REDUCING ELECTRICAL MACHINE NOISE EMISSION

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INTRODUCTION

The advent of noise regulations implementing the 1986 European Community Directive on the protection of workers from noise (1) is likely to stimulate firms to specify noise limits for machines they wish to purchase and to seek ways of quietening existing machinery and plant. Although rotating electrical machines (motors and generators) are usually only one of many noise emitting elements of a machine or process, designers and manufacturers are likely to face increasing demands for lower noise emissions from their products as employers strive to reduce the noise exposure of workers to below 90dB(A) Lepd.

Electrical machine manufacturers should be well prepared to meet their customer's needs since they have devoted much effort over the past 25 years into ways of reducing noise emission in order to meet the specifications of their larger customers in the petrochemical industry and elsewhere. They will, however, now need to reassess the "reasonable practicability" of reducing on load noise emission still further and ensure that the information they have-on machine noise levels and the ways in which they can be reduced-is adequate.

This paper discusses, briefly, the legislative background before outlining how the noise from rotating electrical machines can be reduced by good engineering design and practice. The author's experience is used to illustrate the practical problems which face machine designers.

LEGISLATION: A FRAMEWORK FOR ACTION

Currently, sections 2, 3, 6, 7 and 8 of the Health & Safety at Work Act 1974 as interpreted by the 1972 Code of Practice for reducing the exposure of employed persons to Noise. HMSO, provide the principal legislative framework for action to reduce the noise exposure of workers. This is supplemented by legislation implementing EC Directives which limit the noise emission from specific products such as construction equipment, road drills, lawnmowers etc and in a few cases by specific UK regulations. The implementation of the EC Directive on or before January 1 1990, will define the legislative framework a little more precisely emphasising the reduction of noise exposure by technical means with ear protection being seen as a supplementary measure.

Sections 2 and 6 of the HSW etc Act 1974 are the two most important elements of the current framework, with the latter requiring designers and manufacturers to ensure that their products are safe and "free from risks to health and to carry out any necessary research, testing and development to achieve that end: A further duty is to ensure that information is available on the risks and ways of minimising them.

Customer specifications have an important part to play in achieving reduced machine noise emission and can be particularly effective when clearly specified noise limits are coupled to well selected and defined acceptance test procedures, buttressed by effective penalty clauses. Some years ago, on site testing of two 40 megawatt gas turbine powered alternators revealed a 12 dB excess over the guaranteed limit in the 120 Hz octave band. Bringing the machine to within limits cost the machine supplier £14000 per machine for additional silencers plus the costs of shipping them to site in California , fitting and testing.
Financial penalties can be specified such as "£10,000 per dB excess over the guaranteed levels" and in a competitive tendering situation, such penalties cause designers to become acutely aware of the inaccuracies in their basic data and in the methods used to predict noise emission levels.

There are of course other pressures for change including the environmental noise sections of the Control of Pollution Act 1974 and market forces which are forcing industry to become more efficient in its use of manpower and energy.

ELECTRICAL MACHINE NOISE

The noise from electric motors and generators is a combination of magnetic aerodynamic and mechanical noise and the relative contribution of each of these will depend on the rating, speed and type of machine (Figure 1) as well as the type of weather protection and cooling system (Figure 2) provided. Other important factors include the design of the machine's foundations and supports; the dynamic characteristics of the system of which it is a part; the electrical supply and control system used and the duty the machine is required to fulfil.
High speed machines form the largest proportion of rotating electrical machines sold and in most cases where noise is a problem, aerodynamic noise is likely to predominate. The noise is characteristically broadband, with superimposed pure tones, in the frequency range 250 to 4000Hz. Noise levels at 1m from machine casings can exceed 110 dB(A)- in the case of large high speed, screen protected machines and some traction motors - but generally they are much lower.

AERODYNAMIC NOISE AND ITS REDUCTION

Aerodynamic noise originates in either the rotor shaft mounted fans provided to cool the machines or in the fan like action of rotors and to a lesser extent, couplings. The machine casing and cooling system design has an important influence on noise levels. Screen protected machines are used in conditions where environmental protection requirements are minimal and cooling is effected by an internal, shaft mounted, fan which draws air in at one end of the machine and discharges it at the other. In some cases machines have fans at both ends of the rotor and the cooling air is exhausted centrally.

Where conditions are more arduous, and particularly in the petrochemical industry, totally enclosed machines are required. Small and medium sized machines of this type are cooled by an external, shaft mounted, (usually centrifugal fan, at the non drive end, which blows air over the finned machine casing.
The cooling systems of larger machines, are more elaborate and incorporate either air to air (CACA) or air to water heat exchangers (CACW). The latter arrangement is the quietest since the casing of the machine contains the noise from the internal fan and-unlike the (CACA) system-there is no external fan. (2)

The reduction of aerodynamic noise starts at the design stage. The size of the fan, the power it consumes and the noise it generates depends on the characteristics of the system in which it is used. It is a machine's electrical losses which create the demand for cooling air so these should be minimised. The thermal and mechanical design should be optimised to enable the required temperature limits to be met with a minimum consumption of fan power. (3) Designers are generally interested in doing this for other, obvious, reasons but their scope may be limited by the constraints of the customer's electrical performance specification and to some extent, by national and international standards for machine design and construction which limit the size of stator and rotor cores and the amount of copper that can be designed into windings. A more important restraint is the unwillingness of customers to accept the increase in machine size and cost involved if the designer attempts to achieve low noise levels by derating machine performance.

Fan noise depends on the details of the design of both the fan impellor and the casing in which it is mounted and generally varies with the sixth power of fan speed and the seventh power of the diameter. The more efficient the fan the lower the noise emission for a given duty with a 10% improvement in efficiency reducing noise levels by 5 dB(A). Ideally the most efficient fan should be selected for the application and it should be installed so as to avoid interaction between the impellor and adjacent objects such as windings, cover mounting bolts, ribs, etc or between the impellor and turbulence generated by upstream grilles, bends and changes of section.
This is not as easy as it might sound since the limited amount of space available within the frame of a machine of modular construction or in a traction motor, may prevent the designer from providing adequate clearance or from incorporating the ideal casing shape for optimum fan performance. The task can be simplified by not using the bi-directional fan designs once so popular. These crude, radial bladed, centrifugal fans while possessing the virtues of simplicity, low manufacturing cost and operational flexibility, are inefficient and noisy. Figure 3 shows what can be achieved when such a fan is replaced by an efficient, proprietary, axial flow fan in a well designed casing. Not only were the noise levels reduced by 13dB(A) but the machine's windage losses were reduced by 20% giving a continuous saving of energy throughout the life of the machine. An interesting feature of the design is the use of a stepped inlet to

provide an economical alternative to the conical inlet which is normally used to provide a smooth flow into the impellor.
Noise levels were subsequently further reduced by extending the fan casing and lining it with a sound absorbent material.
Other examples of the noise reductions achievable using this approach are given below:-

MACHINE RATING kW	MACHINE SPEED rev/min	NOISE LEVEL AT 1M dB(A)		NOISE REDUCTION dB(A)
		a. Original Fan	b. New Fan	
224	1500	95	83	12
265	1500	88	80	8
300	1800	92	85	7
670	3000	96	83	13
850	1500	97	86	11
1250	1500	97	84	13

The 13 d(B)A reductions were obtained on totally enclosed induction motors of modular construction with air to air heat exchangers (CACA) by using proprietary broad, backward curved, aerofoil blade, centrifugal fans, running in volute casings, for the external air circuit. As is usual the above fans were mounted on the non-drive and extension of the rotor shaft and this is the most reliable arrangement but for some applications it has proved practicable to use standard, separately driven, axial fans.

There is a great deal of information in the literature on ways of avoiding the generation of pure tones (4) (5) (6). In centrifugal fans with volutes, cut off clearance is critical and can often be increased substantially to give a useful reduction in noise levels without seriously impairing fan performance. In the case of internal fans, there is usually insufficient room for a volute and the clearance that can be provided between the impellor and the motor casing is minimal. Problems can be avoided by modifying the shape of internal casing ribs with which the air flow from the fan interacts. Ploner and Herz (7) showed that differences in noise level of upto 15dB could be achieved by using a trapezoidal rather than a square rib section. Other workers have achieved substantial reduction in fan noise by using fans with randomised blade spacings (-10 dB,; by inclining the fan blades or the cut off edge (-8 to 12dB) and by modifying the acoustic impedance of the fan casing (4). Grilles should be designed with care since the effect of standard grilles on traction motors was found by the author to increase noise levels in the frequency range from 1000 to 8000 Hz by 2 to 6 dB. Designers should also check to ensure that aerodynamic resonances of the internal spaces of motors and generators are unlikely to be excited by the blade passing frequency (number of fan blades, rotor or stator vents etc times rotor speed) or its harmonics. Particular problems arise in the case of large machines cooled by axial flow fans at opposite ends of the rotor. Intakes are usually asymmetrical and this combined with irregularities in blade manufacture and air circuit instablility can give rise to rotating stall if the fan

design is marginal. The result is not only poor cooling of the machine but the generation of strong pure tones at a frequency of 1/2 to 3/4 running speed or 25 to 45 Hz.
Strong pure tones can be produced by the radial cooling slots in large induction motors especially where the rotor slots and the stator slots are alianed. The solution is to use a staggered arrangement with carefully shaped apertures and profiled wedges and spacers between packs of laminations. (8).

In the interests of economy, firms often use standard fan designs for a variety of machines. This approach is unlikely to achieve satisfactory results in many cases unless the fan designs are sufficiently flexible to allow them to be carefully "tailored" to particular applications.
Details of machine design and construction can be very important and a blend of art and science is often required to solve a pressing problem during acceptance testing prior to delivery. It was in such a situation that the author was asked to explain why a motor was outside the guaranteed noise specification and to put matters right as quickly as possible because of the machine's impending delivery to the customer. The noise, a pure tone, was easily proved to emanate from the external fan by blanking off the intake. By then progressively uncovering the intake it was found that the noise only reappeared when the last 50mm segment of the intake grille was uncovered. A plate of the appropriate dimensions was welded onto the grille and a noise reduction of 6 dB(A) was achieved without any adverse effect on machine cooling: the machine was delivered on time.
On another occasion, a 3000 rev/min. TEFC induction motor proved noisier than expected on test - generating a strong 2000Hz pure tone. By removing the bolts securing the fan casing it proved possible to vary the intensity of the tone by 6 to 8 dB thus indicating that the problem was one of resonance between the fan blade passing frequency and the organ pipe like mode of the cavities formed by the fins on the machine frame and the fan cover. Redrilling the holes for the casing bolts to effect a permanent change in the length of the "organ pipe" solved the problem and reduced the noise level by 8 dB(A).

MAGNETIC NOISE

Magnetic noise is caused by fluctuating magnetic forces in the air gap resulting from variations in permeance cause by a number of factors including the presence of slots in the stator and rotor cores to accommodate the windings, the geometry of the air gap and errors in construction. These forces can be considered as a series of harmonic sinusoidal waves rotating at different speeds in the air gap which excite the stator frame and core to vibrate (9) (10) at frequencies which are related to the number of rotor and/or stator slots and the supply frequency. Those of low mode order are the most troublesome particularly when they resonate with a vibrational mode of the stator core or casing which can radiate noise efficiently. Magnetostriction at mains

frequency and its harmonics can also cause strong vibration of machine frames at frequencies of (usually) 100 and 300 Hz and when the aerodynamic noise emission of large turbo alternators has been reduced by silencing, it is noise from this source which predominates.
Electrical and mechanical dissymmetries in machines, especially induction motors, can give rise to a force known as unbalanced magnetic pull which has the characteristics of a negative spring located in the air gap. This force can cause the rotor to strike the stator on start up if the dynamic characteristics of the rotor and stator and the machine mountings are inappropriate. If the machine can run, then a strongly pulsating force may arise at twice slip frequency (twice the difference between the mains frequency and the motor speed. (11)

Magnetic noise problems are most likely to arise in the case of DC machines designed to operate over a wide speed range e.g. traction motors, since it is almost impossible to avoid resonances at various speeds (Figure 5). The casings are thin cylinders with masses attached (the poles) and two fixed points, whose vibration response is modified by the effects of the end covers and, in the case of machines with flexible rotors, the rotor. The attack on magnetic noise starts at the design stage and designers have, for many years had rules of design and, in some cases, elaborate design programmes to enable them to minimise and to predict magnetic noise levels (12)
However, to keep electrical efficiency high and minimise stray losses they need to ensure that the number of rotor slots is not too dissimilar from the number of stator slots and thus problems can arise. By careful choice of slot numbers, the use of magnetic slot wedges, and, if necessary, by skewing the rotor slots (Figure 6) serious problems can usually be avoided.
In the case of DC machines the ratio of slots to poles can be important. By using a fractional number of slots per pole, shading the pole arcs and skewing the rotor slots by one slot pitch over the length of the pole the magnitude of the radial and tangential forces exciting the machine casing into vibration can be substantially reduced with consequent benefits in reduced noise and vibration levels.
Winding arrangements are important since these can give rise to electro magnetic damping. In the case of DC machines the harmonic content (ripplefactor) of the supply can have a marked effect on noise levels and I have measured a 10 dB(A) difference in the noise levels of machine run on two supplies with different ripple factors.
The use of pulse amplitude modulation (PAM) combined with pulse width modulation (PWM) to modify the waveforms in the air gap is a technique which might be used to reduce induction motor noise and it is claimed that reductions of upto 10 dB have been achieved. (13)
Problems experienced in trying to meet the requirements of a forklift truck manufacturer and, on another occasion, a manufacturer of underground trains illustrate some of the difficulties magnetic noise can create.
The forklift truck motor was a 24volt 16h.p., series wound, d.c., machine

which was required to operate over a speed range of from 750 to 2700 rev/min. Tests carried out by the customer had shown it to be 8 dB(A) noisier than a competitor's motor under certain conditions of truck use.
A series of no load and full load tests were carried out and the noise level to speed characteristic revealed a series of resonance peaks in both the noise and casing vibration spectra which were reduced by between 11 and 21 dB when the armature current was reduced from 33 to 100 amps. There was good correspondance between the resonance peaks and the calculated natural frequencies of the machine casing and it was clear that the problem was caused by stator resonances excited by magnetic forces at slot passing frequency (number of armature slots times the rotor speed) and its harmonics particularly the second. At low speeds the 300Hz resonance was most pronounced and the noise had a harsh character.
A series of modifications were then tried, including skewing the armature slots and reducing the pole arc (Figure 6) and it was found that a slot skew of 1/2 to 1 slot pitch combined with the use of a full pole arc gave the best results reducing maximum noise levels from 95 dB(A) to below 80 dB(A). Further modifications, such as doubling the number of armature slots to reduce air gap forces and increase their frequency, were proposed but not tested. The problem appeared to have been solved but a disconcerting effect was noted during testing of the first modified production machine. A strong pure tone was evident during the first, cold, start but when the test was repeated the maximum noise level was lower by 6 to 8 dB and when a third test was carried out (within 5 to 10 minutes of the first) the resonance had disappeared. No explanation was found for this behaviour but it may have been partially a problem of the quality control of the manufacturing process. The control of variations in material properties particularly of core laminations but also of the rotor shafts of machines with "flexible" shaft - such as large turbo-alternators is important. The tightness of lamination packs, the accuracy of assembly, the accuracy of rotor balancing and the tightness of fit of a rotor or stator core pack can, even where the machine design is correct, considerably influence the noise and vibration of rotating electrical machines and much management effort is needed in the control of the production process if problems are to be avoided.
On another occasion a new traction motor for an underground railway application was found to be noisier than its predecesor. Part of the problem was due to aerodynamic noise but magnetic noise was the major problem as was clearly demonstrated by the 15 dB(A) instantaneous fall in noise level which occurred when the electrical supply was interrupted. The problem was due to a 430Hz resonance of the machine casing excited by the slot passing forces in the air gap. By cropping the tips of the main polies to reduce the pole arc from 5.4 to 5.2 slot widths and changing the radius of curvature (grading) of the pole arcs, casing vibration velocity levels were reduced by a factor of 3 and noise levels were reduced by between 6 and 10dB.

Aerodynamic noise was reduced by modifying the fan and its housing but a mechanical noise problem caused by the excitation of vibrational mode of the rotor by the bearings proved intractable until all the bearings and the endrames were replaced. This work also highlighted the problem of carrying out in works tests on machines that produce pure tone noise and vibration. Figure 7 shows the very different noise/speed characteristics obtained for the same machine when tested in two different test areas using different methods of mounting. A further problem is that often the works test is carred out under standard test conditions which do not simulate the in service conditions very well. For instance, in the case of traction motors, the considerable loads which the pinion end bearings carry in service are absent and this can give rise to bearing generated noise which is untypical of that which will be experienced in use. Often too, it is difficult to simulate "Full Load" conditions and standard tests are carried out on "No Load". Fortunately in many cases this has not, in the past, mattered very much since the predominance of aerodynamic noise masked the effects that the No Load to Full Load changes have on magnetic and mechanical noise. However, as customers demand quieter and quieter machines and the contribution of aerodynamic noise is minimised, the situation will change and suppliers will have to provide "On Load" noise emission data. (14)

The importance of taking "On Load" effects into account is illustrated by the problem of a 2MW Synchronous induction motor which, on test, gave 1m noise levels 17dB(A) in excess of the customer's limit. The use of magnetic slot wedges and an enclosure well integrated into the basic machine design would have cured the problem at a cost of £3000 but this was unacceptable to the customer. It was therefore necessary to change the stator to rotor slot ratio from 108/120 to 108/72 by fitting a new 72 slot rotor. This reduced the mean noise level from 102dB(A) to 83dB(A) and brought the machine within specification but at a cost of £8000 or 35% of the machine price.

SILENCERS AND ENCLOSURES

When all that can reasonably practicably be done to reduce noise levels by design has been done further reductions can often be achieved by using silencers or by enclosing machines. Simple sound absorbent lined baffles can give 5 or 6 dB(A) reduction in the noise from a screen protected or hose proof machine and the use of proprietary silencers can increase this to dB(A). Obviously they need to be carefully designed to minimise backpressure on the air flow system but this generally presents no problem. Enclosures either free standing or (more commonly) machine frame mounted, have been used for many years to reduce the noise emission of gas turbine driven alternator sets and portable generators to low levels and packages featuring low pressure loss air systems; good maintenance access; internal lighting and fire quench systems have been installed in a variety of environments around the world ranging from the Sahara desert to the Alaskan wastes and including the demanding conditions on oil platforms in the North Sea. Frame mounted enclosures can give 24

to 30 dB(A) reduction in levels compared to the untreated machine and free standing enclosures can be designed to give greater reductions in noise emission.
On large induction motors and synchronous machines it is possible to incorporate the acoustic panelling into the machine design thereby improving the appearance of the machines and giving the electrical designer latitude in the electrical design of the machine.

To sum up. Electrical machine manufacturers will face increasing demands for still quieter machines and ought to be in a good position to respond quickly and positively with new and improved designs. However, they will need to reassess their test procedures and test facilities to ensure that they will be able to provide good noise data for their customers on the noise levels their machines are likely to produce in use and to review the need for further research and development. If new test standards are required, then work on them should start now. The recommended maximum sound power levels contained in Appendix D to BS 4999 Part 109 1987 are marginally higher now than they were in 1973 and they could and in my view should be reduced by between 5 and 10dB(A). Good designs, data and test methods are not enough - all aspects of machine manufacture that can influence machine noise emission need to be identified and controlled; the influence of the systems to which their machines are coupled and of installation conditions need to be understood if expensive problems are to be avoided, customer satisfaction guaranteed and the noise exposure of workers reduced. Remember too that the achievement of noise reduction is one thing but the maintenance of low noise emission is another and one that needs to be considered in drawing up maintenance schedules.

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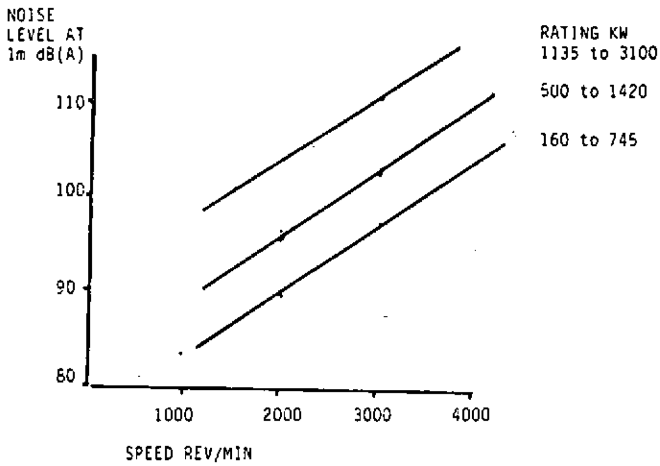

FIGURE 1. VARIATION OF INDUCTION MOTOR NOISE LEVELS WITH SPEED AND RATING.

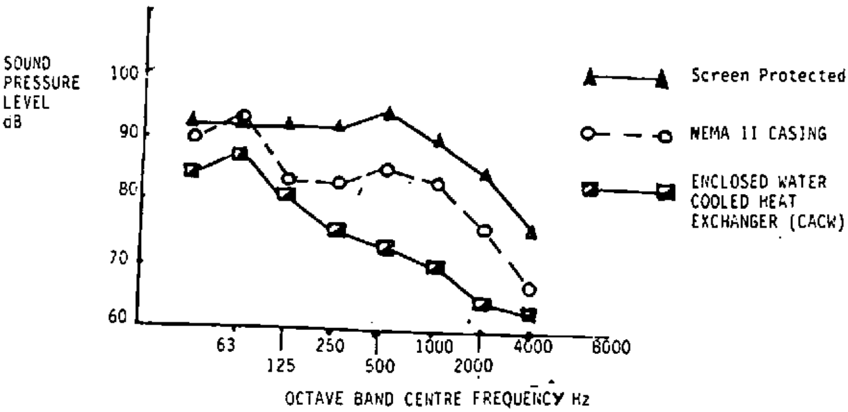

FIGURE 2. VARIATION OF INDUCTION MOTOR NOISE LEVELS WITH COOLING SYSTEM/WEATHER PROTECTION TYPE. 3000 rev/min 350 Kw INDUCTION MOTOR

REDUCING ELECTRICAL MACHINE NOISE EMISSION

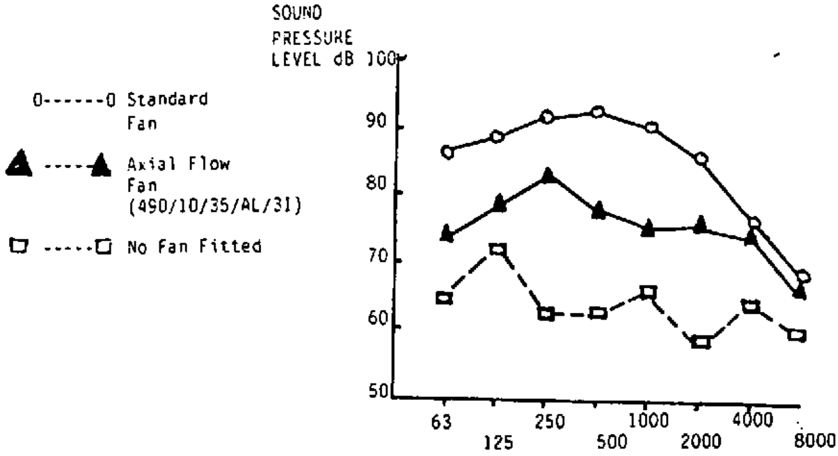

FIGURE 3. NOISE REDUCTION DUE TO FITTING AN AXIAL FAN TO A 75 KW 1500 rev/min TEFC INDUCTION MOTOR IN PLACE OF A RADIAL BLADE CENTRIFUGAL FAN.

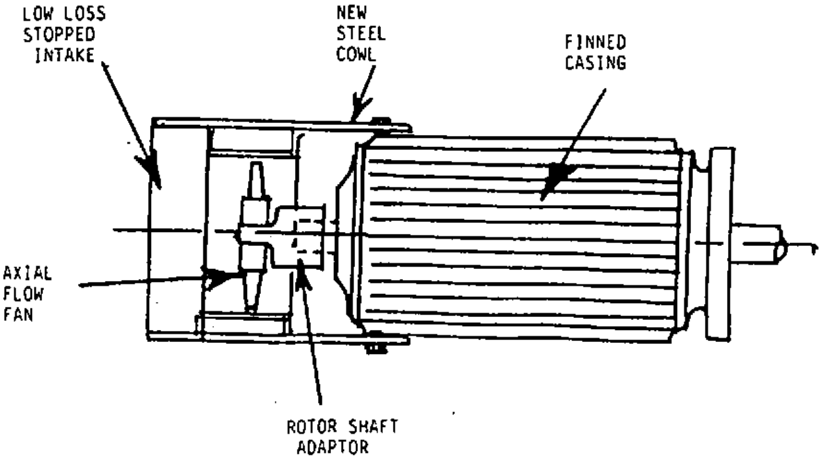

FIGURE 4. SKETCH OF TOTALLY ENCLOSED FAN COOLED INDUCTION MOTOR FITTED WITH HIGH EFFICIENCY AXIAL FLOW FAN.

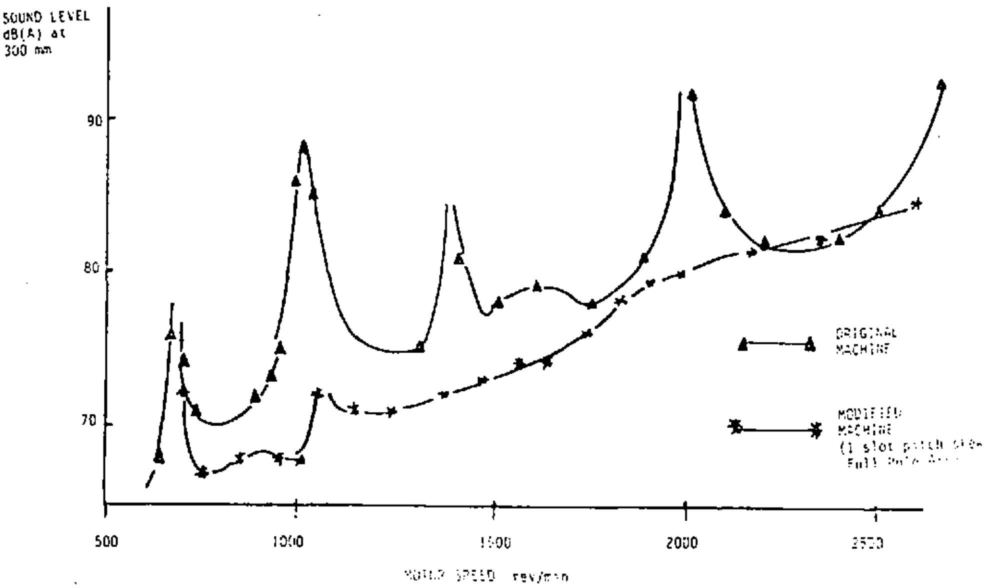

FIGURE 5 NOISE/SPEED CHARACTERISTICS OF [illegible] TRUCK MOTOR PLUGGING AT 300 AMPS SHOWING THE EFFECT OF [illegible].

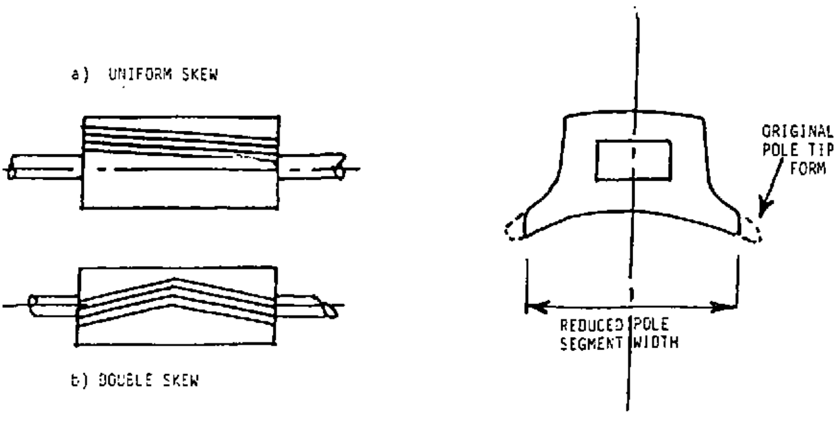

FIGURE 6. SKETCHED ILLUSTRATING ROTOR SLOT SKEWING AND POLE TIP MODIFICATIONS FOR DC MACHINES.

REDUCING ELECTRICAL MACHINE NOISE EMISSION

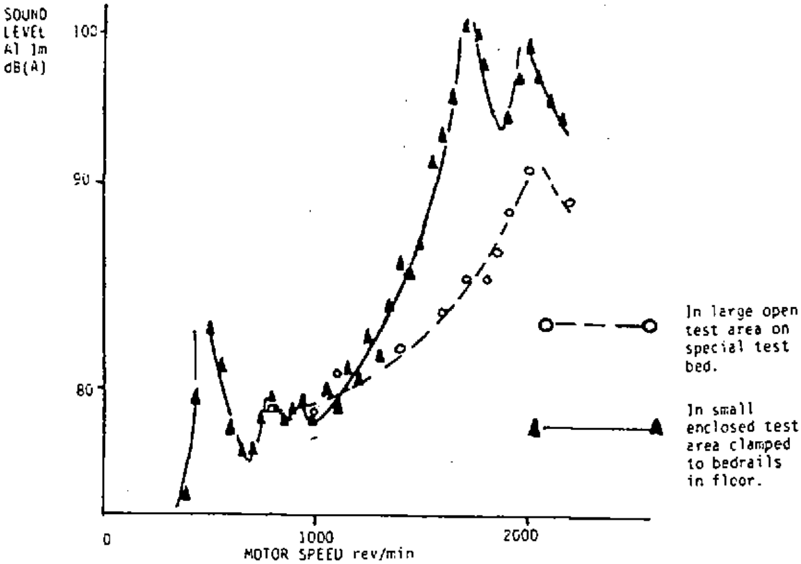

FIGURE 7 SHOWING THE INFLUENCE OF THE TEST BED MOUNTING AND ENVIRONMENT ON MACHINE NOISE LEVELS.

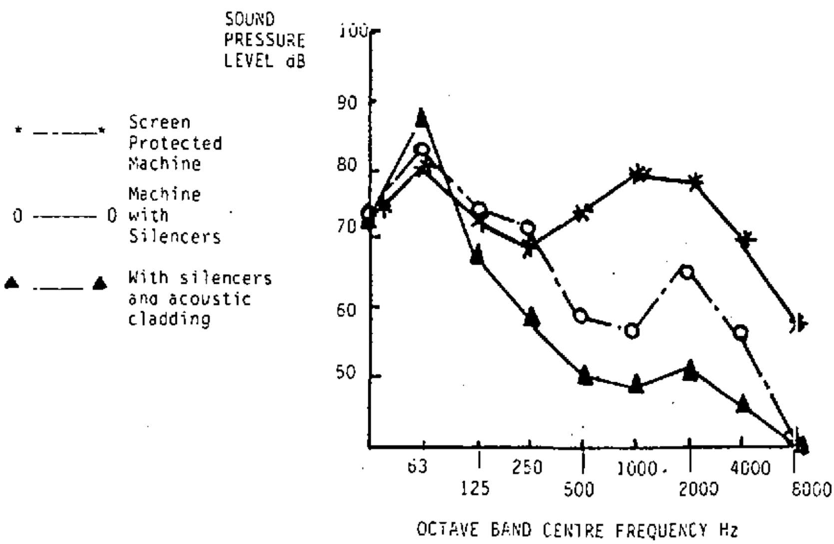

FIGURE 8 THE USE OF SILENCERS AND ACOUSTIC CLADDING TO REDUCE INDUCTION MOTOR NOISE 950 KW 3000 rev/min