CAUSES AND SOURCES OF AUDIBLE NOISE IN ELECTRIC MOTORS

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ABSTRACT

The increasing pollution caused by noise has prompted extensive efforts to either eliminate, suppress, dampen or insulate the electro/magnetic and mechanical sources of acoustical disturbances in electric motors. The purpose of this paper is to present the fundamental sources of audible vibrations in most common electric machines. A survey of current literature and publications is also provided so that the problems of noisy motors can be identified. Various techniques can be employed to yield satisfactory energy conversion from electrical to mechanical using motors without hearing the process. Stepping motors, Induction, Brushless and Switched Reluctance machines are discussed and the causes and solutions are identified.

1.0 INTRODUCTION

The factory of the 19th century was a very noisy place to work due to the power transmission methods used such as water power and steam engines driving overhead line shafts. Large flat belts were used as power take offs to drive various production machines. Factory workers became quite accustomed to the noise from this environment in steel mills, textile mills, machine shop, foundries, blacksmith shops, and railroad shops. This normal acceptance of the harsh noise working environment continued on into the 20th century. Even office areas became quite noisy due to the clatter of mechanical typewriters, comtometers, adding machines and calculators.

As the 20th century winds down and we look toward the 21st century, the shop floor, computerized office and even transportation systems such as cars, subways and airplanes are expected to provide an ever increasing more pleasant environment for humans to live in.

In 1920 there was not one electric motor in an automobile but today, there are between 50 and 75. In 1920 the average home in major cities of America contained perhaps 2 electric motors (fans for cooling) and none in rural areas. Today the average home contains between 20 and 50 electric motors. These motors are not silent and we are becoming more aware of their presence because we can hear them. The term "noise pollution" is a widely used term these days and intensive efforts are underway around the world to identify the sources of motor noise and reduce or eliminate these unwarranted causes for excessive pertabations of our ear drums. The modern factory machinery and office automation equipment contain very little mechanical noise producing hardware compared to older designs. With the invention of the power transistor, microprocessor, sensors, permanent magnets and other modern materials and devices, various electric motors are capable of providing modern machine motions. Therefore, their exponential proliferation surrounds us. Also it is easier to control noise from motors than complicated mechanical systems.

2.0 GENERAL DEFINITIONS OF MOTOR NOISES

Electric motors are constructed of fairly rugged materials, such as iron, steel, aluminum, copper and in some cases permanent magnets. The purpose of the electric motor is to convert electric energy into mechanical work, either rotating or linear. This energy conversion process is achieved by a phenomenon or relationship between electric fields and magnetic fields known as Faraday's Law. Torque on the motor shaft is produced by a moment of force relationship defined by Lorentz. The physical systems for the production of an electromotive force (EMF) in the electromagnetic circuit is a result of the mutual or cross linking of the stator and rotor magnetic flux. The summation of the products of flux and turns ($\Phi \times N$) yields the total flux linkage (ψ). The EMF is produced when the linkage is changing and its time integral is equal to the change. This is the essence of Faraday's law. The EMF direction opposes that change. For example, if the electric circuit is closed, the induced EMF would circulate a current and a self flux would develop. The linkage would then tend to restore the level of the original linkage by opposing a rise or supplying a deficiency. This is the Faraday-Lenz law which can be stated by:

$$e = \frac{d\psi}{dt}$$

The torque produced in the electric motor is derived from the Lorentz force equation from the moment of force produced at the air gap where the rotor and stator flux linkage are concentrated.

$$F = B\,L\,I$$

A torque applied to the motor shaft causes rotation of the shaft. The result is a rotating shaft/rotor in a bearing structure and one or two rotating electro/magnetic fields contained in an electro/magnetic structure. Any mechanical vibration of any of the structural elements of the motor can cause the surrounding air around the motor to transmit sound waves to the human ear drum. This vibration phenomenon causing airborne noise seems to be a byproduct of the electric motor conversion of electro/magnetic energy into mechanical work. The effects of these motor noises on human beings has been shown to cause psychological and physical effects on attributes and behaviors. Therefore, suppression or elimination is highly desirable.

The movement or motion of the solid mechanical elements of the motor (called vibration) causes the air molecules to oscillate (called airborne noise). The generation of these vibrations is a very complex issue and every component of its structure becomes a noise source. The sources of noise can be categorized into five main areas and each will be discussed in some detail.

- Magnetic
- Mechanical
- Viscous or Friction
- Windage
- Electric/Electronic

3.0 MAGNETIC NOISE

3.1 MAGNETOSTRICTION

The first type of noise caused by the electro magnetics has to do with the magnetic material used to contain magnetic flux. This can be considered as one of the magnetic properties of ferrous magnetic materials. It is known as *Magnetostriction*, which means that when a magnetic material is subjected to a magnetic field the dimensions of the material change (either increases or decreases). The amount is so small it is difficult to measure and few actual measurements have been reported. However, a very simple experiment can be conducted to demonstrate the level of audible noise produced when the magnetization of a ferrous material is induced in normal motors such as those listed below:

AC Induction and AC Synchronous
AC Servo (with PM Rotors)
Steppers (VR, PM & Hybrid)
Brushless DC (PM Rotors)
Switched Reluctance

DC shunt series/universal exhibit slight levels of magnetostriction and PM DC with brush/commutators produce insignificant stress on the iron because there are no changing magnetic fields.

The audible hum of a laminated transformer had long thought to be caused by the 60 Hz line frequency causing the laminations to be noisy because they were thought to hit each other due to the AC magnetism. The experiment described in Figure #1. (accredited to Mr. Harry Honeycut, retired chief engineer of Clifton Precision, Murphy, N.C.) clearly yields a distinct audible noise similar to transformer hum with only one piece of lamination.

The experiment is quite simple to set up using a piece of packaging styrofoam as an amplifier and Epstein sample strips of several lamination grades. A close wound and varnished coil of heavy wire (100 turns) is slipped loosely over the strip to induce the magnetic field. A DC lab supply is used with a bi-polar darlington transistor in one side of the line to turn the voltage (and magnetic field) on and off. A pulse generator is used to gate the transistor. A single pulse will cause a distinctly audible "click" as the square wave current causes an instant magnetization and instant change in the lamination dimension (thickness). The pitch of the noise will follow the frequency of

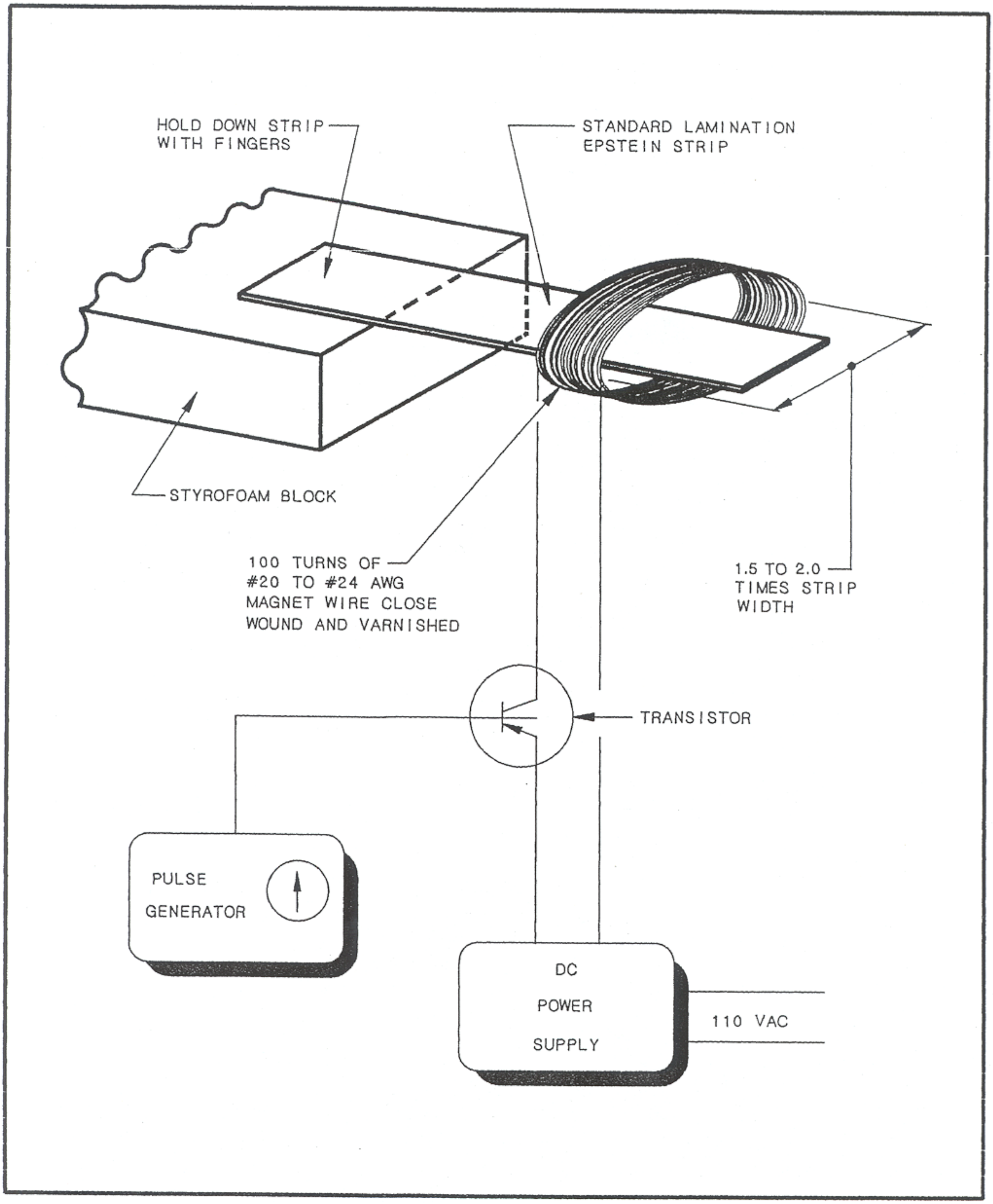


FIGURE 1 MAGNETOSTRICTION EXPERIMENT

the pulse generator setting. In fact actual music can be played through an amplifier into this coil where the lamination Epstein strip functions as a speaker cone. Note that the strip is stationary and does not vibrate as a cantilevered spring but the sound is produced by expansion and contraction of the material as the magnetic field is changed.

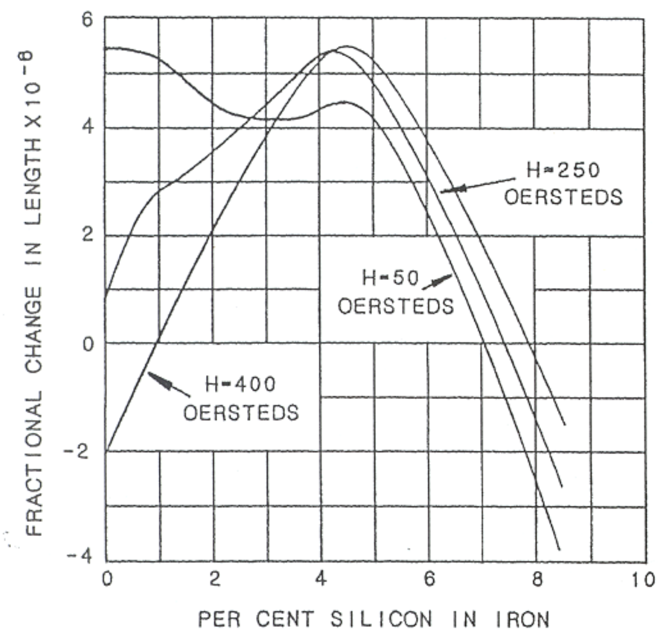


FIGURE 2 MAGNETOSTRICTION OF SILICON STEEL MATERIALS

Certain grades of lamination materials are more prone to this phenomenon than others. These magnetic or quasi-magnetic forces between atoms yield a contraction or an expansion of the lattice by opposing the purely elastic forces between the atoms. In general the magnetostriction of pure iron increases with fields (gets larger) up to a max field strength of around 20 to 70 Oersteads where upon it gradually decreases in size back to normal dimensions at about 220 Oersteads. Any further increase in magnetization causes the iron to get smaller. These effects are influenced by temperature and the addition of various elements such as cobalt, nickel carbon & silicon. The addition of silicon has been used for many years to greatly reduce the eddy current and hysteresis core losses in lamination steels. Unfortunately the addition of silicon greatly increases magnetostriction until about 7% is attained where upon it goes to zero. Figure 2 shows a curve of the dimensional change (Magnetostriction) as a function of silicon percentage with magnetization in Oersteds.

There are special materials available and presumably more on the way which offer a compromise between core losses and magnetostriction. Check with the lamination material suppliers for details.

After all other sources of noise have been identified and eliminated or reduced significantly, the last sound heard is caused by magnetostriction. This is very significant for motors used in disc drives and laser printers or copiers.

3.2 RADIAL DEFLECTION

The other main cause of electro/magnetic noise in a motor is produced by the radial magnetic forces generated in the air gap between the motor rotor and stator. The purpose of the forces generated in the gap is to have only tangential forces (moment of force = torque). It is undesirable to have any radial force component vectors but unavoidable in most motors. For example, Figure 3 shows cross sections of the motors listed. In general the designs with the smooth

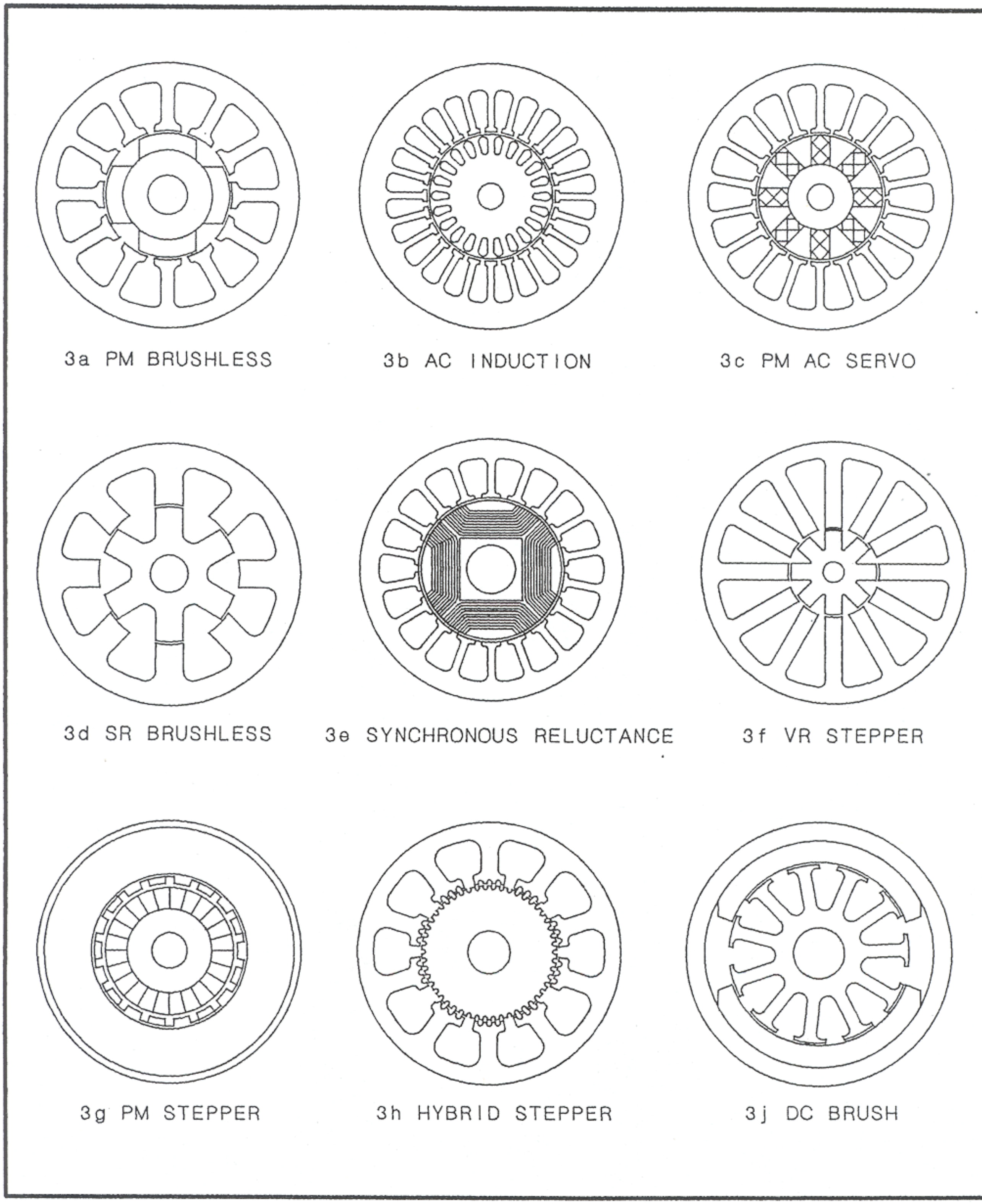


FIGURE 3 ELECTRIC MOTOR CROSS SECTIONS

uniform air gaps yield radially magnetic forces which tend to be in equilibrium so that there are few radial unbalanced forces on the stator. For example, Figures 3a (unless air gap is not uniform) 3b, 3c, 3g, and 3j have reasonably balanced radial components and stator deflection is usually insignificant.

However, Figures 3d, 3e, 3f and 3h have either single or double salient poles in the air gap. In other words, the air gap varies drastically with rotor rotation and the radial forces vary with current. The result of these forces is excessive radial deflection of the steady state shape of the stator iron structure. The pitch of the noise produced is proportional to speed and the intensity is proportional to current, flux density, air gap thickness and motor type.

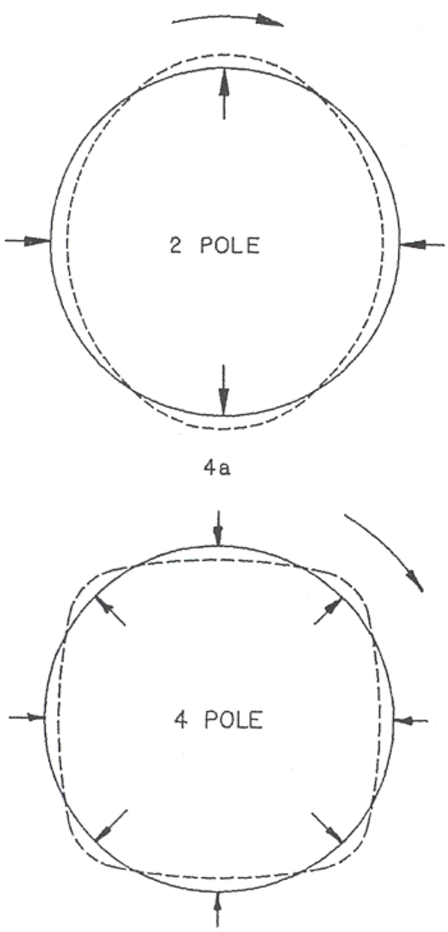


FIGURE 4 STATOR DISTORTION CAUSED BY RADIAL AIR GAP FORCES

The normal state of shape (usually round) of the stator lamination structure is deformed toward a shape as dictated by the unbalance in radial force vectors of attraction or repulsion in the air gap. For example, a distortion shown in Figure 4a would be a result of a 2 pole unbalance while Figure 4b depicts the distortion of a 4 pole unbalance or concentration of radial forces. There is a wide variation of this distortion with different examples of the most obvious motors as shown on Figures 3d, 3e, 3f and 3h. Each case must be carefully examined. The distortion produced rotates with the unbalanced forces as the rotor spins. The contribution to motor noise by radial unbalanced forces can easily be demonstrated by connecting the stator windings to a music amplifier and use the stator housing as a speaker.

Unfortunately, nearly all of the preventative methods will reduce the power density of the motor such as increase the air gap between the rotor and stator and increase the stator yoke thickness to increase its section modules to resist deflection and reduce flux density.

3.3 WINDING NOISE

It is normal practice to varnish or epoxy impregnate the phase windings in electric motors. There are two main purposes for this practice.

1 - Decrease coil thermal resistance for I^2R heat transmission to the outer motor shell.

2 - Prevent magnetic fields around individual coil conductors from causing vibrations of same which can lead to insulation breakdown due to abrasion.

However, copper wire yields a phenomenon similar to the magnetostriction of iron materials which is known as *electrostriction*. In other words, copper expands or contracts as current flows. Although the noise produced by electrostriction has never been observed by this author, it is reported for completeness. The wire vibration by the surrounding magnetic field is very easily observed. For example, when performing the magnetostriction experiment shown on Figure 1 the "coil hum" can easily be observed by using the test circuit on the coil before and after varnishing. The coil must be wound fairly tight with heavy wire and held close to the ear for detection. The audible noise (pitch varies with frequency) is very noticeable before varnishing and unnoticeable after varnishing (must be dry).

3.4 ELECTRONIC SUPPRESSION

Since the noise discussed in this section is electro/magnetic in source and transferred to the mechanical components of the motor, it seems logical that a significant reduction in acoustic noise should be achievable if the motor phase currents can be controlled. This should be possible at least for all inverter/controller driven motors. The AC line or battery driven motors, of course, cannot be improved without the addition of electronics. *Freeman* of Conners and *Cameron, Lang, Umans* of MIT as well as others have shown that certain sinusoidal drives and harmonic elementary current shaping plus phase firing angle control can reduce these electro/magnetic noises.

4.0 MECHANICAL MOTOR NOISE

4.1 HOUSINGS AND END BELLS

It is interesting to point out that if the mechanical sources of motor noise are controlled and attended to, the quality and life of the motor is generally improved. For example, a stator lamination stack which is loose in the stator sleeve or housing will cause a "buzz" noise. In fact, the stack should be a press fit or an adhesive should be used. This can be detected with a tapping of the stator sleeve with a mallet around the OD while the motor is running. When the impact of the tapping deforms the sleeve the lamination stack will be contained and the noise will cease.

Other mechanical factors which contribute to noisy motors are loose fitting brushes in brush holders, commutator defects such as finish and out of around. Bent or non-straight shafts, loose bearing fits, no bearing preload, no thrust washers on sleeve bearings and rotor unbalance also aggravates the above problems.

Motor cooling fans also add to the audible noise of a motor in the range of 600 to 1KHZ. This is caused by the above motor noises being amplified at the resonant frequency of the fan blades. Frequently this can be eliminated by changing the fan material which, of course, changes its resonant frequency. If the fan is steel, change to plastic or aluminum. If the blades are plastic, change to aluminum, etc.

In the case of single phase induction or shaded pole AC motors controlled with triacs, the voltage spikes from the rapid switching of the turned on portion of the AC cycle creates harmonics which causes motor noise. In some cases this noise problem is sufficient cause to change to a brushless DC motor and drive. Otherwise insulation materials and vibration dampening are the best solutions.

4.2 BALANCE OF ROTORS

An out of balance condition of an electric motor can be a serious problem which can cause a significant amount of vibration noise and can cause premature bearing failures. The fundamental frequency of an out of balance condition is a once per revolution spike which is easily related to RPM (its frequency equals the RPS of the motor). The rotor must be balanced to a limit acceptable to the performance requirements of the motor. The audible noise at resonant frequencies will be greatly reduced and the bearing life significantly improved.

4.3 BEARING NOISE

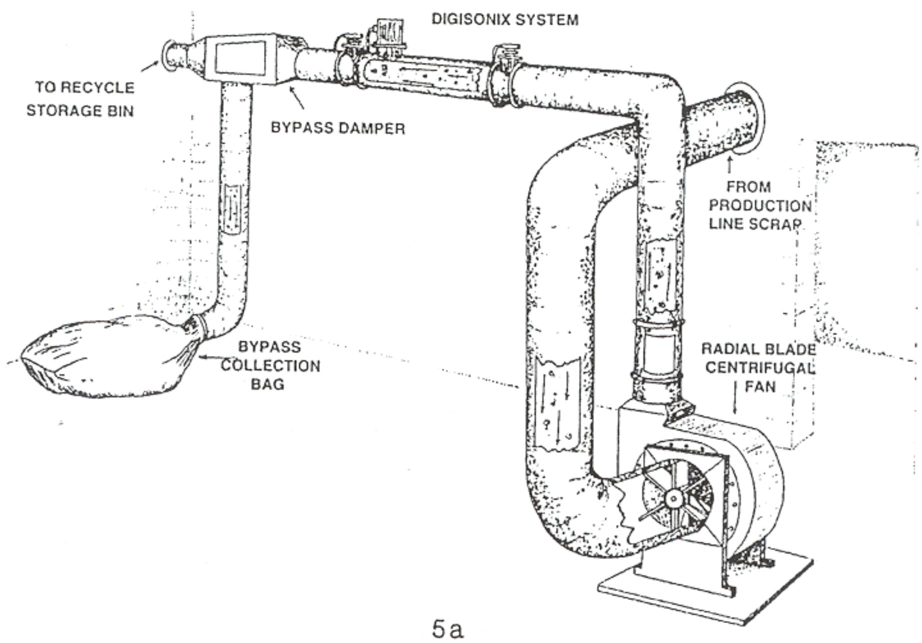
There are several types of bearings commonly used in electric motors including sleeve bearings made from either special bearing plastics or sintered oil impregnated iron or bronze. These sleeve bearings are usually considered to be very quiet running if the clearance between the shaft and the bearing ID is kept minimal for its size. The sintered sleeve bearing cannot be permitted to run dry or excessive noise and eminent failure results. The only noise frequencies produced by a lubricated sleeve bearing would be very high and due principly to the bearing and shaft surface finish.

The other principal types of bearings used in motors belong to the anti-friction family. These rolling bearings (as opposed to sliding sleeve bearings) include deep grove conrad, angular contact and roller bearings. Much can be written about anti-friction bearings for electric motors but in general the main issues which contribute to noisy anti-friction bearings are listed as follows:

- Lube selection (must be filtered).
- Matched balls ABEC 5 or better.
- Motor grade with polished raceways.
- Tight or bonded rotating races to shafts.
- One stationary race clamped or bonded.
- Preload spring on stationary races consistent with radial stiffness requirements. (Must withstand imbalance forces).
- Avoid preload change with temperature.
- Prevent Lubrication contamination. (seals)

4.3 WINDAGE NOISE

Many types of motors including AC induction are air cooled by the use of integral shaft mounted fans. The air motion and fan blade resonance can



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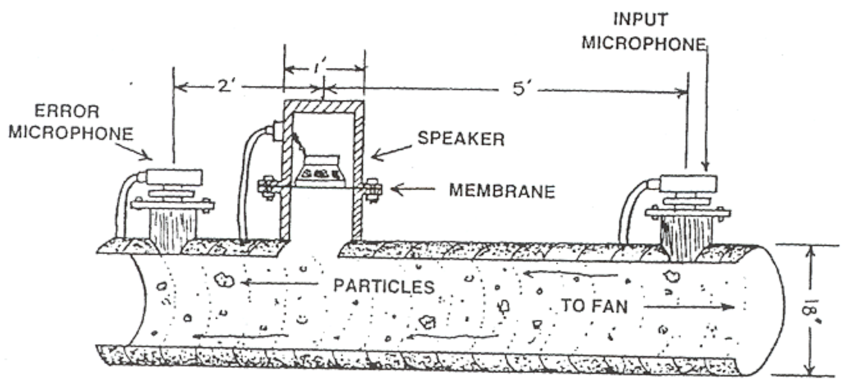

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FIGURE 5 ELECTRONIC NOISE CANCELING IN AIR DUCTS cause severe noise. For example, high speed motors such as power tools (routers and saws produce the most noise) and vacuum cleaners run at 18 to 30 thousand RPM and utilize serious fan cooling to achieve the power density required for portability. The fan noise is near deafening without the use of sound absorbing materials such as plastic housings, rubber supports and foam.

In the case of blower motors, the motors are mounted in rubber to dampen the noise. For example, the HVAC motors in an automobile make extensive use of vibration dampening materials such as rubber mounts. A new family of constrained layer dampening materials is available which consists of two sheets of steel or aluminum laminated with a polymer sandwiched in between for a completely "dead" housing material or bracket material. This can be blanked, formed, drawn and spot welded. The ducting around fans and blowers can be made of the constrained layer laminates to entrap the air and motor noise within a confined area.

5.0 SUMMARY

The noises produced by electric motors for the 21st century factory, home, car and office can be reduced by four methods. First identify the source and reduce or eliminate its cause by structural design, electronic inverter design, material and component selection, as well as assembly procedure. Secondly, the resulting noise can be critically dampened using energy absorbing materials such as gaskets, grommets, constrained layer materials and noise absorbing materials. The third solution to noisy motors is to enclose them in sound trapping and absorbing enclosures. In other words, this means isolate the problem or insulate the source from the human ear.

The fourth method and the newest is known as anti-noise. Some refer to this technique as "active noise control" or "digital sound cancellation". Microphones are used to collect the propagated acoustical noise and convert it to electric signals which a processor synthesizes and determines a canceling wave form and there it is "played" back through a loud speaker. An error microphone is used to measure the residual noise which allows the controller to fine tune the output and maximize cancellation.

This technique is being used in air ducts in large HVAC systems for large buildings. Figure 5 shows a diagram of the system used in a heating duct. Under development are similar techniques for use on automotive and truck engines known as the "electronics muffler". The quiet engine without back pressure translates to better fuel economy which yields lower air pollution as well as lower noise pollution.

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