

Reliability in Electromagnetic Systems : The role of electrical contact resistance in maintaining automobile speed control system integrity

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Keywords: contact intermittency, electronic speed control

Abstract

Electromagnetic systems depend upon the integrity of electrical connections. An intermittent speed sensor connection is shown to generate a false speed signal that may allow an automobile speed control system to engage at low speed and cause a sudden acceleration. Preventive measures are discussed. The current approach to controlling uncommanded sudden accelerations seems to rely upon the driver braking against full engine power to bring the vehicle to a halt. More effective and safer control would be achieved by cutting off the fuel supply the moment that an uncommanded wide open throttle condition was detected, thereby preventing the sudden acceleration.

1. Electrical contacts

Fig 1. shows an engraving of William Sturgeon's original electromagnet (1824)[1] - the first truly practical electromagnetic device - with the connecting wires dipping into "egg cups" containing liquid mercury.

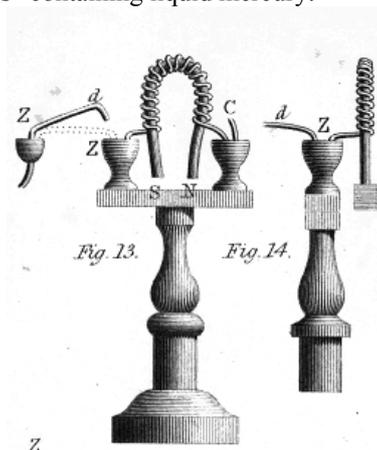


Fig. 1: Sturgeon's electromagnet (1824) showing mercury cup connectors

The mercury wetted the wires and provided low resistance paths for the current to flow. Connections of this kind would be rendered intermittent and very unsatisfactory in the presence of vibration or shock. Sturgeon's arrangement illustrates that the simplest electromagnetic system must have a minimum of two reliable electrical contacts. In practice any electromagnetic device - be it a solenoid valve, relay, actuator, motor, generator or transformer - will depend for its reliability on a multiplicity of electrical contacts: some permanent; some disconnectable; some switchable.

There have been enormous developments in the art and science of making reliable electrical contacts since Sturgeon's time, see ASME [2], Holm [3], Llewellyn-Jones [4], Slade [5] and Braunovic [6] but the reliability of electrical contacts is still sometimes taken far too much for granted. As Slade says [7]: "The reliability of the electrical contact has also been an essential, but often ignored, factor - ignored, that is, until it fails...." This is particularly true of the dismountable electrical connectors that are used on a "fit and forget" basis to connect the elements of electromagnetic systems together, whose long term integrity, notwithstanding the usual presence of a number of degrading influences, is usually taken far too much for granted.

Normally the conducting metallic surfaces that comprise a pair of electrical contacts are covered with a thin layer of oxide. Contact is made when the insulating oxide layers are pushed aside by pressing the contact surfaces together allowing direct metal-to-metal contact at a few microscopic points over a much smaller area than the apparent mechanical contact area. If the contact force should decrease - for any one of a variety of reasons, such as insufficient contact spring force, failure to insert a connector properly, corrosion, fretting etc. - this may result in a reduction in the area of contact and an increase in contact resistance. If the contacts experience vibration or heat cycling, microscopic relative movement may take place between contact surfaces that causes fretting of the oxide layer, exposing the underlying metal to the atmosphere and further oxidation. This results in a build up of loose oxide particles in the hollows between the contact surfaces and this contributes to the development of electrical intermittency.

2 Intermittency in electrical connectors

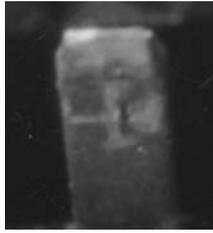


Fig. 2: Single pin of a gold-on-nickel-plated multi-pin automobile connector showing signs of fretting

Fig. 2 shows a single pin of a multi-pin gold-on-nickel plated automobile connector with fretting that in this case was visible to the naked eye. In many cases fretting and/or micro-arcing occurs on such a miniature scale that it may only be confirmed using a scanning electron microscope. Fretting is unlikely to be detected during normal vehicle inspection.

It is part of the normal design process for electromagnetic systems to carry out Failure Modes and Effects Analysis (FMEA) at the design stage at component level, sub-system level and system level. Some manufacturers also carry out what is known as a “PIN FMEA” for the main connector between any electronic control unit and its associated wiring harness. The pin FMEA will detail the potential failure modes of the circuit connected to that pin and the possible associated effects. Thus, for example, in the case of a sensor connection, the PIN FMEA will cover the failure modes of the sensor loop. There are two problems with this approach (1) the failure modes are identified and treated “one at a time”, whereas in practice connector failure modes may occur simultaneously on several connectors in a multi-pin connector and (2) the method does not sufficiently recognise and deal with short duration dynamic intermittent faults excited, for example, by mechanical vibration. The microphonic nature of some electrical contacts was well established by Hughes [8] and others in the late 19th century and was treated in some detail by Fairweather [9] but seems largely to have been forgotten since then. It is far too easily assumed that connector faults will either be short circuits, or open circuits and that they will endure for sufficient time to be readily detectable by the system software.

Connectors for electromagnetic systems in aircraft, automobiles and industrial plant may have to operate in the presence of high levels of humidity, pollution and vibration and, if wrongly specified, may be particularly susceptible to fretting corrosion. This in turn may result in contact intermittencies that may have a deleterious effect on system performance: faults that appear and disappear more or less at random and are extremely difficult to diagnose either by bench testing or by in-service monitoring. Even the use of gold-plated contacts provides no absolute guarantee against fretting if the flashing is of insufficient thickness. [10, 11] With safety-critical electromagnetic components, electrical

contact degradation may have serious consequences. For example, fretting corrosion between tin plated electrical connector pins and gold-plated sockets on F16 fighter aircraft [12] may have resulted in uncommanded fuel shut offs and been the cause of six crashes. Pecht [13] reports the ‘trouble not identified’ phenomenon in automobile electronics that “can range from being critical to the customer’s safety to being a mere nuisance.”

It is recognised by NASA in the field of space engineering that “A failure to conduct powered-on vibration testing may increase the risk of flight equipment containing flaws or intermittencies, such as electrical arcing, open circuits and relay chatter, that may cause mission compromises or hardware failures... ..Supply power to electronic assemblies during vibration, acoustics and pyroshock and monitor electrical functions continuously while the excitation is applied.”[14] There does not appear to be such equivalent attention paid to testing for electrical intermittencies in the automobile industry. Much workshop faultfinding is based upon “wiggling” conductors and connectors in the hopes of spotting an intermittency. This method tends to dislodge fretting products and restores electrical contacts to a temporarily healthy state, thereby hiding the fault condition in many cases. Disconnecting and reconnecting suspect connectors or replacing electronic modules may have a similar effect. There clearly is a need for cost-effective methods of testing for connector and wiring harness intermittencies in the field, but what these might be remains a matter for conjecture.

Intermittent faults, particularly in low-current sensor circuits, may make a circuit noisy but the average circuit parameters may still remain within the bounds of “normal” for the circuit concerned. Consequently, monitoring circuit impedances using software to determine when they go outside pre-specified ranges is not necessarily going to detect intermittencies. Some kinds of vibration-induced intermittent connection faults in acceleration and speed sensors for example are unlikely to be detected and will therefore not necessarily be recorded as fault codes by on-board diagnostic software.

3 Automobile Speed Control

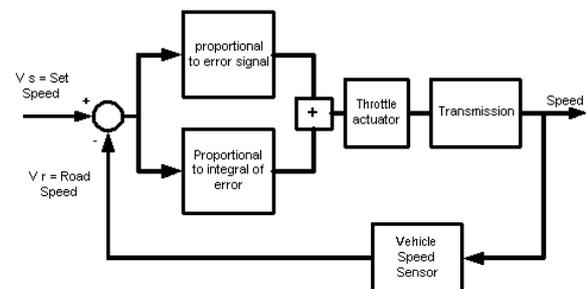


Fig. 3: Block diagram of typical automobile speed control system

Fig 3 shows a block diagram of a typical automobile speed control system in which measured speed is compared with a reference speed stored in memory and the speed error is used to control the movement of a throttle servo and hence control the air/fuel volume flowing into the engine.

4 The generation of false speed signals

Let us take the particular example of the effects of an intermittency on an electromagnetic speed sensor such as might be used as the road speed feedback signal for an automobile speed control system.

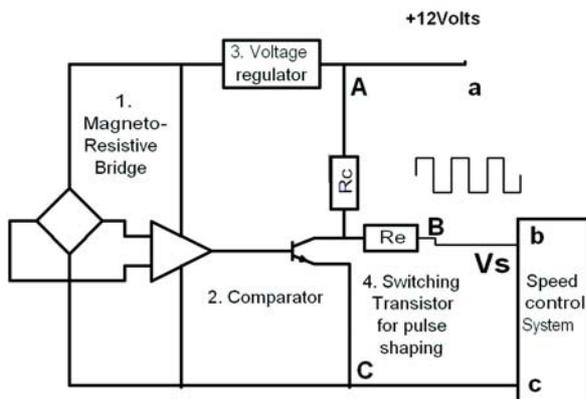


Fig. 4: A typical magneto-resistive speed sensor

Fig 4 shows a typical magneto-resistive speed sensor that comprises:

- (1) a four-element magneto-resistive bridge that senses changes in the magnetic field produced by a multi-polar magnet driven by the transmission
- (2) a comparator that changes state every time the multi-pole field changes direction
- (3) a voltage regulator to regulate the voltage to items (1) and (2) and
- (4) a switching transistor fed directly from the +12V supply that acts as a pulse shaper and produces a nominal +12V/0V square wave pulse train with a frequency proportional to road speed.

Sensors of this kind are cheap and robust and have a high signal-to-noise ratio and work at all road speeds down to standstill. It might be thought that a speed sensor in good working order would always give a reliable digital speed signal, but this is not necessarily the case. Fig 4 shows the three sensor connections: **Aa** to the +12V supply; **Bb** to the speed control system speed sensor input; and **Cc** the speed sensor connection to the Speed Control ground.

The following potential connector fault conditions exist:

- A nominal +12V signal reaching point b will be interrupted if an intermittency occurs anywhere in connection Aa or Bb (for example, in a connector, a crimped joint or in either of the two wires)
- If the signal reaching b is at a nominal 0V, an intermittency in the connection Cc will cause the voltage at B to rise to +12V.

It can thus be seen that a periodic intermittency anywhere in **Aa**, **Bb** or **Cc** will interrupt, or modulate, the speed sensor signal. In the presence of a periodic intermittency, two digital signals of different frequency – the speed signal pulse train and the interruption pulse train – will be beating against one another and giving additional frequency components not present in the speed signal itself. The result will be a false speed signal in the form of a false +12V/0V pulse train that the speed measuring circuitry may interpret as a genuine speed signal.

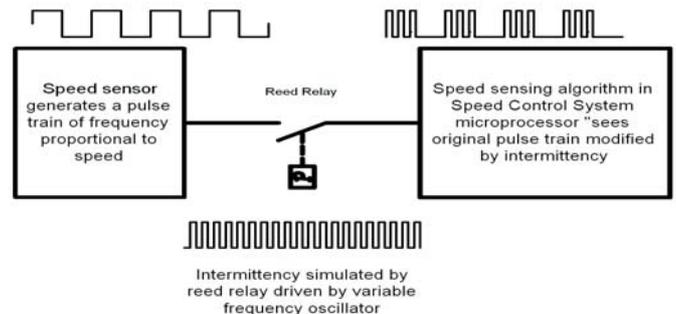


Fig. 5: Simulating the “false speed signal” effect with a reed relay

The “false speed signal” effect caused by a periodic electrical intermittency can be simulated with a reed relay placed at **A**, **a**, **B**, **b**, **C** or **c** driven from a variable frequency supply. Equally, a mechanically excited vibrating contact will produce the same effect. Since the speed detection circuit used in most microprocessor-based speed control systems merely counts the number of pulses in the speed signal pulse train in a given period of time, the false speed signal will be treated by the system in just the same way as if the signal was genuine. With this set up, a commercial automobile speed control system can be caused to operate on a test bench with a false speed signal even when the speed sensor itself is at standstill. In other words, the mechanically excited electrical intermittency is behaving exactly as if it were a speed signal generator that, in effect, it is.

5. The potential consequences of a false speed signal

Let us now consider the situation of a vehicle at or near standstill. Normally the speed control microprocessor would detect the low speed sensor frequency and this would prevent the speed control system from activating. Put another way, no matter which speed control buttons might be pressed when the vehicle was below the critical road speed of circa 30 mph the speed control system would act as if “dead” and would refuse to engage.

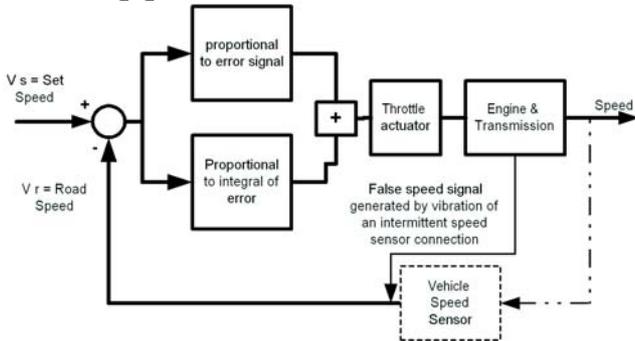


Fig. 6: Low speed operation of speed control system through agency of a false speed signal generated by a vibrating speed sensor connection

However, if a false speed signal were to be generated the situation would change radically. The false speed signal would give an appearance, as far as the vehicle speed control system was concerned, that the vehicle was moving at a speed above, say, 30 miles per hour. Fig 6. In this case, the logic conditions, as determined by the microprocessor software, would now allow the speed control system to engage even though the vehicle was at, or near, standstill. In other words, the supposedly infallible electronic interlock mechanism designed to prevent low-speed engagement of the speed control system would fail in the presence of a false speed signal and would have no inhibitory effect.

If we suppose a set speed value to be held in memory, then the speed control system, working quite normally, would try to control speed against this set speed. If the false speed were less than the set speed, there would be an apparent speed error such as to cause the throttle to open and the vehicle to accelerate. Should the driver try to brake, the throttle would open further in order to reduce the apparent speed error.

Given a false speed signal, there appears to be no lower speed limitation on the operation of the speed control. It therefore becomes possible for the system to “take over” speed control from the driver in situations at low speeds where, previously this might have been considered impossible. All that seems to be required is a single mechanically-induced intermittency in one of the speed sensor connections.

This appears to confirm the suggestion in the 1989 NHTSA Sudden Acceleration Report that “*Intermittent connections in the speed sensing circuitry or intermediate processing stages could conceivably generate electrical noise which could be interpreted as a valid speed signal above the minimum value so that if a driver happened to bump the set or resume controls the cruise control might engage or “resume” to a previously set speed even though the vehicle was actually stopped or going very slowly.*”[15]

It is clear that a multiplicity of different failure mechanisms have the potential to falsely command a speed control system to move to the wide-open throttle condition. It should not be assumed that electromechanically induced EMI as here postulated is the only way, or even the likeliest way, in which false speed control signals may be generated. For example, the engine ignition system and the fuel injectors generate repetitive bursts of EMI that have the potential to cause similar effects, especially in the presence of poor electrical contacts. In other words, potentially at least, the speed control system could lock onto engine speed or some multiple or submultiple of it. Single event upsets likewise have the potential to upset computer software and cause uncommanded system operation. It is clear that no matter what measures are taken, uncommanded wide open throttle events cannot altogether be prevented: hence the importance of detecting them quickly and taking preventive action before the fuel flow into the engine has had time to build up and cause a sudden acceleration.

6 Incidence of sudden accelerations

The true incidence of sudden acceleration incidents from standstill, by vehicle make, model year or country is unknown. The US National Highways Traffic Safety Administration (NHTSA) Complaints Database [16] is in the public domain and records the customer complaints that it receives from within the USA and Canada. However, most of the information is in free text and often the incidents complained of are poorly described. The lack of detail in the complaints tends to prevent effective statistical analysis. Castelli [17] examined the US NHTSA database for customer vehicle complaints up until May 2001 and out of 600,000 complaints found 25,181 (4%) related to sudden accelerations resulting in 5,412 injuries and 303 deaths. Quoting Wards Auto World figures for US production of cars from 1983-2000 and trucks from 1990-2000, Castelli claims that 39 models had rates of sudden acceleration incidents of 50 per hundred thousand vehicles or more and seven models had rates of more than 100 per 100,000 vehicles. Thus it would appear that sudden accelerations may occur somewhere between 1 in 1000 to 1 in 100,000 vehicle lifetimes, depending on the type of vehicle. This compares with 1 blowout per 15,000 vehicle lifetimes for Firestone Tires. In populations of many hundreds of millions of vehicles world wide, sudden accelerations represent significant number of dead and injured

and hence the need for the introduction of preventive measures to reduce the incidence rate.

The majority of these reported sudden accelerations appear to have been from standstill. It is, in my view, reasonable to assume that a significant number of sudden accelerations from standstill may have resulted from the generation of false speed signals and that could have been prevented.

7 Preventive measures

There are three possible kinds of preventive measures that apply to false speed signals: firstly, measures to improve electrical contact reliability; secondly, system improvements that may reduce the likelihood or mitigate the consequences of an uncommanded wide open throttle condition; thirdly, and most importantly, fail-safe mechanisms external to the speed control system that operate when all else fails.

Electrical contact improvements It is generally accepted that about 60% of intermittent electronic failures are caused by intermittent faults in cables and connectors rather than by failures within the electronic control elements themselves. There is no reason to suppose that the situation is greatly different with automobile speed control systems. The likelihood of intermittent electrical contacts developing can be minimised: (1) by using electrical connector systems that have been specifically designed to operate under high levels of vibration to resist fretting (these connector systems usually have some extra springing that keeps contact forces normal to the plane of contact and prevent fretting); (2) by using electrical contact lubricants, for which manufacturers claim improvements in contact reliability by factors of between 10 and 100. Laboratory contact improvement tests are carried out in a laboratory and are typically reported for 500,000 fretting cycles. How the results of such tests might extrapolate to real world conditions, where 500,000 fretting cycles might accumulate in perhaps 1200 miles on the clock and the contacts are subject to a cocktail of pollutants, is however far from clear. Chudnovsky [18] reviews 40 years of published research on contact lubricants and concludes that, insofar as corrosion protection is concerned, it is important to properly choose and thoroughly qualify a lubrication product for a specific contact material and a specific combination of environmental variables. Inappropriate lubricants, rather than preventing fretting may induce a significant risk of developing high electrical resistance between the contact surfaces. In my opinion, electrical contact lubricants, if applied during assembly, should be regarded as having the capability to significantly reduce contact oxidation and fretting in most situations for the first few years of a car's life. It would be unrealistic however not to expect some deterioration in the properties of the contact lubricant with time, especially in the hostile environment of the engine compartment, however re-lubricating at regular service intervals would seem a feasible way in which to maintain contact integrity. Manufacturers already have service protocols for cleaning and re-lubricating steering wheel

slipping assemblies. There seems to be no reason why similar protocols could not be developed for speed control sensor connectors.

System improvements. Some manufacturers have moved away from using a single dedicated speed sensor for the speed control system and now derive the speed signal by averaging the signals coming from several ABS wheel speed sensors. This can provide a cleaner and more reliable speed signal, but still does not overcome the potential problem that would arise if an intermittent contact should occur between the ABS speed signal output and the speed control system input. Nor does it deal with the possibility that other EMI mechanisms – pulsed interference from the ignition or the injectors for example – might also cause a false speed signal. A three channel speed control system with majority voting is technically feasible and would be the normal choice for a safety critical industrial control system. However, such three channel systems would probably be far too costly for automobiles. Another approach might be to identify the occurrence of a false speed signal with the system software. A true speed signal should be characterised by a pulse train of constant mark-space ratio that increases in frequency as road speed increases. In contrast, a false speed signal will comprise a modulated pulse train, see Fig 5. In my view, there is no reason why software should not be able to rapidly distinguish between these two types of waveform and, in the event of “seeing” a speed signal irregularity – i.e. an irregularity in the speed pulse train - prevent the speed control loop from coming into operation, or immediately disengage it. In effect the software would be identifying the equivalent to missing “heart beats” in the speed signal and, acting upon the information, would inhibit the engagement of the speed control system or, if already in operation, would disengage it.

Fail-safe mechanisms. Notwithstanding the importance of the above measures, the possibility of a false speed signal causing a wide open throttle condition cannot be reduced to zero. As long ago as 1975 a US National Highways Traffic Safety Administration (NHTSA) report on the potential effects of EMI in automobiles [19] recognised the inherent difficulty in preventing sudden accelerations from standstill and suggested that the most effective safety measure would be to keep the speed control system electrically de-energised until normal road speeds were reached. This approach is sound from an engineering physics point of view. It is however rarely used. In my opinion, it should become the norm rather than the exception.

Automobile fail-safe design philosophy for speed control systems, as presented by NHTSA in their 1989 Sudden Acceleration Report [15], takes no account of their 1975 report mentioned above. The 1989 Report seems to accept that it is reasonable for the speed control system to be electrically energised at all times and that it is reasonable to rely on the speed control logic to prevent inappropriate operation at low vehicle speeds. The consequence is that in the event that a false control signal should cause a wide open

throttle, maximum fuel is supplied to the engine and reliance is placed entirely upon the driver's capability of engaging the brakes to overcome the resulting sudden acceleration. The driver, in effect, is the fail-safe for the electronic system. To allow an uncommanded build-up of engine power to occur and then call upon the driver to apply the brakes to dissipate the excess power generated is unnecessary, is contrary to sound engineering practice and is potentially hazardous. In the author's opinion the most effective method of dealing with potential sudden acceleration incidents when all else fails, whatever their cause, is to kill them at birth by restricting the fuel supply to the engine from the moment that an uncommanded wide open throttle condition is detected. If fuel cut-offs can be designed to operate in the case of a crash, so fuel restrictors or an additional slam-shut throttle should be capable of being brought in to action when a false speed signal or an uncommanded wide open throttle is detected.

At present the only effective method of restricting the fuel supply to the engine in an emergency is switching off the ignition. The NHTSA Complaints Database records many instances of drivers successfully doing this. Sudden accelerations in confined spaces are particularly dangerous and provide situations where quick emergency action by the driver is essential. In my opinion all drivers should be taught about the potential risks of sudden acceleration and how best to deal with them and, especially, they should become aware of those situations where switching off the ignition would be the most appropriate action and the one most likely to minimise accidents and deaths.

Preventive measures need to be applied in all three areas outlined above, as a combined package, and not in any one area alone.

Acknowledgements

The author is grateful to Mr Melvin Moulton and Mrs Julie Moulton for permission to publish Fig. 2.

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"If, under conditions imposed by a non-moving vehicle the speed controller had a serious EMI problem when the car is not moving, deactivation of the circuit may be the least costly approach to solving the interference problem. Such a circumstance could exist with certain classes of electronic ignition control because of pulsing characteristics of power transistors and the inductive load of the ignition coil. An overlapping pulse rise and decay characteristic which may have radiative additive components could exist at higher engine speeds. The solution with electronic techniques would involve some expensive shielding procedures, but with deactivation of the speed controller, a significant cost savings in EMI assurance would be evident."