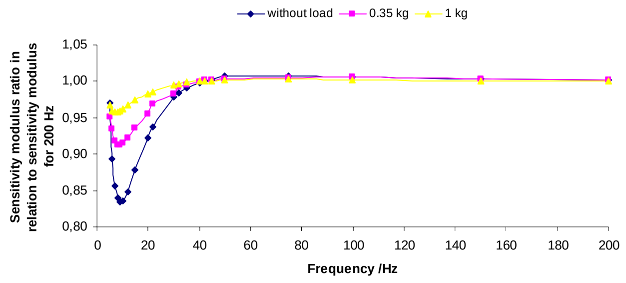

Fig. 2. Plot showing the sensitivity divided by the sensitivity for 200 Hz versus frequency for the INTERFACE 1610 sensor (resistive sensor) for the cases: without load, 0.35 kg and 1 kg.

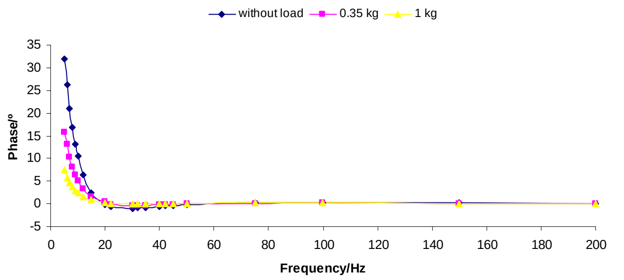

Fig. 3. Plot showing the phase versus frequency for the INTERFACE 1610 sensor (resistive sensor) for the cases: without load, 0.35 kg and 1 kg.

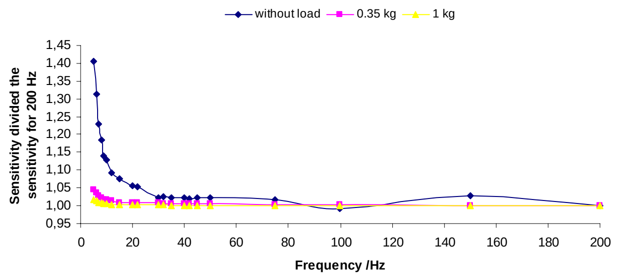

Fig. 4. Plot showing the sensitivity divided by the sensitivity for 200 Hz versus frequency for the KISTLER 9175B sensor (piezoelectric sensor) for the cases: without load, 0.35 kg and 1 kg.

The results of this study can be summarised as follows.

The first issue that has to be remarked is the fact that these effects are not dependent on the acceleration. They do not depend on either its magnitude or the chosen reference to measure it, because the same results were obtained using the laser vibrometer or a reference accelerometer.

They only appear for low frequencies, typically less than 40 Hz.

In the case of HBM 9B sensor, which is a resistive sensor, this effect does not occur. The only difference that distinguishes it from the other tested resistive sensors is its small size, so it is clear that size may have an influence.

These effects increase as the load decreases. In fact it is more important when the sensor is not loaded.

The fact that these effects are not dependent on the acceleration and how it is measured, decrease with frequency and load and decrease with the sensor size, indicates that they cannot be dynamic effects such as rocking motion or resonances. It is therefore thought that an interaction between sensor and vibration shaker may be a possible explanation for these effects. The operation principle of the electrodynamic shaker (the armature moves because of the Lorentz force) makes magnetic fields presence necessary for its operation, so a kind of magnetic effect is thought to be a good candidate for a possible explanation.

3. UNDERSTANDING THE EFFECTS

As a first step the magnetic field in contact with the centre of the shaker armature (where the sensor is connected) was measured obtaining a value of 2.3 mT. At this same point but 15 cm higher the magnetic field is less than 0.5 mT. These fields are relatively small and are within the specifications of the shaker itself.

In order to check whether the observed effects are actually caused by magnetic fields, a large magnetic field generated by a large permanent magnet was put close to the sensor. The intention is to magnify these effects by the presence of the magnet.

As a first attempt the magnet was near the sensor and the sensor was connected to the shaker. Sensor tests were then performed in the range from 5 Hz to 200 Hz with the sensor moving and the magnet hanging in a stationary position. These tests were carried out at several distances, different accelerations and always with the sensors unloaded, so that their output could only be influenced by magnetic effects. As a result no different effects from the ones that had already been observed could be appreciated.

In the second attempt it was decided to reverse the sensor-magnet configuration and connect the magnet to the shaker, so it moves with it, and leave sensor hanging to remain static. With this new configuration the effects presented from Fig. 5. to Fig. 8 were obtained.

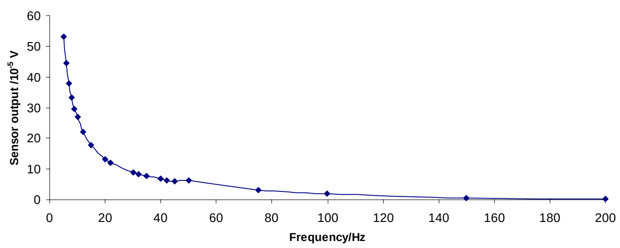

Fig. 5. Plot showing sensor output versus the frequency for INTERFACE 1610 sensor (resistive sensor).

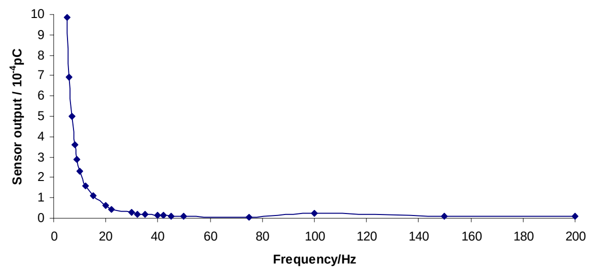

Fig. 6. Plot showing sensor output versus the frequency for KISTLER 9175B sensor (piezoelectric sensor).

These results were completely unexpected because an unloaded sensor in a static position should have a constant output (zero output) that should not depend on other external factors. On the contrary, these results show a clear dependency on excitation frequency: for the resistive sensors as the inverse of the frequency (Fig. 7) and for the piezoelectric sensor as the inverse of the frequency squared (Fig. 8).

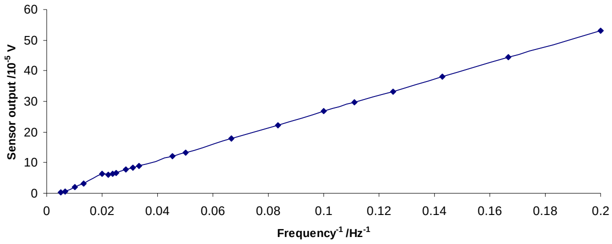

Fig. 7. Plot showing sensor output versus the inverse of the frequency for INTERFACE 1610 sensor (resistive sensor).

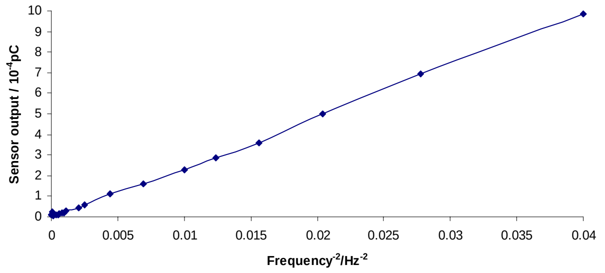

Fig. 8. Plot showing sensor output versus the inverse of the frequency squared for KISTLER 9175B sensor (piezoelectric sensor).

According to Fig. 9 and Fig. 10 for the sensors output phase it can be deduced that the phase is -90° for resistive sensors and the phase is 0° for piezoelectric sensors (± 180º, due to the indeterminacy of the arc tangent function used for calculating the phase).

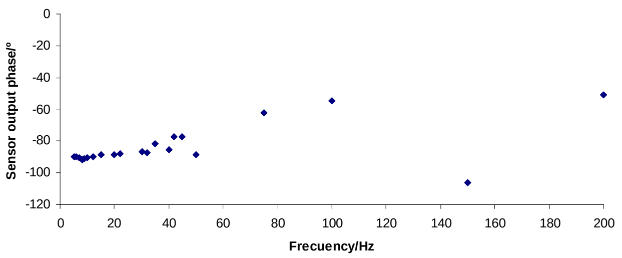

Fig. 9. Plot showing sensor output phase versus the frequency for INTERFACE 1610 sensor (resistive sensor).

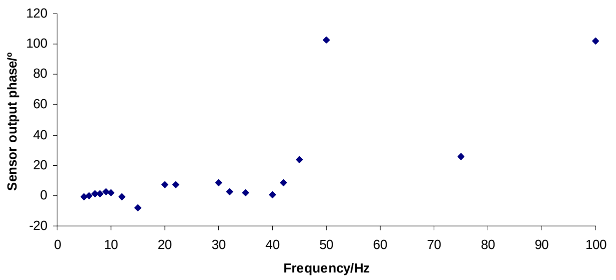

Fig. 10. Plot showing sensor output phase versus the frequency for KISTLER 9175B sensor (piezoelectric sensor).

These measurements are more reliable at low frequencies, where the results are closer to constant values; but generally these constant values can be extrapolated to the entire measurement range, as their measurement errors are related to the fact that the sensors output amplitude will be much lower as the frequency increases.

The conclusion for these experiments is that very similar effects as the ones previously observed were obtained, but magnified. This is due to the high intensity of the magnetic field generated by the moving magnet; but the most important achievement has been to prove that these effects were caused by a magnetic field whose intensity close to the sensor varies sinusoidally with time. In this case the distance between the moving magnet and the sensor varies sinusoidally with time and, therefore, the magnetic field intensity generated close to the sensor varies accordingly.

4. THEORETICAL JUSTIFICATION

The operating principle of the electrodynamic shaker, in order to achieve a sinusoidal motion of its armature, is based in the Lorentz force law. A coil with N turns, length l and a current $\boldsymbol{I}$ passing through, which varies sinusoidally with excitation frequency ω, is attached to the armature. This coil is immersed within a static magnetic field with magnetic flux density $\boldsymbol{B}$. This is necessary so that the armature can move according to the Lorentz force law:

$$\boldsymbol{F}e^{i\omega t} = Nl\boldsymbol{I}e^{i\omega t} \times \boldsymbol{B} \qquad (1)$$

The magnetic flux density $\boldsymbol{B}$ is generated by another coil with a direct current passing through it. There is another coil called "degauss" coil that counteracts the effects of $\boldsymbol{B}$ in the environment. These magnetic fields are static and have no effect on the measurement.

The frequency dependent magnetic field that could explain these effects comes from the current $\boldsymbol{I}(\omega)$, which passes through the coil. This magnetic field $\boldsymbol{B'}(\omega)$ will vary with the excitation frequency and comes from the application of Biot and Savart law [4].

Using cylindrical coordinates (r, z, φ) $\boldsymbol{I}$ will only have one component I_φ, so the magnetic field $\boldsymbol{B'}$ can only have two components B'_z and B'_r. The effect of this sinusoidal magnetic field produces a current density $\boldsymbol{J'}(\omega)$ at the same time, which also varies sinusoidally.

If the medium that generates its output (piezoelectric material for a piezoelectric sensor, metallic conductor for a strain gauge) can be assumed as isotropic and homogeneous as a first approximation, Maxwell equations can be applied as follows [5], where the medium is considered to have permeability μ and conductivity σ and the fields variation with time is sinusoidal with frequency ω,

$$\begin{aligned} \nabla \times \boldsymbol{J}' &= -j\omega\sigma\boldsymbol{B}' \\ \nabla \times \boldsymbol{B}' &= \mu\boldsymbol{J}' \end{aligned} \qquad (2)$$

The solution for this system of equations is rather complex. The current density $\boldsymbol{J'}$ will only have one component, J'_φ, as $\boldsymbol{B'}$ has two components, B'_z and B'_r. This solution is given by equation (3),

$$J'_\varphi(r,z) = K\,exp\left\{-(j\alpha\omega\sigma\mu)^{1/2} z\right\} J_1\left\{(j(\alpha-1)\omega\sigma\mu)^{1/2} r\right\} \qquad (3)$$

where J_1 is the Bessel function for first order and first kind, and K and α are constants. It is required that $\alpha>1$ in order to avoid divergent solutions.

As a consequence, the induced current will have one single component along φ direction and its module will be given by equation (4),

$$I'_\varphi = \int J'_\varphi \cdot dS \approx \frac{1}{j\omega\sigma\mu} \qquad (4)$$

This result shown by equation (4) is very important and it is indeed what explains the observed effects. The induced current is proportional to the inverse of the excitation frequency and its phase shift is -90º. It also explains why this effect depends on the size of the sensor, as this current *I'* also depends on it.

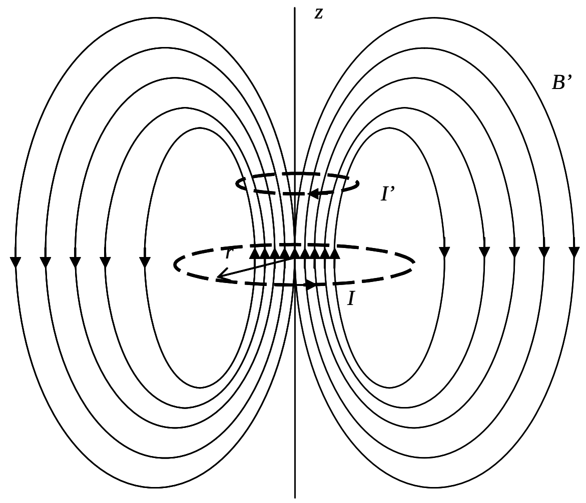

Fig. 11. Schematic diagram showing the current *I* that passes through a turn of the coil, the magnetic field lines for *B'* and the subsequent induced current *I'*.

This is clearly the result that was obtained when the magnet was connected to the shaker and the sensor was hanging freely over it. Although, when only the shaker is considered, the generated magnetic field is smaller and the sensor sensitivity dependency with the inverse of the excitation frequency may not be so clear. On the other hand, the medium that generates the sensor output may not fulfil homogeneous and isotropic conditions in full.

All of the previous statements make sense for resistive sensors. Since their impedance is basically resistive, their output will be directly proportional to the induced current. In the case of piezoelectric sensors, the observed output depends on the inverse of the frequency squared. This case is also justified because these sensors direct outputs are not currents but charges. In general, the charge Q that is generated by a sinusoidal current I with amplitude I_0 is given by equation (5),

$$Q = \int I\ dt = \int I_0 e^{j\omega t} dt = \frac{I}{j\omega} \qquad (5)$$

This result indicates that the charge generated by the current induced by the sinusoidal magnetic field is itself inversely proportional to frequency and with a -90º phase shift. Moreover, it must be pointed out that, in the current use of the sensor with load, currents are never generated and only charges which are proportional to the force are generated. As a consequence, this dependency with frequency and this -90º additional phase shift are never observed. Another way to express this fact is to say that the piezoelectric impedance is basically capacitive ($Z = 1 / jC\omega$).

Therefore, if the current induced by the non static magnetic effects depends on the inverse of the excitation frequency with a -90º additional phase shift, the output voltage induced by this effect in a piezoelectric sensor will show a dependency as the inverse of the excitation frequency squared and a 180° total phase shift (or 0 ° due to the indeterminacy of the arc tangent function used for calculating the phase).

On the other hand, according to equation (3), the induced current density decreases with the vertical distance (*z*) to the armature. Therefore, in order to minimise these magnetic effects, a special coupling has been used to increase the connection distance between sensor and shaker armature with excellent results. As a general result, a sufficient increase in the distance between the sensor and the shaker armature will avoid the problem. This coupling, however, may have the disadvantage of magnifying dynamic effects, which increase with excitation frequency. As a consequence, the coupling should be used only at low frequencies and it is recommended the sensor to be coupled directly to the exciter at higher frequencies.

5. CONCLUSIONS

In this paper the magnetic effects caused by a non static magnetic field on sensors with electrical output have been described and fully explained. The sensors under study have been piezoelectric and resistive force sensors and the non static magnetic field has been generated by an electrodynamic vibration shaker.

It has been discovered that these effects are more important the lower the excitation frequency and the sensor load are, but they increase with the sensor size.

The magnitude of the magnetic effects discovered for force sensors in this study is very important. In the current use of accelerometers with electrodynamic shakers some similar behaviour could be expected, but it may not be so important because the accelerometer size is generally smaller as well as the current that passes through the shaker armature coil used in accelerometer calibration.

On the other hand, a sufficient vertical distance between sensor and armature, which could be achieved increasing the coupling length, assures that these effects could be negligible independently of the sensor size.

ACKNOWLEDGMENTS

The authors would like to thank Eusebio Rubio and Jesús Prieto from Bruël & Kjaer Ibérica (Spain) for their help and support.

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