

## MAGNETOSTRICTIVE ACCELEROMETER USING AMORPHOUS METALLIC ALLOYS

T. Meydan, P. Choudhary

Wolfson Centre for Magnetics Technology, School of Engineering, Cardiff University, PO Box 925, CF24 0YF, United Kingdom

A sensor utilising the inverse magnetostrictive effect was designed for the purpose of vibration condition monitoring. Measurements show that the sensor's output is directly proportional to the acceleration component of the vibration being measured and that the frequency range extends down to DC levels.

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### 1. Introduction

Any piece of equipment in a manufacturing/process plant is subject to failure during its life cycle. At such a time, there is a need for the damaged part to be replaced through maintenance procedures. Condition monitoring can help in predicting the time prior to machine breakdown, thereby providing ample time for maintenance to be carried out [1].

Vibration analysis is the most extensively used condition monitoring technique. Its utilisation stems from the fact that, machines generate vibration as a by-product of normal operation. A well-designed machine with low tolerance components produces low levels of vibration. But as the components wear, foundations settle and parts deform, changes begin to occur in the dynamic properties of the machine [2]. All these factors contribute to the increase in the vibration energy dissipated. This has the effect of exciting resonant frequencies, which increase the load on the bearings and accelerate the rate at which the components deteriorate.

Vibration is measured using motion sensors, which produce electrical signals that represent the mechanical vibration signals in terms of the displacement, velocity or acceleration [3]. The three parameters can be deduced from one another by means of integration/differentiation. However, the use of electrical differentiators/integrators can prove to be problematic; differentiation tends to accentuate noise, whereas, integration tends to smooth it.

Piezoelectric accelerometers, Strain gauge accelerometers using a number of different operating principles, Velocity pickups (often referred to as seismic mass transducers) producing signals that are directly proportional to the velocity component of vibration, and Eddy current probes that are used to measure the displacement component of vibration are commonly used for condition monitoring applications. However, there is plenty of room for improvement through research and exploitation; - magnetostriction provides one such opportunity. Although research has been carried out on magnetoelastic properties of materials and some work has been dedicated towards utilising it for the purpose of sensor applications, its potential has not been fully exploited.

### 2. Design

Magnetostriction (Joule effect) is the name given to the phenomenon, whereby a material experiences a change in dimensions when it is magnetised. As a direct consequence, it has also been observed that the magnetic properties of magnetostrictive materials vary as a function of applied

stress; this phenomenon is called the inverse magnetostrictive effect or the magnetomechanical effect and this is the operating principle used for the accelerometer.

Having chosen the inverse magnetostrictive effect as the operating principle for the vibration sensor to be designed, it is of utmost importance to choose an appropriate sensing material. For magnetoelastic applications, the sensing material is required to possess numerous qualities linked to both its mechanical and magnetic properties; amorphous metallic alloys possess a unique set of mechanical and magnetic properties, which make them near ideal for magnetoelastic applications.

Relative permeability of amorphous alloys tends to be much larger than conventional ferromagnetic materials and this will result in greater sensitivity from the resulting transducer. Coercivity of amorphous alloys is very low and this will allow the material to be magnetised by relatively small currents. Although the saturation magnetisation of amorphous alloys is lower than those of crystalline materials, this will not prove to be a disadvantage in sensor applications where only low levels of power conversion are required. Amorphous alloys have relatively low values of coercivity, which results in lower hysteresis loss and the electrical resistivity of amorphous alloys is relatively high, therefore, the eddy current losses are also quite low; both of these factors will enhance the sensitivity and linearity of the resulting transducer. The Curie temperatures of amorphous alloys range from 350 °C to 550 °C, which are well above the required operating temperatures of most vibration sensor applications. Iron based amorphous alloys exhibit saturation magnetostriction values as high as  $40 \times 10^{-6}$  (approximately), which will contribute towards the sensitivity of the resulting transducer[4,5].

The tensile strength ( $\approx 350 \text{ Kg/mm}^2$ ), elastic limit ( $\approx 2.5 \text{ kN/mm}^2$ ) and Young's modulus ( $\approx 150 \text{ kN/mm}^2$ ) of amorphous alloys are quite large, which allows them to withstand high levels of stress and strain without incurring plastic deformation. In addition to these qualities, bending fatigue limits as high as  $900 \text{ N/mm}^2$  and  $1200 \text{ N/mm}^2$  (for  $10^{+7}$  Load Cycles) have been measured for Fe-Ni and Co based amorphous alloys, which is an indication of their durability and robustness[5,6].

The magnetomechanical coupling coefficient,  $k$ , is a measure of the proficiency with which magnetic energy is converted to mechanical energy and vice-versa. Annealed Fe based amorphous alloys exhibit magnetomechanical coupling coefficient ( $k$ ) and efficiency ( $k^2$ ) as high as, 0.95 and 0.9, which is a true indication of how suitable amorphous alloys are for magnetoelastic applications [4].

The combination of the unique mechanical and magnetic properties mentioned above, coupled with their relatively low cost, make amorphous alloys one of the most suitable ferromagnetic materials for magnetoelastic applications.

The proposed sensor design was to be based on the seismic mass principle, whereby; a load of finite mass is suspended by springs from the transducer's rigid outer frame. The rigid frame is secured to the vibrating surface and therefore, the frame is forced to vibrate at the same frequency and amplitude as the vibrating surface. A motion sensor, attached to the frame, can then be used to measure the relative motion of the seismic mass, with respect to the frame.

The first step towards designing the sensor was to formulate a number of conceptual designs. The next step was to evaluate the various conceptual designs and choose one that appeared to exhibit the best potential qualities as a magnetoelastic sensor. The sensor evaluation was carried out with the aid of a Finite Element Analysis (FEA) package called PAFEC (Program For Automatic Finite Element Calculations)[7]. Two PAFEC Solvers were used:

- Static displacement & stress analysis was used to evaluate how the conceptual sensors reacted to mass loading; i.e. the Maximum Deflection and Stress Distribution due to the action of constant Acceleration. This gave an indication of the sensitivity and amplitude range of the conceptual sensor that was modelled.
- Dynamics & vibration analysis was used to calculate the various natural frequencies and vibration mode shapes of the conceptual sensors. The results obtained from this solver gave an idea of the frequency range that could be obtained from the modelled designs.

The aim was to use a magnetoelastic sensor to measure vibratory motion. In order to achieve this, it is necessary for the transducer to transpose vibratory motion of a reference surface into time variant changes in stress and strain of the magnetostrictive material. This is achieved by attaching a seismic mass to the magnetostrictive ribbon. The next step is to measure these changes in stress/strain. This is best achieved by magnetising the magnetostrictive material and then observing the changes induced in magnetisation due to changes in stress/strain distribution in the magnetostrictive material.

Both the magnetisation and sensing processes can be achieved using coils (magnetising and pickup coils) wrapped around the magnetostrictive material. The material can be magnetised in one of two modes: DC or AC magnetisation.

DC magnetisation of the magnetostrictive material is achieved by passing a DC current through the magnetising coil. Any changes in the stress/strain distribution of the material will result in a change in the relative permeability of the magnetostrictive material and hence, a change in the flux flowing through the material. Consequently, a voltage will be generated within the pickup coil; this voltage is directly proportional to the rate of change of acceleration (shock). Note that in this mode, pickup signals are only produced during the period that the material is subjected to continuously changing stress; application of constant (static) stress does not generate a pickup signal)[8].

AC magnetisation is achieved by passing an AC current through the magnetising coil. In this case, a signal is constantly produced, even when the magnetostrictive material is subjected to constant stress or for that matter, to no stress at all. In this mode, the pickup coil voltage is directly proportional to the acceleration of the vibrating surface (for the case where the frequency of the magnetising current is much higher than the frequency of vibration being measured).

Because of its ability to measure static stress and produce signals directly proportional to acceleration, the AC magnetisation mode was adopted as the operating mode for the proposed sensor.

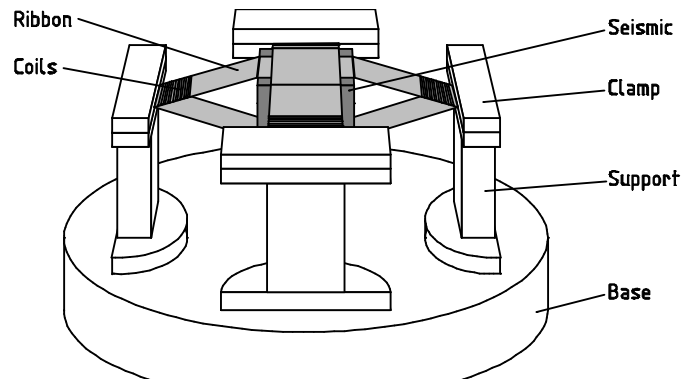


Fig. 1. Illustration of transducer.

Fig. 1 shows the transducer that was designed and tested:

- The sensor's base is made of mild steel and all the other components are secured to this base. The vibration to be measured has to be applied directly to the base, in the vertical direction.
- Four sets of supports and clamps are fixed onto the base. These are made of brass; the reason behind this choice is due to the relatively high density and rigidity of brass, which means that it is less likely to resonate over the operating frequency range. In addition to this, brass is a diamagnetic material; therefore, it will not interfere with the amorphous ribbon magnetisation.

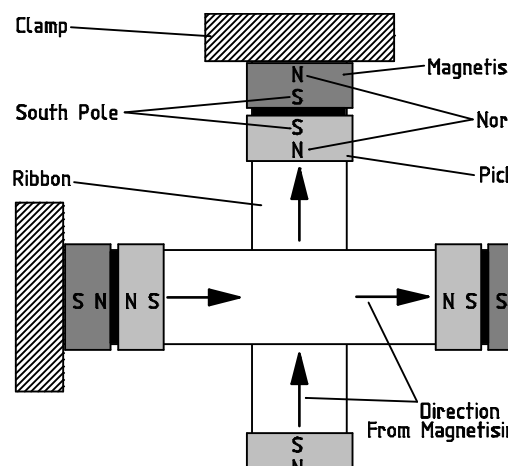


Fig. 2. Coil arrangement on top limbs of sensor (top view).

- The seismic mass consists of a brass cube, which is placed at the central position between the upper and lower amorphous ribbon limbs (METGLAS 2605SC, which exhibits positive magnetostriction) and bonded to them.

- Both the magnetising and pickup coils are wound around a single former, which is secured along with the ribbon by the clamp. Each pair of magnetising and pickup coils are wound in opposition and then all four magnetising coils are connected in series, as are all four pickup coils. The coils have been arranged so that the field produced by the magnetising current is continuous along the entire ribbon length. This can be better illustrated by Fig 2, which shows a top view of the ribbons and coils.

- Minimisation of transverse sensitivity is achieved by incorporating coils on both ends of a limb. The coils act as a push-pull system: relative displacement of the seismic mass in the transverse direction (i.e. in the direction of the ribbon length) will simultaneously compress one half of the ribbon and stretch the other half. Since the pickup coils are connected in series, the signal generated due to the extension of one half of the ribbon will be cancelled by the opposing signal generated by the compressed half the same ribbon. The transverse sensitivity is minimised along both transverse directions by using two mutually orthogonal ribbon limbs.

- The coils were only placed on the upper ribbon limbs. The function of the lower ribbon limbs was to mechanically bias the upper ribbon limbs, so that they remained in a state of tension at all time. By doing this, relative upward motion of the seismic mass is accompanied by an increase in tension of the upper ribbon limbs and conversely, relative downward motion of the seismic mass causes a reduction in tension. The ribbon is not allowed to become compresses.

- Electromagnetic shielding of the transducer was provided by a double walled closed cylindrical case. The case consists of two concentric layers of mild steel separated by a layer of copper. The advantage of such a construction is that it provides higher shielding factor and uses less material than the more conventional single walled shielding. It should be noted that the intermediate layer of copper would further improve the AC shielding factor of the case and reduce the chance of structural resonance of the double walls.

An electronic circuit was designed and a prototype PCB was made to provide the magnetising current and to process the signals from the pickup coils. The magnetising current generator comprises a function generator IC which was configured to generate a 100 kHz sinusoidal signal, a voltage amplifier was used to amplify this signal and finally, and a current driver to generate the required magnetising current. With no vibration applied to the sensor, the only signal produced by the pickup coils, is the 100 kHz signal due to the magnetising current. When vibration is applied to the transducer, in addition to the 100 kHz signal, the pickup coils also produce a signal, which is directly proportional to the acceleration component of the applied vibration. In other words, the 100 kHz magnetising signal acts as a carrier wave and the lower frequency vibration signals act as a modulating wave. In order to extract the vibration signal, the signal from the pickup coils needs to be demodulated; this is achieved through the use of a full wave rectifier and a sixth order Butterworth filter. The end result is a signal that is directly proportional to the acceleration component of the applied vibration.

### 3. Results

The first series of measurements involved measuring the B-H characteristics of the sensor's ribbon-coil arrangement. The B-H characteristics were measured by driving a 100 kHz current through the four magnetising coils and monitoring the voltage induced in the four pickup coils. The results reveal that the ribbon approaches saturation at around 200 mA and that greatest transducer sensitivity will be obtained by using a magnetising current of approximately 150 mA. However, in order to gain a thorough understanding of the sensor's behaviour, measurements were taken using magnetising currents of 25 mA, 50 mA, 75 mA, 100 mA and 150 mA. Fig. 3 shows the frequency response (amplitude) obtained using a magnetising current of 75 mA; the error bars indicate the standard deviation for the measurements. Prior to measurements, the sensor was calibrated to give an output of 100 mV/g pk ( $g$  is the acceleration due to gravity). The sensor was mounted on a shaker,

which provided the vibration (1 g (pk)) to be measured. At magnetising currents less than 75 mA, the sensor's output signal was prone to interference from the DC field emanating from the shaker.

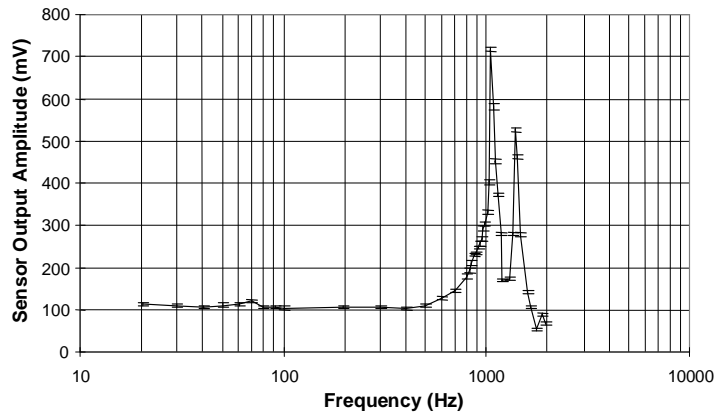


Fig. 3. Frequency response (amplitude) at magnetising current of 75 mA.

This effect was particularly pronounced at 20 Hz, corresponding to the maximum displacement produced by the shaker; the effect was negligible at vibration frequencies above 30 Hz. At the fundamental natural frequency (approximately 1050 Hz), the sensor's output signal is at its maximum, corresponding to approximately 7g acceleration. The responses obtained at 1050 Hz, for magnetising currents of 100 mA and 150 mA, produced lower than expected outputs; this can be contributed to the ribbons becoming saturated at the very high acceleration levels. A second resonance was observed at a vibration frequency of approximately 1350 Hz; it was deduced that the each of the two resonant frequencies were due to each of the two orthogonal ribbon loops. The two resonant frequencies did not coincide because the two ribbon loops were not tensioned to the same degree. The glitch in the response at 70 Hz can be attributed to the structural resonance of the mounting plate, which was used as an interface between the sensor and the shaker. A flat frequency response is obtained between 20 Hz to 600 Hz and the maximum linearity error over this range is 12.2 %.

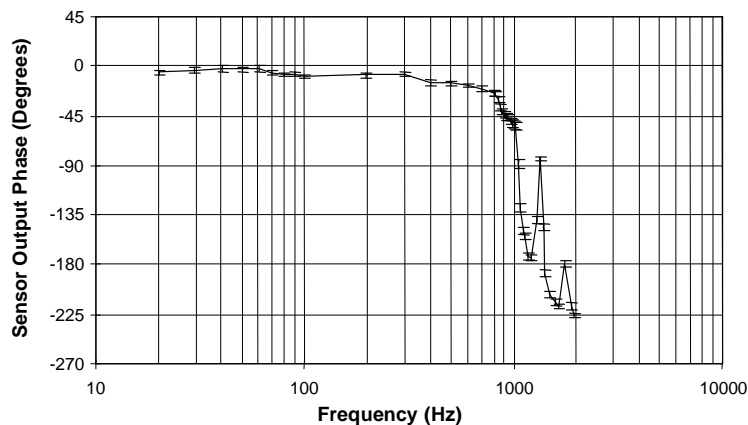


Fig. 4. Frequency response (phase) at magnetising current of 75 mA.

Fig. 4 shows the corresponding phase response for the above case. The results confirm the presence of the two fundamental resonant frequencies at 1050 Hz and 1350 Hz. There is very little phase shift over the 20 Hz to 600 Hz range, followed by an abrupt 90° phase shift at 1050 Hz. The phase increases momentarily rising to 90° just prior to the second resonance at 1350 Hz, before it continues down towards 180° and beyond.

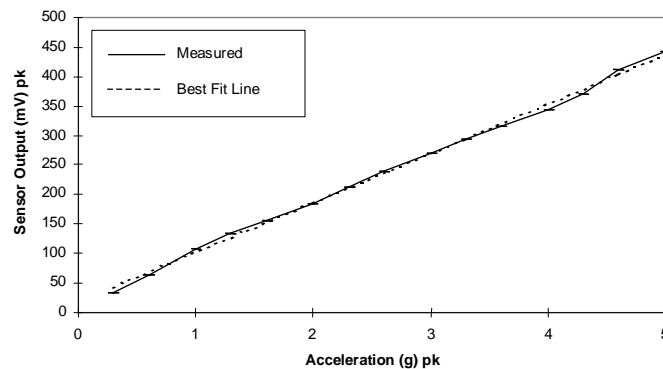


Fig. 5. Acceleration response over 0 to 5 g(pk) acceleration range.

The following measurements were taken to assess the amplitude range of the sensor. This was achieved by monitoring the sensor output while it was subjected to vibration at various levels of acceleration; the frequency of vibration was set at 100 Hz (reference frequency). Preliminary tests showed that at magnetising currents above 75 mA, the sensor's output began to saturate at approximately 4 g (pk). Fig. 5 shows the sensor's response compared to that of a best fit linear line. The linearity error as a percentage of the full scale is 3.4 % FSO and the repeatability error was found to be 3.0 % FSO over the 0 to 5g (pk) range.

In order to deduce the resolution of the sensor, it was necessary to measure the minimum change in input (i.e. applied acceleration) that can be detected by the sensor. It was also important to ensure that the change in sensor output due to a finite change in acceleration input, conformed to limits dictated by the sensor's linearity. The minimum change in input acceleration required was found to be 0.05 g (pk); this produced approximately 5 mV (pk) from the sensor.

The transverse sensitivity of the transducer was also successfully assessed by mounting the transducer horizontally on top of the shaker and subjecting it to vibration in the vertical direction, in the same manner as the frequency response measurements, i.e. vibration of 1 g (pk).

#### 4. Conclusions

The proposed magnetostrictive sensor can be used to measure the acceleration of a vibrating surface. The design is simple and utilises inexpensive materials; therefore, the production costs will be relatively low.

The design comprised two orthogonal ribbon loops in order to minimise transverse sensitivity. This proved to be both effective and cost effective in terms of both material and assembly costs.

The designed and constructed sensor can be operated to produce signals that are proportional to either shock (rate of change of acceleration) or acceleration.

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