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# ACOUSTIC SUITABILITY OF VARIABLE SPEED DRIVES FOR USE WITH FANS IN THE H & V ENVIRONMENT

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## 1. INTRODUCTION

The use of speed control as a method of varying the operating duty of fans has long been established. In recent years the use of inverters and other types of variable speed drive has grown enormously. With the increased use of these controllers it was essential that Woods, as a major supplier of fans, was aware of the physical effects on the prime mover using synthesised supply control.

## 2. NATURE OF FORCES IN THREE PHASE INDUCTION MOTORS

The analysis of the steady state operation of an electric motor has to take into account a large number of components of electromagnetic force, which are obtained by multiplying the equation for the magnetic permeance wave by that for the m.m.f. wave.

The discontinuities such as are due to stator and rotor slots, together with the effects of saturation and eccentricity, create an infinite series of terms in the permeance equation; similarly, the discontinuous distribution of conductors in both stator and rotor create another series of terms in the m.m.f. wave, whilst slot skew and harmonics of stator current are usually present to make matters more complex.

The product of the m.m.f. wave and permeance wave equations yields a flux density wave, and the electromagnetic forces are finally obtained, proportional to the square of the flux density.

It is not surprising, therefore, that the noise spectrum of an induction motor contains many discrete frequencies, their amplitudes depending on the magnitude of each force component, and the response of the motor and the structure to which it is fixed.

The fundamental and low-order harmonics associated with the supply frequency, and with the numbers of stator and rotor slots, are normally the most significant, but the possibility of resonance in one mode or another can obviously affect tthe motor response.

Calculation of vibration amplitudes and of the resulting sound power has been tackled by a number of researchers, but in small machines it is doubtful if the accuracy of such predictions justify the effort. One major cause of uncertainty is the damping associated with windings and insulation, which present an ill-defined, semi-rigid mass effect, within the complex body of the stator iron and enclosure.

## 3. FORCES IN SINGLE PHASE MOTORS WITH SPEED CONTROL

This far we have dealt with a simple sinusoidally-varying, mains frequency voltage applied to a three phase machine. Further complications are introduced when a small single phase motor is considered, because the m.m.f. produced by even a permanent-capacitor design will not, in practice, be rotating with uniform amplitude, and hence has additional low-order harmonics associated with it.

A permanent capacitor design is usually regarded as the best choice for a single phase fan motor, as it will offer the best material utilisation, efficiciency and noise of the several options available. When the fan load matches the designed output the noise spectrum will not differ greatly from the equivvalent three phase machine, but operation well away from this optimum output is likely to result in increased levels of noise at fundamental and harmonic frequencies (100Hz and its multiples on a 50Hz supply frequency). Fig 1 shows spectra comparing the full load and no load performance of a 0.37kW fan motor.

It is well known that low power, single phase fans are often used in conjunction with speed regulators which, by means of electronic switches (Triacs or thyristors) interrupt each half cycle of the supply waveform reducing the r.m.s. voltage and, therefore, the fan speed also. The voltage harmonics thus introduced are of a low order and the motor response is invariable reflected in a number of pure tone enhancements which can be objectionable to the user, and difficult to attenuate. Anti-vibration mounts will obviously be of value, but in a noise-sensitive environment it is preferable to adopt a regulator which does not introduce voltage harmonics - using an auto-transformer to reduce fan speed avoids these effects, possibly carrying a cost penalty and to some users a cosmetic one also.

Fig 2 shows the additional vibration amplitude due to electronic speed regulation, compared with sinusoidal control.

## 4. FORCE EFFECTS WITH INVERTER CONTROL OF FAN MOTORS

Finally, we have to take note of the further degrees of complexity associated with the control of speed by variable frequency inverters.

Although there are several concepts incorporated in the large number of inverters currently on the market, there are only two basic groups, so far as their effect on noise is concerned - these are :

(a) The quasi-square wave type, sometimes known as Pulse Amplitude Modulation (not to be confused with Pole Amplitude Modulation which, with the same acronym, is a special type of two-speed motor winding).

(b) The Pulse Width Modulated type

Typical voltage waveforms are shown in Fig 3, it only being appropriate here to note that with the QSW type, voltage amplitude reduces as wavelength increases, while with the PWM type, the need to reduce r.m.s. voltage when frequency is reduced is achieved by varying the mark-space ratio, and usually the number of pulses of (constant) d.c. voltage, in each half cycle.

There are three different effects that have been observed when an induction motor, controlled by an inverter, is used to drive a fan - these effects are not unique to a fan drive, but may appear to a greater degree sometimes sufficient to cause dissatisfaction to a user. they are :

(a) torsional oscillation due to the inter-action of low-order force harmonics; a backward rotating 5th and a forward-rotating 7th will be potentially the most severe, with a three phase machine. The resulting 6th harmonic oscillation was sufficiently severe in one installation to cause more than one fatigue failure of the mountings of an axial fan. However, this effect is not only peculiar to a simple quasi-square wave inverter (i.e. it would not occur with the PWM type) but a cure was quickly found, by ensuring that the voltage/frquency relationship matched the characteristics of a fan - this implies that the r.m.s. voltage from the inverter reduces from its maximum value more rapidly with frequency than would be the case with a simple linear relationship. The effect of a non-linear V:Hz relationship is an improvement in efficiency and power factor and a reduction in the electromagnetic forces at both fundamental and harmonic frequencies. It would be standard practice these days to select this so-called fan and pump option.

(b) noise emission associated with forced vibration at the primary switching frequency of a PWM inverter. This frequency will not be apparent initially by looking at the voltage waveform from such inverters. The waveform, though, is usually generated by the combination of a triangular voltage wave, at a relatively high switching frequency, and a sinusoidal wave at whatever fundamental frequency the inverter output happens to be set at. This switching frequency has proved to be the dominant source of discrete frequency acoustic noise with all the PWM inverters which the authors have tested.

Fig 4 shows noise spectra on a particular fan when ccontrolled to half speed by three different inverters. All noise spectra were measured in the same anechoic facility as was used for previous work (see Reference 4). In this case, all measurements were free field, at 1m distance and at an angle of 45° from the discharge of the fan.

(c) Resonant vibration and noise at one or more speeds within the operating range of a system, both the risk and the effect being enhanced by the series of force harmonics associated with the inverter waveform. In this case, any type of inverter could cause an unsatisfactory match. The fan type and construction will have an influence, though, by virtue of its modal characteristics. It might be expected that the lower frequency modes associated with the geometry of a centrifugal fan would, with advantage, be mis-matched with the higher force frequencies from a PWM inverter, while the axial fan would be better if controlled by a QSW inverter.

A particular feature noted with a belt-driven fan has been a severe resonance of the belts such that at a particular narrow band of speed, they were making hard contact with the fan guard. Effects equivalent to a severe out-of-balance could similarly appear when anti-vibration mounts are in use.

Fig 5 illustrates resonant noise peaks from a centrifugal fan, excited by inverters of two very different types and with the second of these, a further comparison with the stiffer assembly of an axial fan is included.

## 5. RECENT DEVELOPMENTS

As might be expected with the pace of development in electronic device performance, several inverter manufacturers have, in the last one to two years, introduced designs having significantly higher base switching frequencies than their previous models, which were working typically at 500Hz to 1kH. There are, from first hand knowledge, at least four manufacturers who offer switching frequencies in the range 6 to 18 kHz. While at the lower end of this band the vibration is by no means ultrasonic, the dBA level will be reduced usefully. Although the manufacturers have responded thus to widely expressed dissatisfaction over motor noise, they have difficulties in extending the kW rating of their new designs much above 7.5kW. This is an unavoidable consequence of the fact that the power switching devices dissipate most heat during the short periods when they interrupt and re-initiate current flow, and to switch at such very high rates is more and more demanding as the amps increase. The authors are certainly not qualified to predict how far this trend will go - in any case, their Company is in the fortunate position that at the present time, a variable geometry (variable pitch) fan remains a more cost-effective variable-duty fan option for most applications where unit power is above about 10kW.

## 6. CONCLUSIONS

Speed control of fans provides a useful alternative to the variable geometry method of controlling air volume, particularly with fans of low power. In most cases the adoption of speed control introduces the risk of higher perceived noise and vibration levels, and since the noise is pure tone in origin, it is likely to be more apparent subjectively, than in terms of a significant difference in octave band levels. Suppliers will rarely be able to quantify these effects, except by testing the fan-plus-controller combination over the full range of operation. Nevertheless, it is important that specifiers and users are aware of the possible inter-action between power electronics and the environment, including interference with other apparatus over a wide range of frequencies, and the subjective effects on the local population in the ways described in this paper.

## 7. REFERENCES

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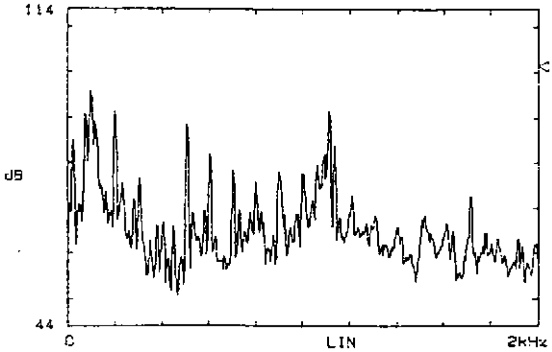
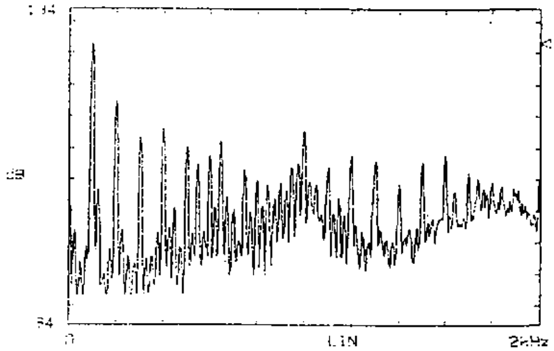


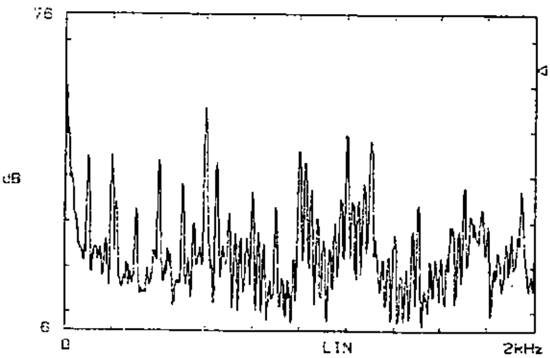

| | | |
|---|---|---|
| 1 | 25.0Hz | 84.8dB |
| 2 | 100.0 | 95.8 |
| 3 | 200.0 | 91.3 |
| 4 | 300.0 | 76.5 |
| 5 | 405.0 | 66.9 |
| 6 | 505.0 | 88.6 |
| 7 | 605.0 | 82.2 |
| 8 | 705.0 | 78.3 |
| 9 | 800.0 | 75.7 |
| 10 | 900.0 | 77.9 |
| 11 | 1000.0 | 77.7 |
| 12 | 1110.0 | 91.6 |
| 13 | 1210.0 | 73.0 |
| 14 | 1520.0 | 68.3 |
| 15 | 1715.0 | 72.8 |
| 16 | 1920.0 | 63.5 |
| 17 | | |
| 18 | | |
| 19 | | |
| 20 | | |

(a) Fan Motor Vibration : Full Load




| | | |
|---|---|---|
| 1 | 25.0Hz | 64.3dB |
| 2 | 100.0 | 122.8 |
| 3 | 125.0 | 76.9 |
| 4 | 200.0 | 104.8 |
| 5 | 300.0 | 93.7 |
| 6 | 400.0 | 96.2 |
| 7 | 500.0 | 90.6 |
| 8 | 545.0 | 85.2 |
| 9 | 600.0 | 87.0 |
| 10 | 645.0 | 92.0 |
| 11 | 745.0 | 83.3 |
| 12 | 900.0 | 79.8 |
| 13 | 1000.0 | 95.6 |
| 14 | 1100.0 | 84.3 |
| 15 | 1200.0 | 87.8 |
| 16 | 1300.0 | 86.2 |
| 17 | 1400.0 | 76.8 |
| 18 | 1500.0 | 85.9 |
| 19 | 1600.0 | 87.0 |
| 20 | | |

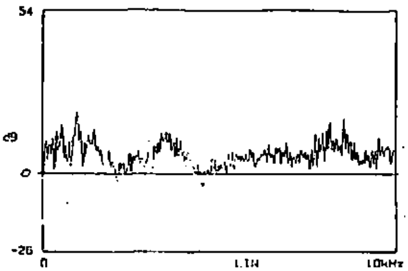
(b) Motor-only Vibration : No Load




| | | |
|---|---|---|
| 1 | 100.0Hz | 44.5dB |
| 2 | 200.0 | 44.7 |
| 3 | 300.0 | 32.8 |
| 4 | 400.0 | 43.7 |
| 5 | 500.0 | 38.4 |
| 6 | 600.0 | 55.4 |
| 7 | 650.0 | 43.1 |
| 8 | 700.0 | 32.2 |
| 9 | 800.0 | 36.7 |
| 10 | 900.0 | 33.4 |
| 11 | 1000.0 | 45.9 |
| 12 | 1025.0 | 43.3 |
| 13 | 1050.0 | 37.3 |
| 14 | 1200.0 | 49.5 |
| 15 | 1300.0 | 48.2 |
| 16 | 1505.0 | 34.1 |
| 17 | 1705.0 | 37.8 |
| 18 | 1945.0 | 36.9 |
| 19 | | |
| 20 | | |

(c) Motor-only Noise - No Load

Fig 1. SINGLE PHASE FAN AND MOTOR SPECTRA




| | PWR SPECTRUM | ChA |
|---|---|---|
| 1 | 100Hz | 10.9dBEU |
| 2 | 425 | 14.3 |
| 3 | 575 | 16.3 |
| 4 | 1025 | 20.4 |
| 5 | 1525 | 14.9 |
| 6 | 3550 | 13.7 |
| 7 | 3650 | 13.4 |
| 8 | 4600 | -4.0 |
| [illegible] | 7725 | 13.0 |
| [illegible] | [illegible] | [illegible] |
| 11 | [illegible] | [illegible] |

Fig 2. CHANGE IN FAN MOTOR VIBRATION DUE TO NON-SINUSOIDAL VOLTAGE WAVEFORM

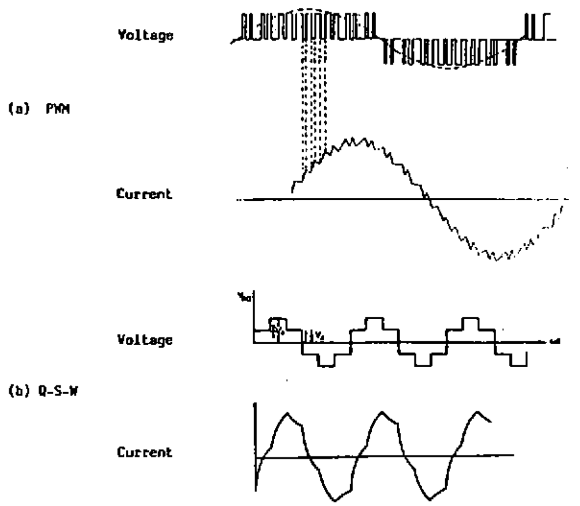



Fig 3. TYPICAL INVERTER WAVEFORMS

(a) PWM Inverter
2.2kHz Switching Frequency

(b) PWM Inverter
11.7kHz Switching Frequency

(c) Q-S-W Inverter

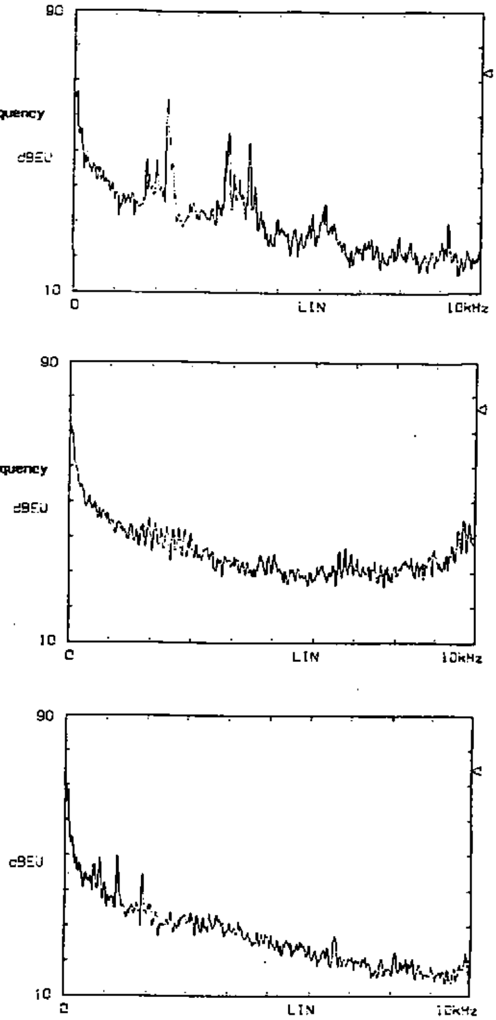



Fig 4. NOISE SPECTRA FOR 2.5kW AXIAL FAN WITH INVERTER SPEED CONTROL : 25Hz

(a) 450mm Centrifugal Fan :
Q-S-W Inverter

(b) 450mm Centrifugal Fan :
PWM Inverter, 6.6kHz
Switching Frequency

(c) 30" Axial Fan : PWM
Inverter, 6.6kHz
Switching Frequency

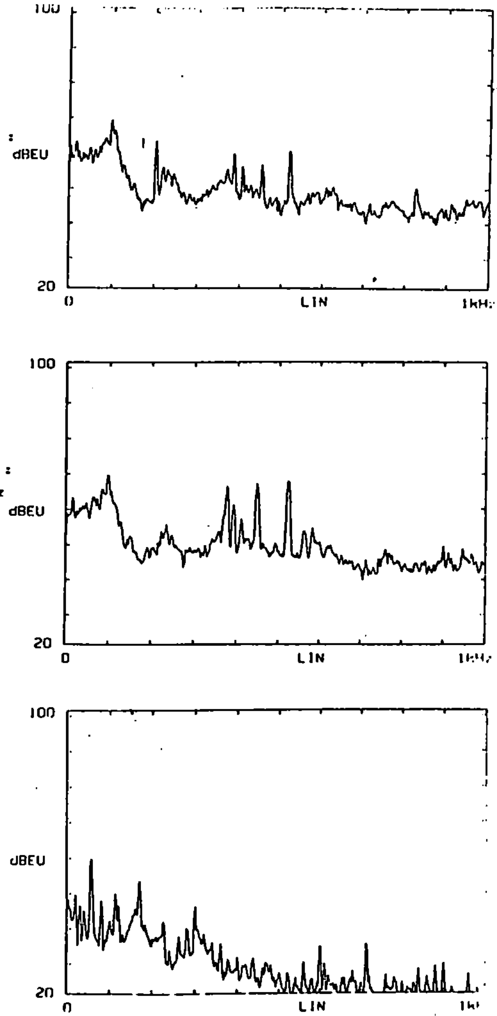



Fig 5. LOW FREQUENCY NOISE SPECTRA WITH INVERTER SPEED CONTROL