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The Study of DC Motor Noise and Vibration

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ABSTRACT

The noise and vibration characteristics of permanent magnet direct current motors along with the associated primary sources of noise, vibration and transmission paths are presented in this paper. Included are various methods and techniques to reduce or attenuate the levels of noise and vibration which emanate from the motor. The sources of noise and vibration are the results of the interactions from the brush and commutator, the gear and worm meshing characteristics, and the armature shaft and bearing system. The noise and vibration emanating from the motor sources are transmitted to the motor housing, supporting mounting structures, and subsequently radiated into the environment. The various methods found to significantly reduce the levels of motor noise and vibrations from their sources are discussed in detail.

INTRODUCTION

Permanent Magnet Direct Current (PMDC) motors are widely used in automobiles for such applications as window lifts, seat actuators, antenna lifts, windshield wipers and sun roofs, etc. Their noise and vibration levels contribute to the overall noise and vibration experienced in the passenger compartment of today's automobiles. An in-depth understanding of the noise and vibration sources within the motor is essential to effectively explore methods to reduce the levels of motor noise and vibration. The simplest methods to reduce the motor noise and vibrations are to reduce the excitation force, to block the transmitting paths, and to eliminate the amplification factors. The noise and vibration of the structure (system) to which the motor is assembled, are related to the characteristics of the individual structure and motor. In this presentation, the discussion is limited to the noise and vibration characteristics of the motor only and does not consider the influences of the supporting structures to which the motor is mounted.

All the vibration (linear motion) measurements used to accumulate the data presented in this paper were taken with mini accelerometers (B&K and PCB) attached to the measured structures with wax. An amplifier (or conditioner) was used to condition the vibration signals for the analyses performed. The noise measurements were made in a semi anechoic chamber, in the far field, using a single microphone. A sound level meter (Larson & Davis) was used to condition the noise signals for analysis. A dual channel analyzer (HP) or DAT recorder (SONY) with a PC was used for the data acquisition and signal processing.

NOISE SOURCES AND PATHS

PMDC motors typically consist of a stationary steel housing in which the magnetic material is permanently fixed and a rotational armature with coils embedded in parallel slots. The armature is supported by bearings located in the housings while the brushes are constrained in a brush holder which is attached one of the housings. The brushes are used as means of carrying the current from the external to the internal circuit via the commutator which is fixed to the armature. Torque is produced as a result of the current carrying conductors in the magnetic field, leading to the continuous rotation [1]. In applications such as in widow lifts, a worm and gear reduction is incorporated to increase the output torque and reduce the output speed.

The major sources of noise and vibration emanating from the motor are due to the interaction between the brushes and the commutator, the gear meshing characteristics, and the interaction of the bearing system and the armature shaft. The driving force of the motor is the electromagnetic force (torque) acting on the armature which fluctuates at the commutation frequency (numbers of bars on the commutator times shaft rotational frequency). The radial component of the electromagnetic force acts on both the armature and the motor housing as long as the armature is not located in the center of the magnetic field. This radial component is evident at the armature rotational and commutation frequencies (for two pole motors). A radial force exists due to the armature unbalance. The impact force exists between the brush and commutator, fluctuating at the commutation frequency. A frictional force acts between the brush and commutator, fluctuating at the shaft rotational and commutation frequencies. The gear meshing force is acting on both the gear and worm at the gear meshing frequency (numbers of teeth times gear rotational frequency). The other forces include the friction force between the journal bearing and shaft, the impact force between the journal bearing and shaft under excessive clearances, the force due to the bearing misalignment (if any), and the spring force pushing the brush into the commutator surface. The major excitation frequencies are the armature rotational frequency and its harmonics, the commutation frequency and its harmonics, and the gear meshing frequency and its harmonics. The fluctuating forces within the motor can induce vibrations in the associated motor components. Since many of the motors in the types of applications described earlier are sealed to prevent ingress of moisture and water, the motor noise is the result of the vibrations induced into and radiated from the motor housing. The sources of noise and vibration and the associated transmission paths are as shown in Figure 1.

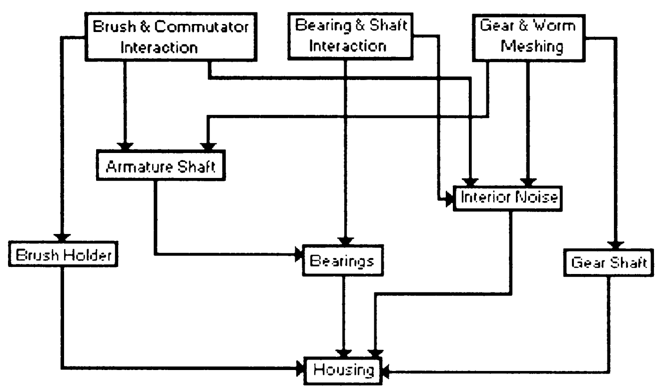

Figure 1: Motor noise and vibration sources and paths.

MOTOR SPEED AND TORQUE

From the DC motor equations for the motor speed and torque, it is known that the speed and torque of the motor are directly related to the applied voltage and the armature current [1]. Higher armature currents will result in higher output torque and lower motor speeds. The dynamic component of the current (current fluctuation) will directly relate to the dynamic components of the motor speed and torque characteristics. A typical plot of the armature current fluctuation is shown in Figure 2. Similar fluctuations can be expected for the motor speed and torque characteristics. The resulting frequencies of the current fluctuation were found to be directly related to the commutation frequency and its harmonics.

The torsional vibration of the armature shaft can influence the dynamic loading of the worm and gear and vice versa. the worm and gear meshing characteristics can influence the torsional vibrations of the armature shaft. The resulting effects of the torsional vibrations were found to influence the frictional characteristics of the commutator/ brush interface. The levels of torsional vibration(magnitude) were found to vary with the type of motor tested and its operating load point. However, the frequency of torsional vibration (velocity) was observed to be mainly at the armature rotational frequency (which is also the gear meshing frequency) as shown in Figure 3. These results indicate that the rotational speed of the armature is not being held constant. The torsional vibration at the commutation frequency (the frequency of the fluctuating electromagnetic force) was found to be not as significant as that at the rotational frequency, due to the dampening effects of the armature inertia. A non-contact, laser torsional vibration meter (B&K) was utilized to conduct the torsional vibration effects study.

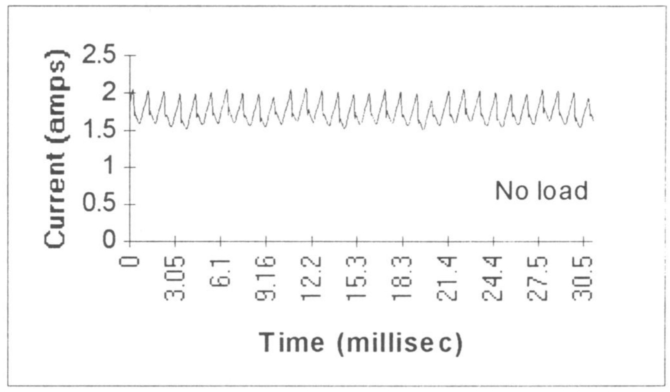

Figure 2: The measured current fluctuation

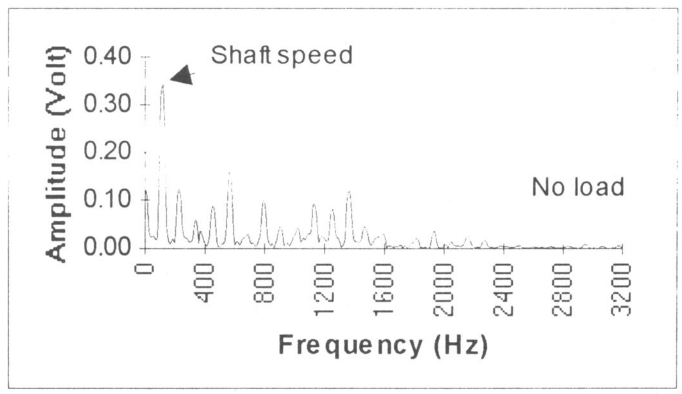

Figure 3: Spectrum of shaft torsional vibration (velocity)

BRUSHES AND COMMUTATOR

The primary sources of noise due to brush and commutator interaction are the result of brush bounce (brushes bouncing on the commutator surface), the fluctuation of friction between the brush and commutator, and the impact experienced by the brush each time it passes over a bar (slot) on the commutator. Figure 4 shows the possible vibration modes of the brush riding on the commutator. The vibration spectrum of the brush holder (Figure 5) shows that the major vibrations are at the commutation frequency and 2x & 3x commutation frequency. The high vibration peak at 3 times the commutation frequency is likely due to coincidence with the natural frequency of the brush and brush holder. Figure 5 also shows that the brush holder vibrations cover a wide range of frequencies, from the commutation frequency to about 8000 Hz. The brush noise can be readily measured when the subject motor is driven by another quiet motor through a flexible cable or belt and pulley system. The driving system should have a noise spectrum with major peaks outside the frequency range of interest and should be about 10 dB lower when compared with the combined noise in the frequency range of interest. The driven motor noise with and without the brush is shown in Figure 6. It further indicates that the brush noise is at a relatively high frequency range.

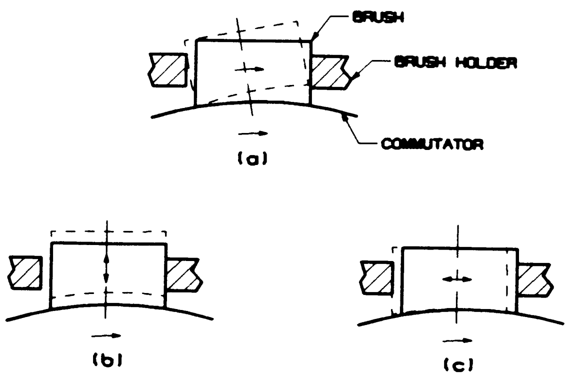

Figure 4: Vibration modes of the brush

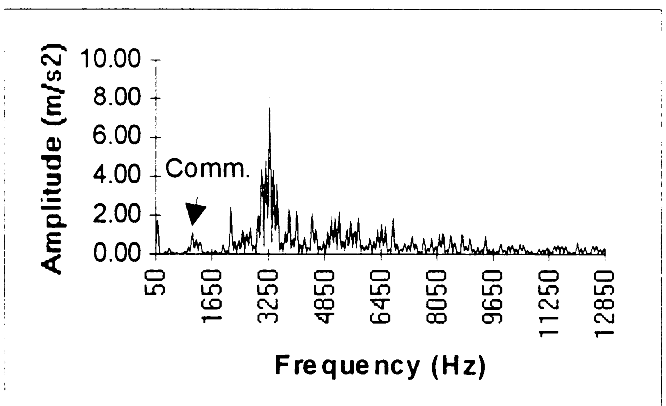

Figure 5: Spectrum of brush holder vibration (acceleration)

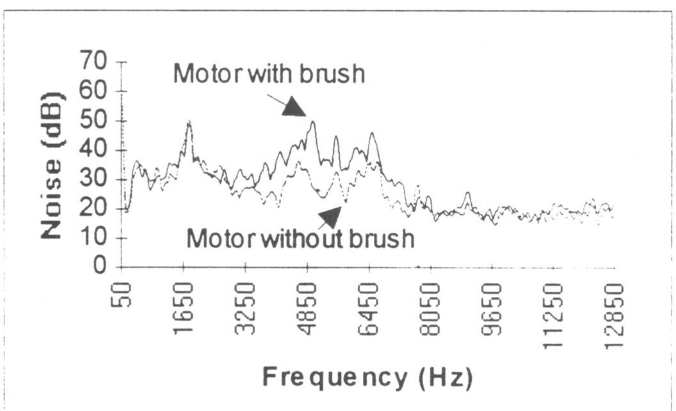

Figure 6: Motor noise with and without brush

The roundness of the commutator is a very important parameter that influences the brush noise and vibration. The profile waviness on the commutator, especially from bar to bar, is responsible for the brush bounce. The impact can occur between the brush and commutator each time the brush crosses the slot between the bars. Figure 7 shows the profiles of two commutators with different roundness measurements. A 4-5 dB difference, in overall motor noise level, was obtained between the two commutators. A finer commutator roundness (or less bar to bar profile variation) can reduce the brush noise and the overall motor noise. The roundness of the commutator is often related to the roundness of the armature shaft at the bearing journals. This is because the armature shaft is supported at both journals when the commutator is machined. The finer roundness at the armature shaft journals not only improves the roundness of the commutator but also reduces the bearing noise, especially in rolling element bearings.

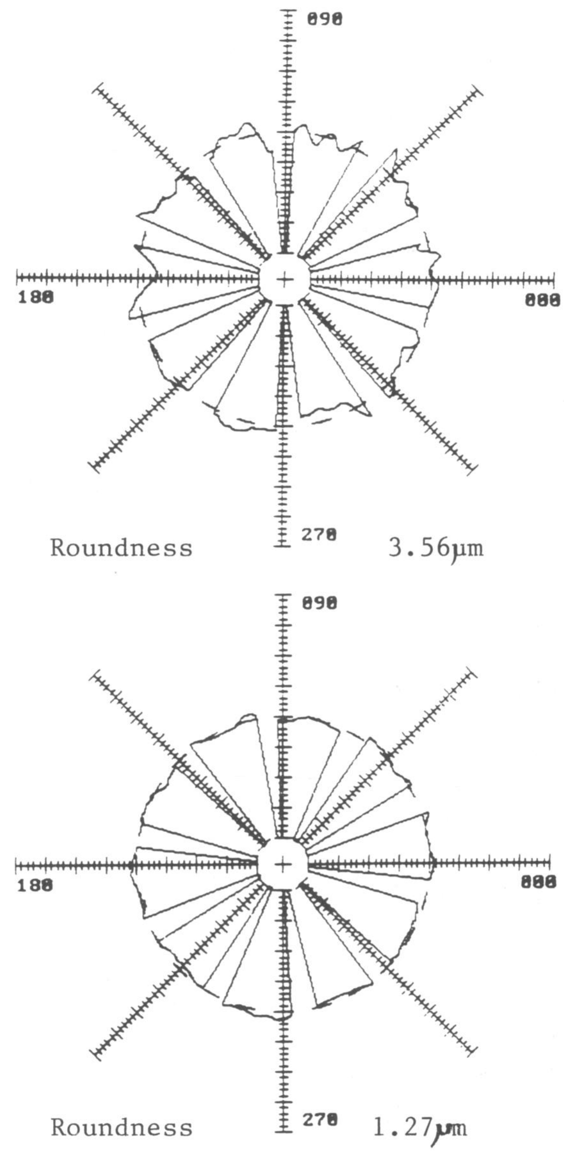

Figure 7: The profiles of two commutators

Brush noise is also related to the armature rotational speed. The armature rotational speed can be adjusted by changing the applied voltage. The higher rotational speeds of the shaft result in higher brush noise as shown in Figure 8. The higher impact forces between the slots or high spots on the commutator and the brush are the main reasons for the increase in noise. To obtain this data the armature of the measured motor was coupled to a loading device via a flexible coupling and measured. Increases in the load (torque) of the armature did not seem to influence the brush noise as dramatically as the rotational speed.

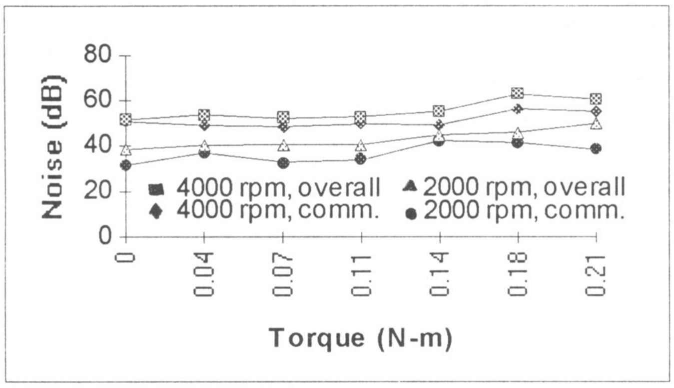

Figure 8: Brush noise at various speed and load

The friction and its fluctuation can also influence the brush noise [2]. The frictional force exerted on the brush is related to the brush material, brush design, commutator surface conditions, brush spring pressure, temperature, and relative speed between the brush and commutator. Reducing the friction between the brush and commutator is preferred for high efficiency and low noise. The friction influence between the brush and the commutator on the brush noise was studied by using various metal graphite brush materials. Figure 9 shows the average noise level of 18 measurements with various brush grades of the same design (metal graphite brush) running under the same conditions. It indicates that the lower copper content (more graphite) results in lower noise levels from the motor. The lubrication effect of the graphite helps to reduce the friction between the brush and commutator [3].

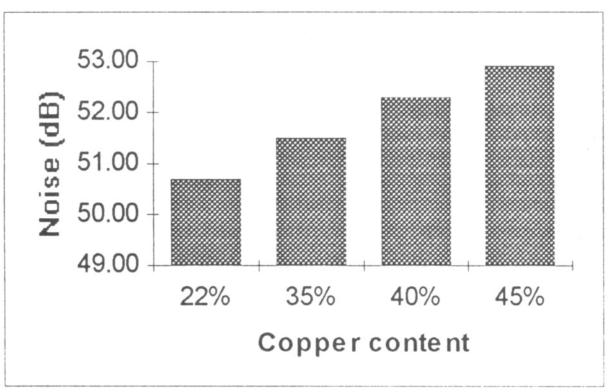

Figure 9: Motor noise with various brush materials

During the initial running of a motor, the high spots on the brush and machined commutator can lead to the vibration of the brush, brush holder, and armature. These high spots will be removed after the initial running and a larger (and more stable) contact area are obtained as the components wear. The noise and vibrations are lower and more consistent for a motor with the seated-in brush and full commutator contact area (see Figure 10).

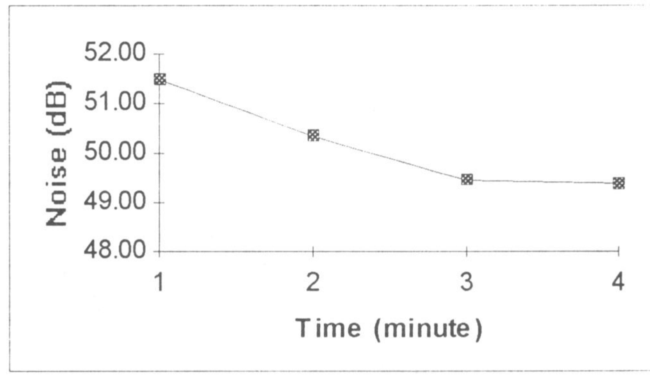

Figure 10: Motor noise during the initial running

GEAR AND WORM

Gear and worm reductions are commonly used in PMDC motors for automotive applications (such as window lift) to reduce the output speed and increase the output torque. Plastic gears are normally used in such applications due to cost , weight and noise considerations. The plastic gears are usually quieter than the steel gears due to their low contact (impact) stiffness and higher internal damping characteristics. The low bending stiffness commonly associated with plastics can result in large deformations of the gear teeth and gear body under loads. Gear manufacturing, assembly and processing tolerances (profile errors, tooth spacing errors, etc.) in conjunction with the tooth and body deformations of the plastic material can result in a significant degree of noise generation.

Figure 11 shows the noise spectrum of the motor with the plastic gear under load and without the gear (motor only) running at the same speed. Besides the noise increase at the gear meshing frequency and its harmonics, the gear noise is amplified at the commutation frequency and its harmonics. It is shown that the gear contribution to the motor noise covers a wide range of frequencies. When the harmonics of the gear meshing frequency coincides with the natural frequencies of the system, higher noise levels can be produced. To reduce this noise, it is necessary to reduce the gear tooth and body deformation, the gear and worm shaft deformation and the deviation from equispaced and perfect involute tooth profiles. Increasing the contact ratio between the gear and worm can help distribute the same load evenly to more teeth and reduce the deformation of the gear tooth and shaft as well as averaging out the individual tooth errors from the manufacturing process.

The amplitude modulation is sometimes observed in the time signal (Figure 12) and frequency spectrum of the motor noise. This amplitude modulation is the "source" of the low frequency cyclic noise often experienced. The digital signal analysis (Momentum DSP) reveals the modulation characteristics of the motor noise. It indicates the existence of the sidebands of the worm rotation frequency around the tooth meshing frequency and its harmonics, especially at the natural frequencies. Tooth spacing errors are the likely cause of such noise [4]. The deflection of the worm shaft will result in poor meshing conditions (increased center distance) between the gear and worm and can produce modulated noise.

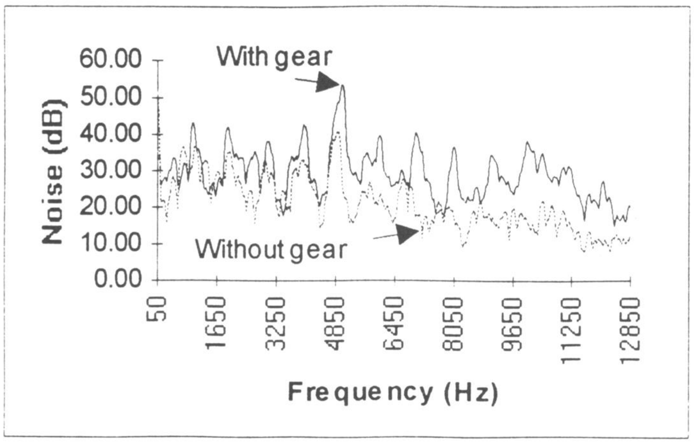

Figure 11: Motor noise with and without load (gear)

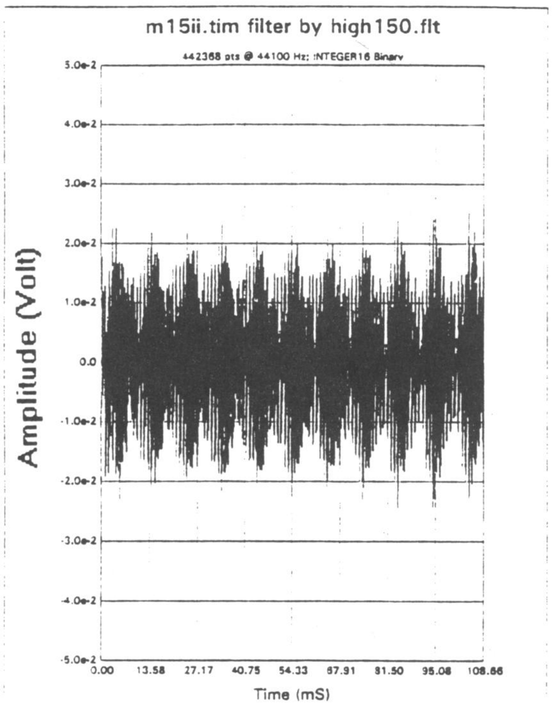

Figure 12: Motor noise with amplitude modulation

BEARINGS AND ARMATURE

The shaft and bearing interaction is one of the major sources of noise and vibration in rotating machinery. The armature shaft usually consists of the laminations, windings, commutator and worm and is supported by two bearings. Ball and journal bearings are commonly used in these applications where the armature is rotating at relatively high speeds (several thousand rpms).

The armature unbalance is one of the major sources of the motor vibrations. It can produce excessive noise and vibration when the motor is assembled on to a structure (system) with the natural frequencies near the motor rotational frequency and its harmonics. It can produce the impact (bouncing) between the shaft and bearings due to the unbalance and bearing clearances, which can be seen from the shaft vibrations measured with a proximity sensor. The impacts can create vibrations at the higher orders of the rotational frequency. Better dynamic balance (both 0 & 180 degrees on two planes) will definitely reduce the vibrations and noise.

Reducing the clearance in the bearings can reduce the impact due to the armature unbalance. However, the noise and vibration of the motor are more sensitive to the bearing misalignment. Misalignment can reduce the performance of the bearings due to the increase in friction and create excessive forces between the shaft and bearings. Figures 13 & 14 show the influence of bearing misalignment on the shaft vibration. It indicates that the vibration at the commutation frequency is amplified when the bearings are not aligned compared with that when the bearings are aligned. The bearing misalignment can result in the armature being located off the axis of the magnet housing where it should be. The magnitude of the electromagnetic force due to the off center location is increased. This misalignment actually increases the stiffness of the journal bearing due to the pre-load exerted on the armature shaft. The higher bearing stiffness makes it easier to transmit any interaction (vibration) of the brush and commutator through the bearings to the motor housing. A reduction in the rotational speed is experienced due to the frictional forces and the noise increases due to the misalignment at higher frequencies, especially at the commutation frequency and its harmonics. Self-aligning bearings are recommended to reduce the possible misalignment and the noise.

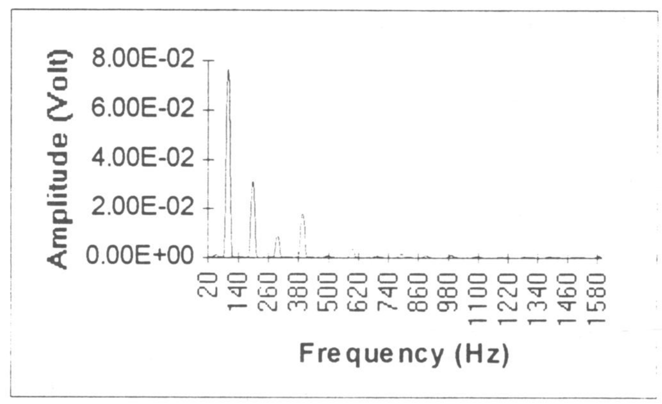

Figure 13: Spectrum of shaft vibration (displacement) without misalignment

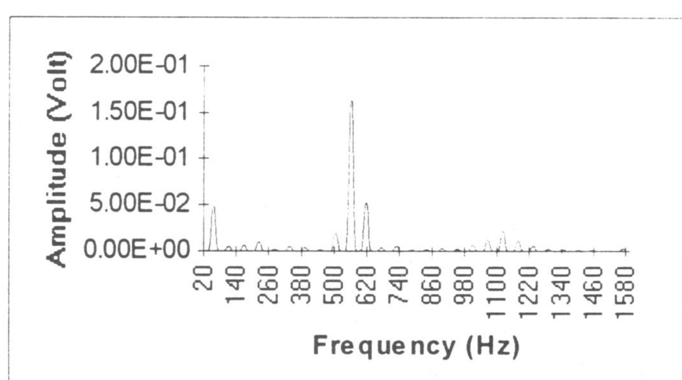

Figure 14: Spectrum of shaft vibration (displacement) with misalignment

NOISE RADIATION FROM HOUSING

Typical construction of worm and gear reduced motors for applications such as window lift have two primary housings; a motor housing and a gear housing. The motor housing is made of steel for magnetic properties and the gear housing typically made of aluminum, zinc or plastic. The dynamic coupling between these two housings is usually relatively weak. The natural frequencies of the housings and its modes can be measured using the impact method[5]. The measured frequency responses (SMS STARModal) of the motor housing and gear housing of a motor are shown in Figure 15 & 16. The typical noise spectrum of such a motor in the 1/3 octave band is shown in Figure 17. It is shown that the major peaks in the motor noise spectrum, such as at 5000 Hz, are at the natural frequencies. This is due the broad range of harmonics of the motor excitation frequencies. Since the motor, for applications such as window lifts, is sealed, the resulting noise is transmitted out of the motor through the housings. The housings will vibrate at the frequencies of the excitation with the amplitude related to the excitations. However, the vibration amplitudes of the housings will be amplified at their natural frequencies if they are the same as the excitation frequencies. The natural frequencies and their mode shape can be found to correlate with the major peaks in the motor noise spectrum. Structural modifications of the housing can be made to change the natural frequencies and to reduce the radiation efficiency (noise) of the housings.

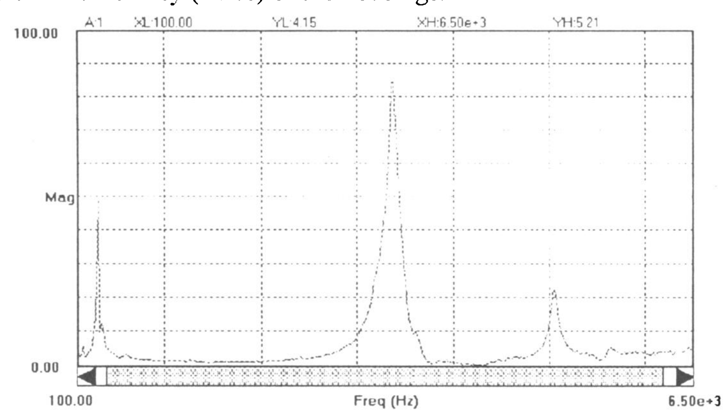

Figure 15: Frequency response (motor housing)

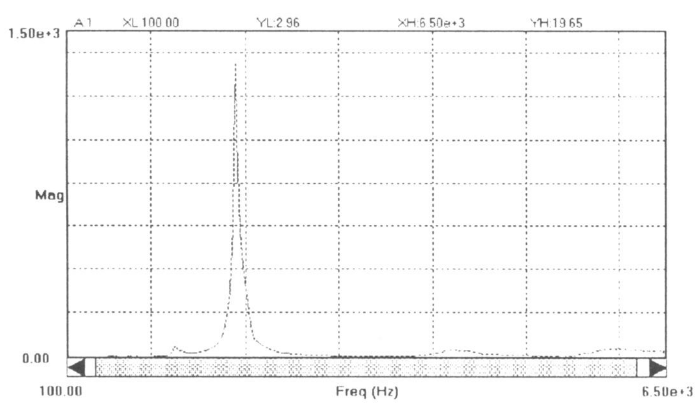

Figure 16: Frequency response (gear housing)

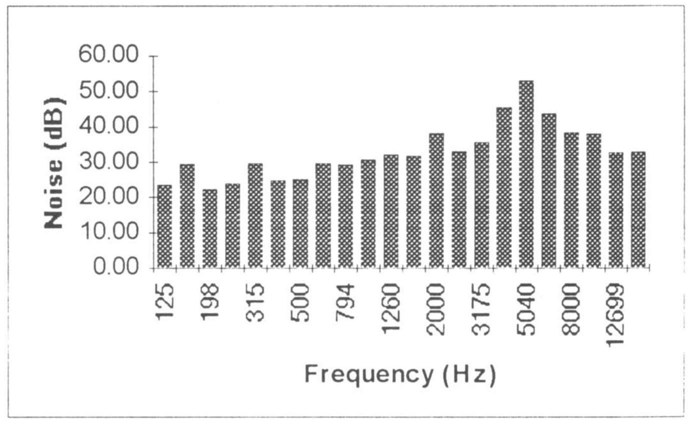

Figure 17: Motor noise spectrum (1/3 Octave)

The acoustic intensity of a motor can be measured using an acoustic intensity probe (Larson & Davis). It is calculated from the measured cross power spectrum of two microphones in the one-third octave bands (SMS, STARAcoustics). The intensity vector (amplitude) at each measurement point of the motor housing is shown in Figure 18 at 5000 Hz (natural frequency of motor housing). It is seen clearly that the noise at 5000Hz is mainly from the motor housing. However, significant noise is also observed coming from the gear housing at a frequency of 1800 Hz (natural frequency of gear housing) as shown in Figure 19.

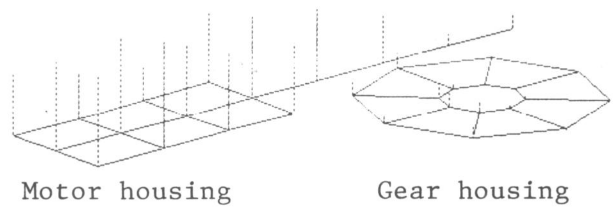

Figure 18: Acoustic intensity vector (5000 Hz)

Damping materials and ribs were added in the motor housing based on the study of the modal analysis and acoustic intensity. The effect of the damping treatment is to reduce the housing vibrations at the major peaks (natural frequencies), especially at relatively high frequencies. The ribs shift the natural frequencies from the major excitations and reduce the amplitudes of the noise and vibrations. Figure 20 shows the results of such modifications.

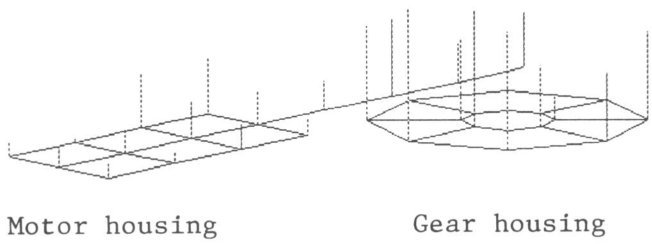

Figure 19: Acoustic intensity vector (1800 Hz)

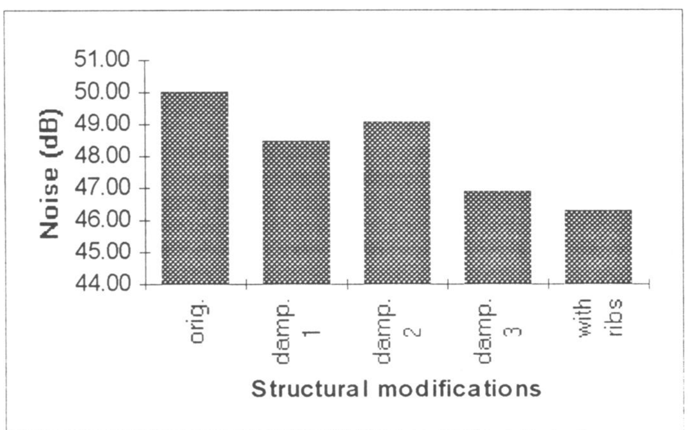

Figure 20: Motor noise with added damping and ribs

SUMMARY

There are several sources of motor noise and vibrations which result in radiating noise from the motor housings. They are the result of interactions: between the brush and commutator, the gear and worm meshing characteristics and the armature shaft and bearing system. The frequency characteristics of motor noise and vibrations are mainly associated with the commutation frequency and its harmonics, the gear and worm meshing frequency and its harmonics, and the armature rotational frequency and its harmonics. The motor noise and vibrations are amplified at the system natural frequencies if the above excitation frequencies coincide with the natural frequencies.

In order to effectively reduce the noise and vibration from PMDC motors, of the types described, particular attention must be paid to the following parameters: The commutator roundness (or bar to bar variation) should be as small as possible, the brush material should be such that it exerts less friction on the commutator, the worm and gear deformations (tooth, body, and shaft) should be held to a minimum and the higher contact ratios are preferred. The unbalance of the armature should be minimized and the clearances in the bearings should be kept as small as possible with tradeoff considerations given to the total effects of misalignment. And lastly, the motor housings should have natural frequencies away from the major excitation frequencies.

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