Invited Paper

Research on Acoustic Noise in Hard Disk Drive Spindle Motors at Chulalongkorn University

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Abstract

This paper aims to give an overview of the on-going research on acoustic noise in fluid dynamic bearing spindle motors in hard disk drives at the mechanical engineering department, Chulalongkorn University. The main objective of this research is to seek ways to reduce the level of the spinning motor's emitted acoustic noise. Vibro-acoustic investigations on the source of noise and vibration to noise transmission were carried out. The primary source of noise and the range of frequencies that deemed important to the noise problem for the hard disk drive spindle motor are identified. The influence of supply waveform from the driver is then studied. It is found that the noise can be reduced through reducing the electromagnetic source especially from imperfect supply waveform. In addition, it is known that the motor structure and its resonances affect the acoustic noise level as the path for vibration transmission. Hence, the structural resonances of the motor and vibro-acoustic modes are experimentally investigated. If the harmonics composition in the electromagnetic excitation is close to the structural resonance frequency, it will result in the amplified vibration and hence the high level of sound at that frequency. Reduction of noise can also be done by shifting the resonances or the excitation frequency and reducing vibration transmitted to the motor surface.

Introduction

A hard disk drive (HDD) is found in many electronic equipments including a personal computer (PC), a small form-factor PC, and a consumer electronics system such as a video media player, an electronic jukebox, a game console, etc. These devices are often used in a quiet environment, such as in a bedroom, a meeting room, etc., where the operating acoustic noise must be low. Hence, with this stringent requirement, HDD manufacturers need to offer low noise HDDs to the market. One of the primary sources of vibration and acoustic noise emitted from a HDD is the spindle motor.

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In an operation of a conventional motor, the sources of vibration and noise are electromagnetic, mechanical, and aerodynamic (Berane and Ver, 1992). The electromagnetic sources are the unbalance forces or torques caused by the electric supply or the design of motor's permanent magnet and stator coil. The motor inverter or so-called the driver provides an electric supply for the operation of a motor. The supplied current is oftentimes rich in harmonics resulting in irregularities in the electromagnetic forces exerting on the rotor and the stator. The other source of the electromagnetic noise is the design of the rotor's permanent magnet and stator coil, which are the causes of unbalance forces and torques such as the unbalanced magnetic pull (UMP) and the cogging torque. The unbalanced magnetic pull is the resultant force that is caused by the unbalanced magnetic field in the air gap of the motor. The unbalanced field is originated from, for example, the eccentricity of the rotor center to the stator center, the unbalance of the permanent magnets, and unbalanced armature current distribution due to the unbalanced armature windings. The UMP is generally present in the case of nonsymmetric pole/slot motors. Hence, this force can be avoided by selection of a symmetric pole/slot ratio (Jang et al.1996; Hartman and Lorimer, 2001). The cogging torque is generated due to the permanent magnet and the geometry of the tooth - even perfectly made - and is independent of the supplied current. It has the tendency to move the rotor to the equilibrium position whose number is twice the least common multiple of number of pole and number of teeth (Jang et al.1996). Cogging torque can be controlled by manipulating stator geometry and permanent magnet magnetization patterns. For instant, cogging torque can be greatly reduced by skewing the magnets relative to the stator slotting.

The mechanical sources are mostly the unbalance forces due to defects in manufacturing process and assembly defects including stators or rotor that are not perfectly round or symmetric, permanent rings and magnet back-irons that are not perfectly cylindrical, rotor eccentricity, defects in bearing, etc. In addition to noises from the electromagnetic, and the mechanical origins, a motor emits acoustic noise that caused by the flow of air inside and outside of the motor called aerodynamic noise. Aerodynamic noise could be discrete noise peaks due to rotating components such as fan blades or broad-band unpitched noise due to random pressure disturbances in a flowing fluid stream (Yang,1981).

The above mentioned unbalance forces from the electromagnetic and mechanical sources induce mechanical vibrations of motor parts, which possess their own vibrational characteristics such as the structural resonances. The vibrational energy of the motor parts is then transmitted to the motor surface and that within the audible frequency range is converted into acoustic noise. The path of acoustic noise generation in a motor is shown in Fig.1 as a flowchart starting from the driver to the emitting acoustic noise. In the case of HDD spindle motors, all of the noises from three sources are then transmitted through disk housing, base casting and top cover and then radiated from the HDD case. Note that the acoustic noise in the figure concerns only noise generated from the motor. The disk vibration and fluttering leading primarily to the aerodynamic noise are thus excluded.

The motor structure is considered as the path for transmission of the audio-frequency vibration that subsequently results in sound radiation. Therefore, the inherent vibration characteristics of the motor structure must be considered. The resonance

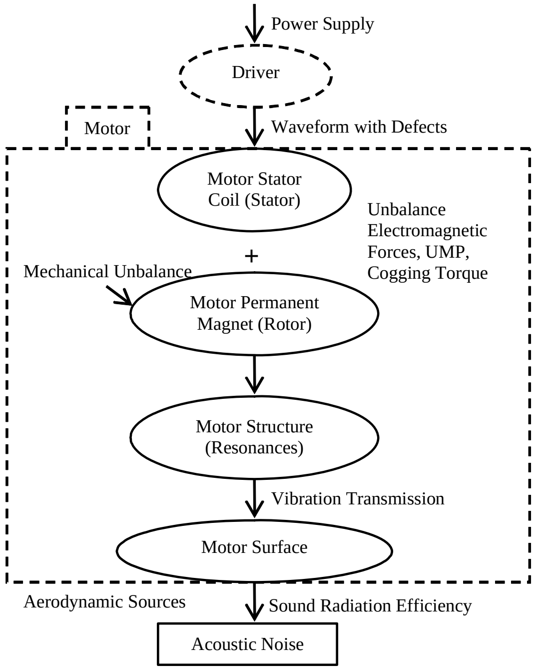

Figure 1. Path of acoustic noise generation

frequencies of the whole motor structure as well as its components can be identified by the modal testing. The modal testing is done by exciting the motor structure with either a mechanical or an electrical excitation. Mechanical excitation is the excitation that is applied to the motor by an impact force or by other types of external forces exerted by an actuator such as a shaker. For an impact testing, the excitation is applied to the structure using a hammer or other types of impacting device such as an electric gun or a suspended mass. The impact hammer, the most commonly used device, is employed in our modal testing. Electrical excitation is the excitation that is applied to the motor by feeding the motor stator coil with an electrical supply to create a magnetic force on the motor rotor and stator. These forces excite the motor structure resulting in deformation and vibration of the structure. The structural vibration is then measured with vibration sensors such as accelerometers or laser vibrometer sensors at the motor structure at certain important positions. The measured acceleration or velocity is recorded in the timedomain and the graphs of the magnitude and phase of the ratio of the force excitation (input) to the vibration response (output) versus frequency are then obtained in the frequency domain. These graphs are called frequency response function (FRF). The resonance frequencies can be determined from the FRF as the peaks with 90 degrees lag/lead between the excitation and the response. A motor may experience a resonant vibration if the exciting force frequency is near one of its resonance frequencies (Yang, 1981; Cameron et al.2001).

With its small size, high spinning rate, and usage of a fluid dynamic bearing (FDB), compared to a conventional motor; in order to achieve the goal of reduction of acoustic noise in FBD spindle motors, vibration and noise of a HDD spindle motor must be investigated in particular. Recently, HDD industry increasingly use the FDB in place of the metal ball bearing because of its improved vibration and acoustic performances as well as high shock resistance and durability (Bi,2003). Along with precise manufacturing and assembly of the motor parts, the mechanical source is less dominant. The spindle motor is quite small in size and has a simple physical shape without a fan or any major air flow obstruction. The aerodynamic noise is low due to minimal air flow (Jang et al.1996). As a result of many reasons mentioned, it is believed that the effects of the electromagnetic source on the acoustic noise of the HDD spindle motor are more obvious than the other two sources (Bi,2003).

It is known that not only by reducing the noise source but cutting off the transmission of noise generation the noise level can be decreased. In this paper, in the first section the primary source of noise is identified to confirm that the electromagnetic noise contributes the most to the overall noise level. The frequency range considered important is determined. The influence of the supplied waveform from the driver on the electromagnetic noise is investigated in following section. The vibro-acoustic behavior of the motor is then pursued in the last section.

Identification of primary noise source

The electromagnetic, mechanical, and aerodynamic noise sources contribute to the generation of vibration and noise at different levels and frequencies in the sound spectrum. The primary noise source of a spinning FDB spindle motor is, hence, needed to identify by investigating the relative contribution of the electromagnetic noise and the noise of each frequency range to the overall noise level. To identify the primary noise source, experiments were done by performing the sound pressure measurements in the anechoic room in two distinct cases. In the first case, the measurements were done when the motor was running at its normal speed of 7200 rpm. As a result, the obtained sound spectrum was originated from all of the three noise sources: electromagnetic, mechanical, and aerodynamic sources. In the second case, the motor was first running at the normal speed, and then the sound pressure measurements were done at the moment immediately after the power supply to the motor was disconnected while the running speed is still close to the rated 7200 rpm. Thus, in this situation, the noise was mostly caused by mechanical excitation and aerodynamic source whereas the electromagnetic noise was minimal.

From the test results of the two cases where the major difference is the degree of electromagnetic excitation, the relative influence of the electromagnetic noise source compared to the other sources can be identified. First, the overall level of the measured sound pressure is much higher in the first case, 25 dBA compared to 8.3 dBA in the second case. Furthermore, it can be observed that most of the densely populated discrete peaks found in case 1 disappear in case 2 along with the supplied power from the driver. Therefore, these discrete peaks are attributed to electromagnetic excitation. Hence, among the three noise sources, in FDB spindle motor, the electromagnetic noise source is the primary source of noise. In addition, the reduction of noise from mechanical origins via improvement of the manufacturing and assembly processes usually comes at higher cost. Hence, it can be said that focusing on the electromagnetic source is the most promising path to noise reduction.

Another question worth exploring is the relative contribution of noise in each frequency range toward the overall sound level. Since the previous measurements cover the entire audible range of 20 Hz to 20 kHz, the data are then separately identified by low (0 - 6.7 kHz), medium (6.7 - 13.3 kHz), and high (13.3 - 20 kHz) frequency range. The contribution of sound pressure in each frequency range is determined from the sound spectra and shown in Table I in percentage of the overall sound level. It can be observed that the high frequency range is important as it gives the most contribution to the acoustic noise of the motor among the other audible range of frequency. This agrees with the occurrence of densely populated high peaks at frequencies above 13 kHz in the sound spectra.

Influence of supply waveform on electromagnetic noise

It is found in the previous section that electromagnetic excitation is the primary source of noise in a HDD spindle motor. The electromagnetic excitation could be a result of the design of permanent magnet and stator coil in the motor machine and the imperfect supply waveform from a typical commercial driver. The logical next step is to identify the dominant source of noise between the two sources. It is well known that the electromagnetic noise from the imperfect waveform from the commercial drive can be almost entirely eliminated by the use of symmetric sinusoidal drive current. To clarify this issue and determine the degree to which the imperfect waveform affects the noise level in the current situation, a benchmark driver is developed. For the acoustic tests, the sound spectra of the motor driven by a typical commercial driver are compared to that of the motor driven by the perfect sinusoidal waveform from the benchmark driver.

Table1. Contribution of the noise from each frequency range to the overall noise

Frequency Range	Percentage
0-6.66 kHz	8.4 %
6.67-13.3 kHz	25.0 %
13.4-20.0 kHz	66.6 %

Considering the sound spectra of the two cases, it is found that sound power level from the motor driven by the benchmark drive is significantly lower than the sound power level of the motor driven by the commercial drive. For this particular case, the noise levels are 18.0 dBA and 37.6 dBA respectively. Moreover, when observe more closely into the sound spectra, the drastic improvement in the noise level from the use of the benchmark drive comes as the mountain peaks that appeared in the high frequency range for the motor with original driver was removed once the perfect sinusoidal waveform is used. The number of discrete peaks of the test with the benchmark drive was also considerably less than that of using the original drive. Hence, this investigation leads our focus to reducing the electromagnetic noise source by getting rid of the source that generated from the irregular waveform of the driver as much as possible.

Vibro-acoustic Behavior

Another way to reduce the acoustic noise is by decreasing the transmission of audio-frequency vibration into noise radiation. The motor structure is considered a path for transmission of the vibration and subsequently results in noise. Hence, the inherent vibration characteristics of the motor structure must be investigated. A modal testing was performed to identify the resonance frequencies of the whole spindle motor as well as its components including the base plate, stator, rotor, etc.

For the present study, the electrical excitation was the method of choice for its superior consistency over the mechanical excitation. One of the main reasons against the use of mechanical excitation is the small size of the spindle motor. The mechanical excitation is usually done by hand. This makes it very difficult for the quality of excitation in terms of the impact angle between the hammer head and the motor structure, impact duration or impact positions to be consistent from one test to the other. Alternatively, the present modal testing on the spindle motor was performed using an electrical excitation. A digital signal analyzer works as a function generator with an external amplified to feed a sinusoidal wave to one phase of the motor. The other two phases are left unexcited, thus the rotor does not spin. The waveform used in the test was the sine-swept function, which is the sinusoidal waveform whose frequency and/or amplitude are continuously varied over time. With a sine-swept waveform, the motor was excited only one frequency at a time and its frequency was continuously increased from 0.1 to 20 kHz, while the amplitude was kept below a certain value to avoid the magnetic saturation of the stator coil.

Comparing the FRFs obtained from electrical excitation to those from mechanical excitation, it is found that the electrical excitation approach provides clear and accurate FRFs especially at high frequency compared to the mechanical excitation approach. Another reason behind this besides the better consistency of results is thought to be the way the electrical excitation apparently simulates the magnetic force excitation that actually occurs inside the motor in operation.

The vibro-acoustic modes can be found by comparing the FRFs and the sound power spectra of a spinning motor. At each resonance mode when the frequency of electromagnetic excitation meets the resonance frequency of the motor structure, the vibrational energy will be transported most effectively to air media through the vibration wave at the base and the hub of the motor. This results in the amplified sound wave in the air. The summary of the vibro-acoustic modes observed from the modal testing along with their distinct characteristics for different frequency range are listed in Table II. In conclusion, by avoiding the coincidence of the resonance frequency of the motor structure and force excitation frequency, the noise can be significantly reduced due to the diminished vibration-to-noise transmission at that frequency range.

Table 2. Summary of vibro-acoustic characteristics

Frequency Range	Remark on Vibro-Acoustic Mode
0-6.67 kHz	- Single-peak modes - Values of natural frequencies depends on the boundary conditions of the motor
6.67-13.3 kHz	- Several undistinguished modes - More difficult to identify from mechanical excitation
13.4-20.0 kHz	- Greatest contribution of acoustic noise in this frequency range - Up to five modes observed in this range - Due to high modal density, some modes are close to each others and cannot be distinguished.

Concluding remarks

This paper describes an on-going research to understand the vibro-acoustic phenomena of the FDB spindle motors leading to the ways to reduce their vibro-acoustic noise. From the study, the research directions for noise reduction in FDB spindle motor are clearly identified. It was revealed that in the operation of FDB spindle motors, the acoustic noise originated from electromagnetic excitation plays a significant role to the overall noise level. The electromagnetic excitation is mostly attributed to the imperfect supply waveform of the driver than to the stator and rotor design of the motor. The benchmark driver generating the perfect sinusoidal waveform was developed and the evaluation tests using the benchmark driver show that the sound pressure level of the motor when driven by the benchmark driver is significantly lower than that of driven by the original driver. A closer look into the sound spectra also reveals that the characteristic of the sound spectra of the motor is drastically improved once the bench-mark driver is used. By eliminating the irregularity in the supply waveform, the acoustic noise can be significantly reduced.

The modal testing using an electrical excitation to determine the frequency response function (FRF) of the motor structure is preferred to the mechanical excitation. The electrical excitation not only yield better consistency on the test data for such a small size of the spindle motor but also better simulates the actual electromagnetic forces in the operating motors. A further comparison of the FRFs obtained from the electrically-excited modal testing and the sound power spectrum indicates that the resonance frequencies of all vibro-acoustic modes that found in the FRFs closely match with the sound resonance frequencies. The motor structure and its resonances affect the acoustic noise level as the path for vibration transmission. It is clearly seen that if the harmonics composition in the electromagnetic excitation is close to the structural resonance frequency, it will result in the amplified vibration and hence the high level of sound at that frequency. The acoustic tones from the motors at discrete frequencies can be reduced by avoiding the coincidence of the electromagnetic excitation and the structural resonance. Further study in terms of the vibration transmission through the motor structure could lead to another approach of noise reduction. With all of the above and upcoming investigations, it is believed that a methodology for reducing vibro-acoustics in FDB motors can be achieved.

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