Performance Assessment and Reinstatement of Vibrating Wire Strain Gauges in Nuclear Power Plant Structures

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ABSTRACT

This paper presents the results of the analysis of failed gauges in Prestressed Concrete Pressure Vessels (PCPVs) and their recovery at a Nuclear Power Station. Internationally, a significant number of nuclear power plants have now been operating for a period in excess of twenty years and some for more than thirty years. As a result, interest in the management of the ageing of civil engineering structures has received a higher priority than was hitherto the case in order to confirm or extend the operational life of nuclear power plants. It is now generally accepted that the installation of structural monitoring systems at the time of construction provides useful information for the lifetime management of nuclear power plant structures and the detection of ageing effects. In older plants, initially installed structural monitoring instrumentation has been utilized for long term monitoring programs.

This paper describes work carried out on vibrating wire strain gauges (VWSGs) to confirm their performance after approximately 25 years of service, the types of failure encountered, how such failures may be identified and suggested methods for restoring recoverable gauges to operation.

DESCRIPTION OF THE VIBRATING WIRE STRAIN GAUGE

The vibrating wire strain gauge consists of a thin steel wire held in tension between two anchorages. The wire is set into transverse vibrating motion by exciting it with a short pulse of current passed through the coil of an electromagnet positioned near the centre point of the wire, thus affecting the magnetic field at the centre of the wire. It is possible to use the same coil for two additional purposes. First, the coil can be used to detect the frequency of the vibrating wire. Due to the vibrating motion of the steel wire cutting the flux of the magnet, the induced frequency sets up a signal in the coil that can then be monitored by the local electronic equipment. Second, this copper wire coil can also be used as an RTD so as to verify the temperature at the location of the strain gauge. The electronic circuitry measures the resistance of the two electrical loops wired to the monitoring system, subtracts the lower resistance from the higher, and reports the difference. The resulting resistance represents the temperature environment at the VWSG position. The higher resistance represents the combined resistance of the plucking coil and the interconnecting wiring. The lower resistance represents only the end to end loop resistance. The ability to determine the temperature at the area of the coil is necessary in order to calculate microstrain (ε) corrected for temperature effects. When the distance between the anchorages changes, the tension of the wire and its natural frequency also change. The strain experienced by the gauge changes the tension of the steel wire and therefore, the natural frequency. Originally, the accuracy and technique was described in depth as far back as 1944 [1]. This type of gauge was therefore used in monitoring the stresses in steel structures, prestressed concrete buildings, roads, mines, and steel-concrete highway bridges as reported in 1953 [2]. An inexpensive VWSG gauge was described for use in long term internal monitoring [3]. The normal range of operational frequencies as being 500hz to 1400hz representing a normal range span of 4100$\mu\varepsilon$ [4].

HISTORY OF THE VIBRATING WIRE STRAIN GAUGE IN PCPVs

As a result of the accuracy and potential durability of the VWSG, it formed part of the instrumentation installed in the PCPVs during construction and used for verification of design data, commissioning, and monitoring of performance data. A great deal of testing was undertaken during the early stages of PCPV development to verify the performance and suitability of the VWSG for monitoring purposes. The measurement of strain in concrete pressure vessels and associated problems were discussed in detail in a paper presented in the 1967 ICE conference [5]. Specifically, the gauge must be able to operate in a high alkali, high humidity environment within the concrete and potentially at elevated temperatures and high radiation dosages. Gauges are normally cast into a concrete briquette (dog bone) to protect them from damage during handling and installation. It is important that the elastic and creep moduli, Poison’s ratio, thermal and moisture movement of the associated dog bone briquette must be as similar as possible to those of the concrete that it replaces in the structure. Due to many of the known problems with the installation of strain gauges into PCPVs and the calibration of those strain gauges, a procedure was produced by the Central Electricity Generating Board [6]. This calibration was required in order to obtain the correct gauge factor for the vibrating wire strain gauge. The calibration also defined the datum temperature (T_o) value of the gauge at a specific datum frequency (F_o). As temperature affects the response of VWSGs, a temperature correction must be applied during the calculation of strain. The plucking coil of the gauge is used as a resistance thermometer to measure the temperature at the gauge location in order to avoid the requirement for a separate transducer. The datum resistance for the gauge is measured at a datum temperature (in this case20°C) and the gauge temperature in service is derived using the change in resistance from this value with an appropriate coefficient of resistivity The coils used in the current application have a datum resistance of 99.2Ω, and a change of resistance of 4Ω per °C.. In order to provide adequate processing of information, Hornby suggested that where large numbers of gauges are used on a structure, with readings taken at regular intervals over an extended period of time, an automatic data handling system is cost-effective [4]. The type of gauge used in the current application is the BRS/E type with a 140mm-gauge length (5 ½”) [7]. A previous study of strain gauge reliability in the Oldbury Station identified a 24% failure rate after 10 years [8]. Further research in support of a statutory Long Term Safety Review (LTSR) at Oldbury indicated that the gauges would have a failure rate of between 33% and 50% associated with the two reactors after 25 years operation [9]. In that case the type of gauges used were a Strainstall PC657/s with a 133mm-gauge length.

TYPES OF KNOWN FAILURES

Deterioration of the bonding agent for the electromagnet has previously been identified in VWSGs installed in higher temperature applications. This interference either impeded or embalmed the wire and therefore subsequently interfered with the gauge’s vibration characteristics [10]. If harshness is evident in the signal response, this could be due to a distorted waveform resulting from the wire in the gauge striking the pole faces of the magnet-giving rise to harmonics. If the gauge historical return period/frequency shows a sudden change from the normal operational range to a higher range near the double harmonic period/frequency band, this may be the result of the adhesive bonding the coil to the magnet interfering with the vibrating wire.

The oscillation resulting from the plucking of a gauge decays over a relatively long period. If this oscillation is not allowed to decay sufficiently then subsequent plucking may interfere with continuing oscillation due to the previous signal pluck, giving rise to harmonic distortion and an incorrect return of frequency from the instrumentation. Abnormal loop resistance may be due to a short in the coil, an open circuit in the gauge loop, or oxide build-up on some or all of the electrical terminal connections in the loop. These loop problems will affect the temperature measuring capabilities of the gauge and contribute to loss of signal and incorrect temperature corrections being applied. If the gauge response is indicating noise (white noise), this may be due to poor electrical connections. This may be due to either loose connections, or an oxide build-up on some or all of the electrical terminal connections in the loop. Noise can also be due to stray currents resulting from insufficiently clean earthing of the system. If no loop resistance is measured at the nearest cabling or connection access point to the gauge, then it is likely that the circuit has become open. In such cases there is no remedial solution, since the interconnecting cabling and gauge are permanently buried within the concrete. The signal may be attenuated due to earth faults or by a high resistance joint in series with the cable. A weak signal may also be the result of an accidental reversal of gauge polarity, resulting in demagnetization of the center core in the gauge. If the signal strength is exceptionally weak, or if the returned signal dies away rapidly, this may be caused by foreign matter in the gauge assembly. It might also be an indication that the plucking voltage is insufficient to cause the wire to vibrate long enough, or with sufficient amplitude, to enable a frequency to be measured. As a result of the above failure modes it is advisable that serviceability checks should be carried out periodically on each gauge. This provides a comprehensive record of the status of each gauge that can be used in future should the gauge response characteristics change. In the current investigation, the typical returned frequency from the gauges showing erratic behaviour was in excess of 1700hz.

VIBRATING WIRE STRAIN GAUGE LOGGING EQUIPMENT

During the analysis of the failures at the test site, it was necessary to understand the design of the installed monitoring equipment. This included circuit analysis to locate any existing low pass filters and band pass filters. The threshold cut-off points concerning the monitored signal and the sampling rate in connection with the counting circuitry were determined during the analysis as was the delay in the counting circuitry, after the initial initiation signal to pluck the VWSG. Confirmation of the manner in which the logging equipment operates was necessary in order to understand how the computed microstrain is obtained. Any deficiencies of the logging equipment could affect the complete system and all the gauges. Strain changes are calculated from measured and datum values using the following formula [11]:

$$\Delta\varepsilon = Q\,(F_0^2 - F^2) + (\alpha_s - \alpha_c(T_0 - T)) \quad (1)$$

where Q = Gauge Factor (=2.94 x 10^{-3})

α_c = coefficient of thermal expansion of concrete

F = measured frequency (Hz)

T = gauge temperature (°C)

F_0 = datum frequency (Hz)

T_0 = datum temperature (°C)

α_s = coefficient of thermal expansion of steel

Temperature (T) is calculated as:

$$T = 20 + (R + R_{20} / r_{20} * R_{20}) \quad (2)$$

where R = measured resistance of plucking coil (Ω)

r_{20} = temperature resistivity of copper at 20°C (°C^{-1})

R_{20} = resistance at 20°C (Ω)

It should be noted that compressive strain in concrete is positive.

TESTING OF IDENTIFIED FAILED GAUGES AND ASSESSMENT

Testing consisted of loop resistance tests, loop inductance tests, isolation of individual loops from adjacent loops to confirm cross-talk isolation, and system operation for frequency. Physical inspection of the system and random connection installation verification (pull test) were also conducted. The results of all of these tests were reported [12] [13].

INSTALLATION INSPECTIONS

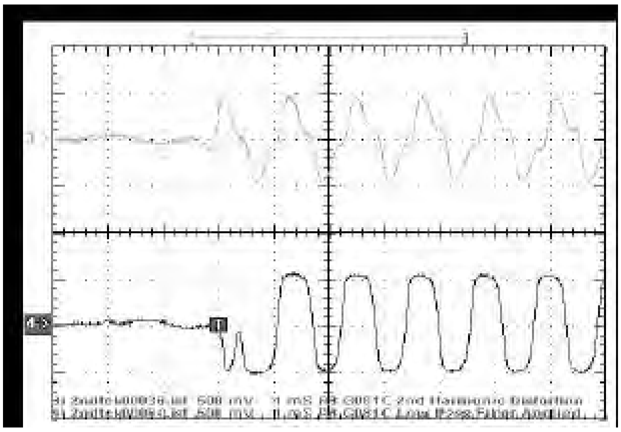
A random inspection of the local Junction Boxes (JBs) and Marshalling Boxes (MBs) indicated that many of the terminations within the JBs and MBs were not crimped. Since the interconnecting cable cores consisted of stranded wire, and the standard installation practice for stranded wire is that crimps are installed, it was considered that this omission may have been contributing to gauge failures. All cable terminations were therefore crimped to improve their performance. It is recommended that the system screens be tied down at one point as close to the instrumentation as possible. Inspection of the junction boxes identified that the cable screens had been tied down at both the instrument and MB ends. The resulting gauge signals may, therefore, have been contaminated due to the screening arrangement with noise due to transients or electrical interference from adjacent cabling.

SYSTEM RESISTANCE AND INDUCTANCE TEST RESULTS

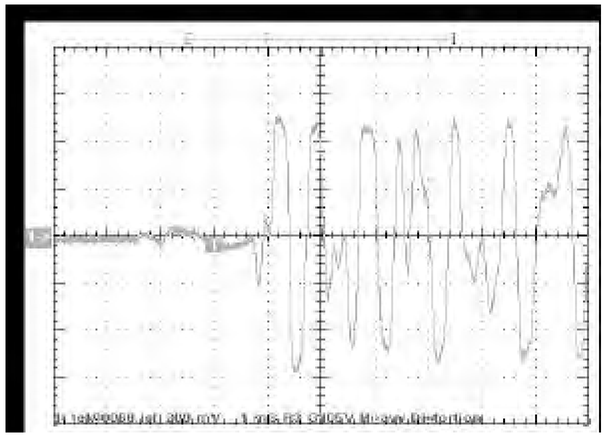
Upon completion of all wiring repairs within the MBs and resolution of some gauge identification anomalies, loop resistance testing was conducted on all vibrating wire strain gauges both connected to the logger rack and routed to the marshalling room. These results were recorded in the strain gauge spreadsheet against the respective strain gauge number. Additional testing to earth on all gauges was conducted, after isolation from the logger rack, to identify those gauges that appeared to have a low earth path. The testing conducted under this project indicated that earth problems do have an influence on the quality of the monitored signal frequency. All earth-testing results were recorded in the strain gauge spreadsheet. The resistance testing clearly identified those gauges that potentially would not return good temperature or frequency readings using the instrumentation and test software. The inductance testing clearly identified that there was no noticeable deterioration of electromagnet coils. After completion of all resistance testing, a series of frequency, period and temperature readings were obtained for all gauges. This included both the gauges wired to the logger rack and those routed to the Logger Room marshalling boxes but not wired through to the logger rack (spare gauges). The testing identified those gauges that required further examination. The development of a test software package was undertaken to facilitate the ability for all gauges to be monitored for frequency and temperature on an individual basis. During the testing it was possible to identify faults within the instrumentation wiring and correct these faults. Testing also verified that no cross talk between any of the monitored channels existed. This testing established both the suitability and robustness of the test software in conjunction with the instrumentation to obtain frequency and temperature results for all gauges. As previously indicated, the useable frequency range for a 125mm gauge is 500 Hz to 1400 Hz this represents a strain span of 4100 $\mu\varepsilon$. All gauges outside this frequency band gave either no readings or unstable readings. It should be noted that the instrumentation testing using the test software produced frequency and temperature readings for all gauges bar those that clearly had failed. As a result of the individual pluck test software, it has been possible to analyse various failed gauge signal characteristics. It was noted that since the instrumentation counts any pulse that is above the electronic cut-off circuit value of 60mv, then second and third order harmonics were causing incorrect results for several gauges. The instrumentation equipment was capable of monitoring all gauges and reported readings for all gauges that were working.

TEST RESULTS ASSOCIATED WITH THE RESEARCH PROJECT

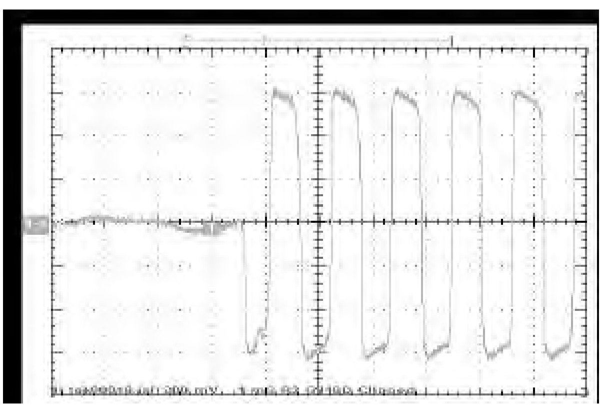
As a result of the above failures, additional testing was conducted using an oscilloscope to observe the returned frequency from both normally working gauges and gauges that fall outwith the normal operational band. This testing clearly identified those gauges showing normal frequency response curves, harmonic distortion, and weak signals, earthing interference characteristics, and unrecoverable gauges. Without this additional in-depth testing of all signals and the insertion of an appropriate band pass filter to correct for the harmonic frequency problems it is not possible to verify a fix for each gauge presently designated as failed. Part of the testing procedure included various low pass and high pass filters in an attempt to strip the unwanted harmonics from a failed gauge so that the instrumentation reported accurate frequencies. Problems can arise due to the possible interaction of capacitive coupling errors in the interconnecting wiring and wiring faults. Further work is under way to investigate digital filtering and digital stripping to remove harmonics from the signals. The following pictures of returned gauge signals and the types of associated failures clearly show the importance of the storage scope for analysis of VWSGs. A diagram of the test circuit is also shown.



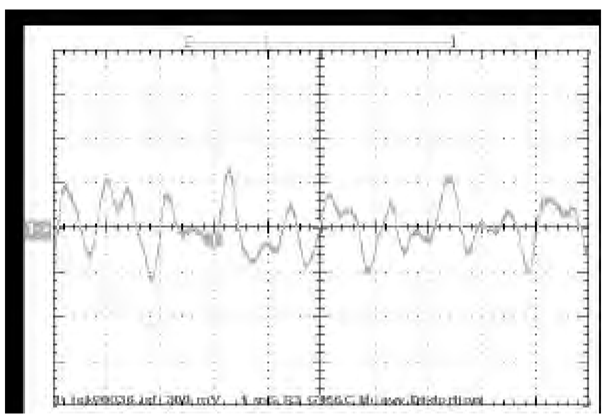
A gauge showing harmonic distortion and the correction of the distortion with a suitable filter.



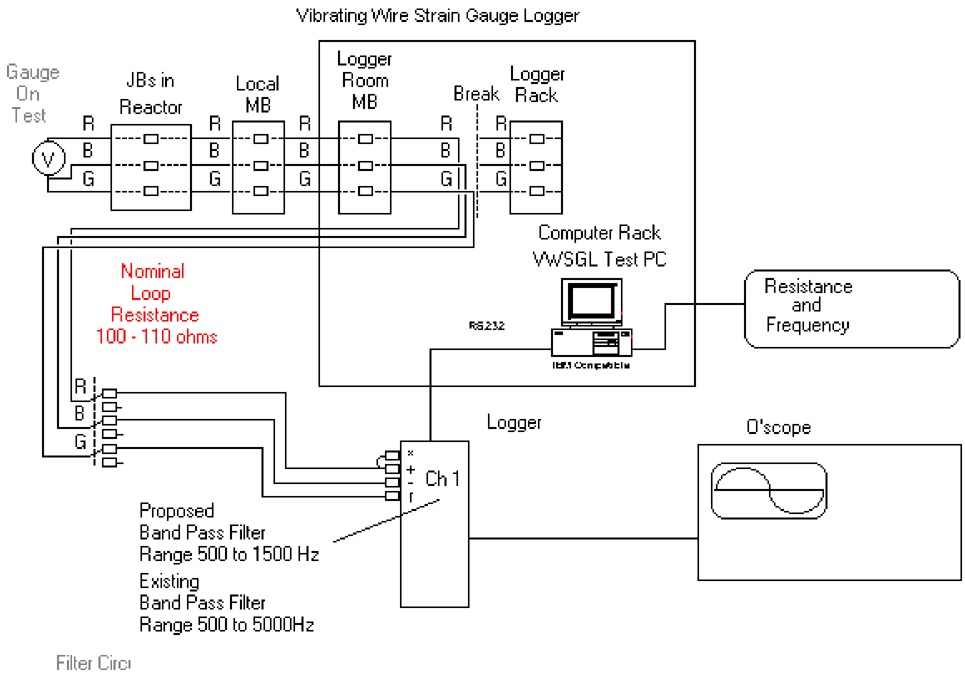
A gauge showing heavy distortion and has been proven to have an earth fault.



A gauge showing clipping on the top and bottom of the returned signal.



A gauge showing heavy distortion. Appropriate band pass filter should recover this gauge.



Diagrammatic representation of the test system used during the analysis.

DISCUSSION

The test results indicate that through the use of modern wave distortion technology it is possible to analyze the returned frequency of the vibrating wire strain gauge. The analysis of each failed gauge indicates that the main problem with the gauges is signal degradation associated with interference with the vibrating wire. This takes the form of either harmonics above the normal frequency range or low frequency distortion. A desk study has indicated that he higher than normal harmonics appear to be particularly associated with interference with the vibrating wire. As discussed earlier, the potential cause of failure is the bonding adhesive of the induction coil to the permanent magnet breaking down as a result of aging and environmental effects and expanding into the path of the vibrating wire. The low frequency distortion is most likely indicative of the vibrating wire strain gauge end plate retention screws loosening, or relaxation of the wire such that the wire becomes slack. Earth faults and oxidation and loose electrical connections in the JBs and MBs may also be a contributive factor to any gauges that indicate distortion failures.

The testing during this research project has also indicated that harmonic analysis of supposed good gauges should be considered. A record of all gauge testing should be maintained for lifetime records, to monitor the status and aging of gauges for the remainder of the station's life. The circuit diagram for the instrumentation indicates that the measurement circuit equipment will respond to a signal level above a 60mv. The distortion analysis of several of the gauges during the testing indicated that the harmonic distortion for reported bad gauges is above this 60mv level. The gauges that are starting to show some degradation, though still classified as good, have harmonic distortion that presently is below this 60mv threshold. It would appear that most gauge failures were associated with some internal mechanical interference with the strain gauge wire, electrical interference caused by degradation in earth resistance, or poor connections, or a combination of the two. It was observed that good gauges were not affected by the insertion of any filtering combination.

CONCLUSIONS

- Signal analysis using oscilloscope and Fast Fourier Transform (FFT) analysis can identify harmonic distortion on failed gauges.

- Although research exists indicating that reverse plucking can lead to weak signals, due to demagnetization of the plucking coil, there was no indication that this was a failure mode.

- Extensive oscilloscope testing was conducted using filters on both known good gauges and on gauges demonstrating different types of failure and it was demonstrated that recovery from incorrect frequency reporting by the instrumentation was possible.

- Interaction between the low pass filter and identified failures in the JB wiring can lead to problems identifying the type of failure that has occurred. Further work is under way to investigate digital filtering and digital stripping to remove harmonics from the signals.

With the knowledge that has been gained from the testing associated with this project, it has been shown that many gauges previously thought to have failed may be brought back into service. It is necessary to correct earthing problems and ensure that all connections are properly made and secure. Following repairs, the system must be re-tested and monitored for a period of time to verify that the calculated micro-strain associated with corrected gauges produces stress strain charts indicative of the real strain in the pressure vessel [12]. It is possible to improve the results from lost gauges due to the harmonic distortion problems by modifying the band pass filter installed within the circuitry of the instrumentation so that it operates between 500Hz and 2400Hz or to increase the signal cut-off voltage level for returned signals or a combination of both. The present research has demonstrated that poor strain gauge frequency results are associated with degradation of internal materials within the strain gauge, degradation of wiring, or slackening of the tension on the strain gauge wire. Any material interfering with the natural frequency response of the vibrating wire will generate harmonics, with the result that those harmonics will be counted by the instrumentation if above the voltage threshold. The resulting frequency count is therefore not indicative of the strain in the concrete. A variety of factors can contribute to the incorrect operation of monitoring systems including earth faults, open circuits, intermittent connections, poor standards of cable identification and gauge to database identification, incorrect datum assignment to gauges, incorrect temperature compensation, excessive gauge operation, and noise interference from adjacent power cables (cross-talk). Interference between the plucking electromagnet and the vibrating wire (partial and total interference) and a damaged or broken wire may lead to harmonics being superimposed onto the actual gauge resonant frequency. Oxidation of poorly terminated connections, inappropriate wiring for instrumentation circuits and deterioration of insulation on interconnecting wires between the instrument and the logger may lead to noise or poor signals from gauges. Excessive operation of the VWSG, electromagnetic and electrostatic interference, and demagnetising the permanent electromagnet by a reversed plucking current may lead to a loss of signal. A full system assessment including all of the reported methods of examination should be considered when a system has several failed gauges. Upon the completion of such an investigation, it is then possible to recommend appropriate action to recover those gauges that have not permanently failed.

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