Preface

It is hard for us to imagine today's world without electric motors. And their use keeps expanding into ever new areas of our lives. At the same time, we are becoming increasingly demanding when it comes to the acoustic quality of these motors. Manufacturers of motors and other equipment increasingly need to have broad competence in dealing with noise. In fact, success in the competitive marketplace is coming to depend on having such acoustic know-how.

Unfortunately, manufacturers often have a hard time finding solutions to their noise problems. It is often extremely difficult even to describe a problem in a qualified manner. Frequently, this is not even attempted. Instead, people come up with vague statements like "We have a noise problem!" Many times engineers and technical people who are not experts in acoustics are assigned the task of solving this noise problem. This book is intended to help them arrive at an efficient and effective procedure for eliminating irritating vibration and acoustic problems with small electric motors. It is based on real-world industrial experience and is not intended to be an academic text, but rather a practical manual.

Until now there has not been any literature on possible approaches to the analysis and elimination of vibrations and noises in small motors. The purpose of this book, therefore, is to provide users and manufacturers of small electric motors with the basic understanding needed for dealing with noise. In the first chapter we introduce the vibration and noise behavior of small electric motors and present key terms and the relationships between these terms. We then describe various options for reducing noise. Finally, we address the key principles of mechanical vibrations and acoustics needed to achieve success. The remaining chapters deal in detail with measuring vibrations and noises, with the analysis of these measurements, and with the problems associated with noise testing in large-scale manufacturing.

The principal methods are illustrated, together with their advantages and disadvantages. The book concludes with a series of examples from actual industrial practice.

Contents

1 Introduction to the topic

When motors of all types and sizes are evaluated, the main concerns involve the quality of the desired functions, service life, and purchase and operating costs. Side effects such as heating, vibrations and noise are generally undesirable, and they play a very important role in the decision to use a specific motor.

Small motors are usually installed in tight spaces in equipment, so that the heat they produce can be particularly disadvantageous, even when the actual heat output is small, since the surrounding equipment itself often offers little opportunity for removing heat. Since these motors are usually located close to humans and to their ears and sense of touch, the noise and vibrations that they are permitted to generate are significantly less in relative terms than would be permitted for larger motors.

For large electrical machines and motors there are standards that must be used to measure and evaluate noise and vibrations. Considered in isolation, a small motor is barely audible because of its small dimensions. Even the vibrations it produces are generally not found to be objectionable. A small motor does not have a significant impact until it is installed in or on a piece of equipment and then evaluated subjectively, usually only in this installed environment. This subjective evaluation of the noise and vibration characteristics of the motor installed in the equipment must be quantified by means of measurement technology. From this information, specifications for the vibration and noise limits for the motor alone must be derived and agreed upon and then met when the motor is manufactured. The description and derivation of such limits can be very complex in individual cases; therefore test standards like those used for large motors do not make sense for small motors.

Above all, the small motor manufacturer wants to be successful in the marketplace. So he will work to identify the causes of objectionable vibrations and noises in his product and try to eliminate them as much as possible. In the final analysis the motor is the source of the noise, and the equipment in which it is installed is “merely the loudspeaker.” Working together with his customer, the manufacturer must also try to figure out how an anticipated or existing vibration or noise problem can be optimally solved with regard to the entire system in which the motor operates. It may often be easier and more cost-effective to overcome an undesirable vibration or noise along the path from the motor itself to our sense of hearing or touch than it would be to eliminate the problem at the source. Frequently, if certain rules are not followed, the vibrations caused by the motor along its transmission path become “the mouse that roared.” This means that the path itself must be analyzed and taken into account.

In the section below we shall first explain some important terms relating to the noises and vibrations produced by small motors. We will then describe the basic principles relating to the transmission paths. This will be followed by a look at the causes of noises and vibrations in small motors, as well as the unique characteristics of such noises and vibrations and the technical options for reducing them.

Before any measurements are made, the vibration behavior of the equipment in which a motor is installed must first be considered conceptually. Systematic measurements and testing derived from this conceptual analysis should then follow to support or reject the conceptual model; but efficiency demands that the brainwork comes first. Only if the measurements are carefully planned and systematic will their consequences be clear. Therefore, a detailed description of acoustic and vibration measurement technology, combined with suitable methods, follows. In this way, it is possible to move from subjective judgments to descriptions based on actual measurements in order to obtain limit values that can be used in the development, manufacturing, application, and quality testing of motors.

1.1 Basics of vibrations, structure-borne noise, and airborne noise

Noise and vibrations are oscillations, namely changes of states or conditions that occur with periodic regularity. We describe an oscillation by the duration of its period or **frequency** and by the maximum value of its state over time (**amplitude**). There are many kinds of oscillations. In the text below we shall only consider those whose states involve periodic movement in space (**mechanical vibrations**). Such movements can be generated by periodically changing forces, such as those encountered in a crank mechanism (**forced excitation**). But they can also be produced independently by a spontaneous exchange of energy between various energy stores, such as that which occurs with elasticities (stores for deformation energy) and inertial masses (stores for kinetic energy), if these stores can in some way be energized (for example: a swing, bell, violin string, whistle). An oscillation that is controlled by means of these energy stores is called a **natural oscillation**. Its frequency (**natural frequency**) is often determined solely by the properties of the energy stores and not by the energy that is stored in them. Because of the unavoidable **damping** that causes energy to be "lost" (for example: the energy that is consumed when materials change shape), a natural oscillation cannot be maintained indefinitely unless a source of appropriate energy is applied further to the system. In addition to the supply of energy by means of an appropriate forced excitation, a supplier of power that is constant over time can, as a result of the properties of an oscillatory system, produce self-controlled, i.e. self-generated, natural oscillations (such as friction-caused vibration, whistling noises).

In addition to its manifestation over time, a natural oscillation also always has a specific spatial distribution of its peaks and valleys (**natural waveshape**), which can only form if no disruptive forces can act upon the oscillatory system via mounting systems. A natural waveshape can simultaneously have identical motion excursions throughout the waveshape; when this occurs, it has the **mode** $r = 0$. This is the case, for example, when a ring is "breathing," i.e. when it changes its diameter in all directions in the same way over time.

If a natural waveshape is characterized by simultaneously having two points of maximum but opposite oscillation excursion amplitudes (**oscillation antinodes**) and two points at which no motion is present between them (**oscillation nodes**), it has a mode of $r = 1$. The flexural oscillation of a motor illustrates how mounting systems can hinder the formation of waveshapes: radial vibrations are hindered if not prevented at the bearing points. However, the shaft can vibrate radially. In this case at two opposite points on the circumference of the rotor the radial movement is maximal but is equal to zero at the points offset by 90°. Seen in the circumferential direction, the mode is $r = 1$. But in the axial direction, this is not the case because only a single antinode can be seen between the bearings. The bearings hinder the free formation of $r = 1$, and therefore radial alternating forces (vibratory forces) occur in the bearings. If the rotor were not hindered by the bearings, it would vibrate on both ends in the direction opposite to the vibrations in the middle of the rotor, and two nodes would form between its ends. If the bearings were placed at the nodes and the outer ends of the shaft were allowed to oscillate freely, the free rotor flexural oscillation would not be impeded. In fact, $r = 1$ also establishes itself when hindering bearings are present because the bearing system, with its elasticity and mass, simply needs to be included as part of the oscillatory system. The corresponding flexural natural frequency, of course, is different from that of the rotor without bearings.

The oval deformation of a tubular metal package is characterized by the mode $r = 2$ (two full waves along the circumference, four antinodes, four nodes, etc.). Antinodes and nodes can change location relative to time, but the deformation pattern, in other words the mode, remains intact (see also chapter 4.6, p. 50 f.).

A configuration with more than two possibilities for storing various forms of energy (such as potential and kinetic energy) is capable of having a number of different natural oscillations with various corresponding natural frequencies and waveshapes, i.e. with a number of different antinodes and nodes superimposed on each other in time and space.

In industrial applications, forced excitation and the ability to engage in natural oscillation usually occur in combination. If a forced excitation acts upon a system that is capable of natural oscillation, the system continuously oscillates at the rate of the forced excitation, but also temporarily at its own natural frequencies, provided that the forced oscillation is not applied precisely at the node of the corresponding natural waveshape. If the forced excitation frequency and the natural frequency are identical, the term **resonance** is used. In this case the corresponding waveshape movements can become very large if damping is small. If the natural frequency is less than the excitation frequency, **operation above resonance** occurs. In the reverse case **operation below resonance** occurs. Given that industrial equipment generally has a number of natural frequencies (and natural waveshapes) and given that the forced excitation can also contain a number of frequencies, operation above resonance and operation below resonance are often both done. Tuning can greatly alter the effect of forced excitations.

The point at which the forced excitation is applied or how the excitation is spatially distributed also plays an important role! If the forced excitation is only applied at a single node of a waveshape, then no resonance occurs (at least not theoretically), even if the natural frequency of this waveshape and the frequency of the forced excitation are the same. In general: **For resonance to occur, the frequencies and the modes of the waveshape and the forced excitation distribution must be the same.** If forced excitation is applied at specific points outside of the natural waveshape node, it is important to consider that such excitation at specific points is comprised of excitation components that theoretically can have an infinite number of modes, so that a resonance can result with any one of these components.

Oscillations from and in solid and liquid materials are referred to as **structure-borne noise**; in the case of liquids, they are also referred to as **fluid-borne noise**. We humans experience such structure-borne noise with our sense of touch. Vibrations from and in gases (air) are referred to as **airborne noise**. We perceive this noise with our sense of hearing and, at very low frequencies and high amplitudes, also with our sense of touch.

While structure-borne noise is transferred as a result of the elasticity of solid substances, airborne noise or fluid-borne noise is transferred as a result of the compressibility of gases and liquids; the losses that result from the change in the shape of objects (material damping) and friction in the air weaken the transfer along the transfer path.

Our sense of hearing has a large range of perception across approximately six powers of 10 of the amplitude of the vibration between the (lower) **threshold of perception** (**auditory threshold**) and the **threshold of pain**, and it has a large frequency range with highly frequency-dependent sensitivity. In addition, there are also individual evaluations of frequency mixtures (**spectrum**) and changes in noises over time, as well as the **stereo effect** that results from hearing with both ears, along with overlapping individual psychological effects. Therefore, the effect of airborne noise on human beings cannot be completely emulated by using measurement technology (see also chapter 5, p. 72).

1.2 Transmission paths

A **transmission path** is the path over which the oscillation is carried from the generator to our sense of hearing or touch. It extends from the source of the oscillation as structure-borne noise to the surface of the source (in this case the motor) and from there as structure-borne noise across the mounting system into the driven device and from there as structure-borne noise to the outer surface of the device housing. At the same time, airborne noise is produced at the surface of the motor. In the equipment in which the motor is installed, this noise strikes the inside surface of the housing and from there is transferred as additional structure-borne noise through the housing wall to the outer surface of the equipment. If the housing has openings, the “inner” airborne noise also escapes directly to the outside and is added on to the airborne noise that comes from the oscillating housing surface and is radiated inward and outward. With our sense of touch we feel the vibrations on the housing surface and, in some cases, also the vibrations that are transferred from the housing surface into a cover or mounting system. The airborne noise reaches our sense of hearing.

The effect of the properties of the structure-borne noise path (distribution of masses and elasticities) to the surface that generates airborne noise is shown by the comparison of the noise produced by a small motor in installed condition (light blue spectrum) and in uninstalled condition (dark blue spectrum) (Fig. 1.1): An uninstalled motor is almost always significantly quieter because of its smaller surface area and its vibration distribution.

Therefore, the airborne noise that it generates is small and is largely short-circuited acoustically because its dimensions are small in comparison with the wavelengths of the sound oscillations. The fact that it can often still be heard is due to the large range of sensitivity provided by our sense of hearing. In this case, though, we only hear the high-frequency noise components since these components short-circuit acoustically somewhat less than the low-frequency noise components, to which our sense of hearing is also less sensitive. This is one of the reasons why the sound impressions produced by an uninstalled motor and those produced by an installed motor usually differ significantly. Another reason is that the system used to mount the motor in the equipment only transfers the structure-borne oscillations that are present at the mounting point. Therefore, the nature of the mounting system plays a very important role in acoustics and vibration!

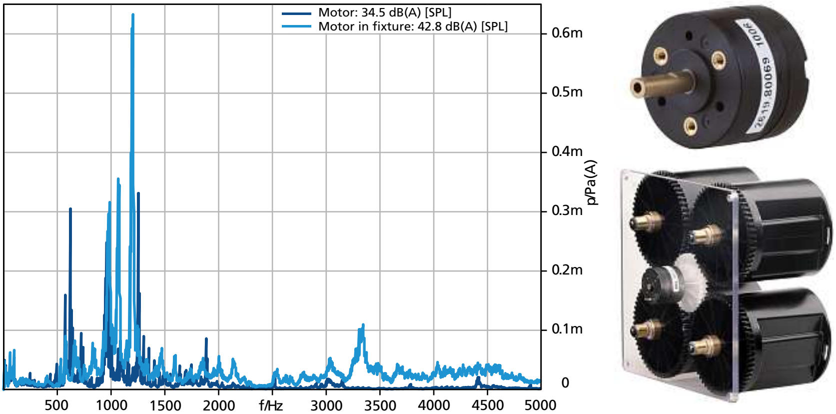

Fig. 1.1: Effect of installation situation on noise radiation characteristics

In the example shown in Figure 1.1, the motor is mounted directly on an acrylic plate without any decoupling. The center of the acrylic plate was chosen as the mounting location – theoretically the worst case. The antinode of the first natural oscillation mode with the corresponding lowest natural frequency of the acrylic plate is located here. Applying a vibration at this point therefore has the maximum effect and will generate the largest conceivable noise radiation – which is by no means desirable.

The transmission path to our sense of touch is limited to the transfer of vibrations by means of structure-borne noise to the surface that is touched. Airborne noise and structure-borne noise often work together; an everyday example is an electric shaver whose motor vibrations are felt on our skin and heard with our ears. Measures to reduce undesirable airborne noise are generally the most effective when they are applied to the noise source and/or the path of structure-borne noise, in the latter case in particular at the motor mounting area.

Airborne noise is also produced under variable flow conditions in blowers, sirens, etc., causing localized fluctuations in air pressure. If we want to reduce this noise, we must design the blower in such a way that the flow of air ahead of, inside, and downstream of the blower is as homogeneous and constant over time as possible. Airborne noise caused by oscillating surfaces can be reduced by decreasing the vibration excursions at the surface of the object, by reducing the surface area, and by utilizing time-phase positions of the surface vibrations that are different at different locations (natural waveshape distribution and therefore acoustic short-circuiting). Such a short-circuit can also be achieved by openings in housings. Oscillating perforated panels are therefore quiet compared with solid panels.

Exactly the opposite approach is used in designing a loudspeaker. The coil that vibrates in the magnetic field is small (Fig. 1.2) and therefore, like a small motor, it can only produce a small amount of airborne noise on its own. However, because it is desired that as much airborne noise as possible be produced, the coil is mounted as rigidly as possible on a speaker diaphragm. In order for this diaphragm to vibrate as much as possible in the same phase at all locations on its surface, it is designed to be lightweight and essentially rigid and therefore is not flat but rather conical or concave and is flexibly and elastically attached to the housing at its outside edge, and only there. In order to prevent acoustic short-circuiting between the front and back of the diaphragm, the loudspeaker is installed in a relatively large wall (acoustic wall) or a housing.

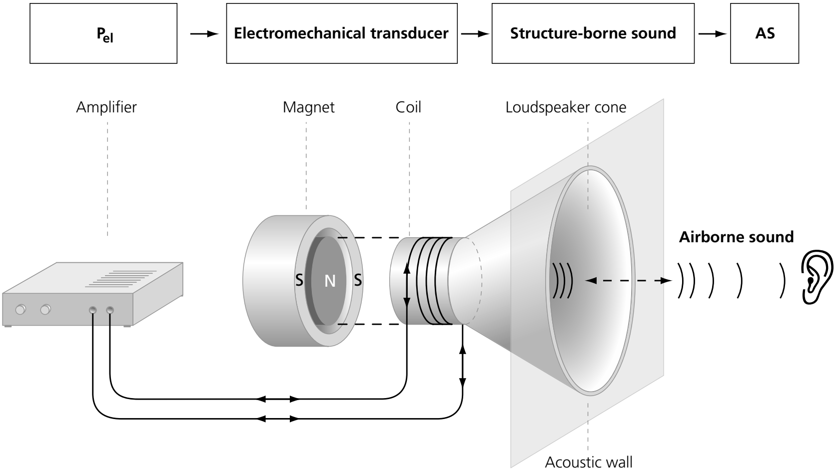

Fig. 1.2: Transmission path in the production of sound in a loudspeaker

2 Causes of vibrations and noises in small motors

In each motor undesirable forces, torques, and motions are unavoidably produced in addition to those that are desired. Undesirable fluctuations (oscillating torques) are superimposed on the desired electric motor torques. This results in oscillating rotational movements. Radial forces caused by imbalance and magnetic effects cause radial movements. Friction forces that fluctuate over time occur in bearings and on sliding contacts and cause undesirable movements. When gearboxes are installed in equipment, undesirable rotational oscillations are caused by the gears. All these movements constitute structure-borne noise, and they are transferred as such to the vibrating surfaces of the motor. Figure 2.1 shows typical examples of the main locations at which vibrations and noises can be produced in an electric motor.

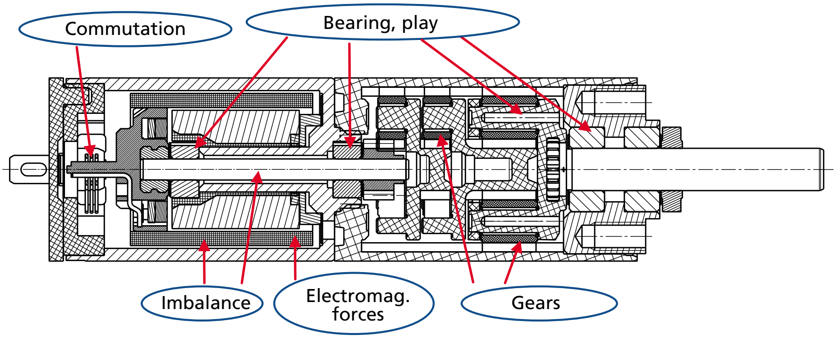

Fig. 2.1: Sources of vibrations and noises in an electric motor

2.1 Electromagnetically induced vibrations

The surface and the shaft of each electrical machine also move in undesirable ways. This is the result of the heteropolar concept that is always used for electrical machines for functional reasons and that has significant advantages over unipolar machines. As a result of this concept, the distribution of the magnetic energy density that is needed to generate the machine's torque in the air gap between the stator and rotor of an electrical machine must unavoidably fluctuate in time and space. Slotting (the distribution of the magnetic permanence for the magnetic air gap), the design of the permanent magnets, the distribution of the current-carrying winding, the way the current is applied, and the curve of current over time are all factors in these fluctuations. On the peripheral surface of the rotor and on the air gap side of the stator, the fluctuation of the spatial energy density distribution over time causes fluctuating tangential and radial forces that are applied at different locations – so-called **force excitations** (Fig. 2.2).

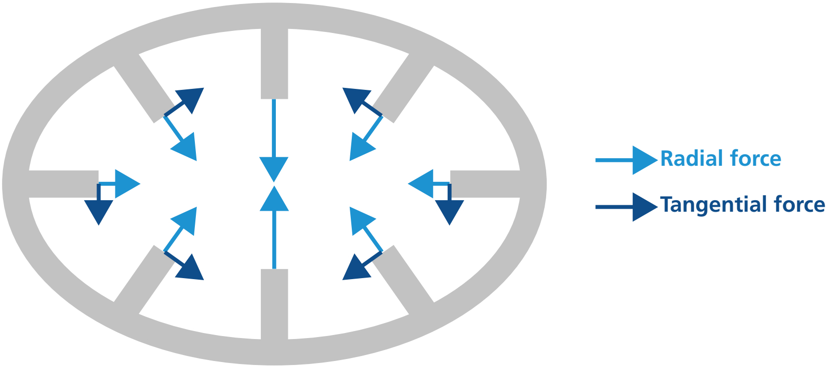

Fig. 2.2: Force excitations on the stator of an electrical machine

If the motor is suitably designed, the fluctuations in the tangential forces within the torque have very little effect because, when they are added up along the circumference, the large number of local fluctuations offset each other over time. In this way, oscillating torques can be kept low. This also applies to the cogging torques of motors equipped with permanent magnets. Locally caused tangential force fluctuations, however, cause tangential flexural deformation oscillations – for example, on the teeth of the metal packages of the stator and rotor (if teeth are present). The distribution of the radially oriented magnetic tensile forces causes radial movements and deformations of the stator and the rotor. Depending on the nature of the spatial distribution of these forces, this can be a resting or circumferential shift or a vibratory movement. In the stator and rotor, these shifts in movements are out of phase, and the overall center of gravity is maintained. Likewise, a flexing of the shaft and a possible deformation of the bearing cover with a modal order number of $r = 1$ (see also chapter 4.6 "Oscillation modes," p. 50 f.) or an oval, triangular, or polygonal elastic deformation of the stator ($r = 2, 3, ...$) occur. In this case the rotor body is barely deformed at all because of its greater radial flexural rigidity. The deformation of the stator can vary over time depending on the force distribution, and it can be circumferential, in other words it can oscillate. As a rule, movements having several modal order numbers r overlap at the stator. Generally, with small motors only movements with $r = 1$ are objectionable because small motors are small and inherently have sufficient rigidity. (With large motors movements with $r > 1$ are noticeable, although this is seldom the case in those with $r > 4$.)

Movements with $r = 1$ are usually the result of an eccentric position of the rotor in the stator, which can be static, for example when the rotor bearing locations in the stator are eccentric or circumferential, as would be the case with a bent shaft. They are harmonic or pulsating, usually with a number of harmonics, and they act in a spatially fixed radial direction and/or are circumferential, in other words the direction in which they are applied rotates. In the worst case, nearly all the frequencies of the movements lie within the audible range. Additional details on the causes of the radial and tangential forces of the various modal order numbers r can be found in the specialized technical literature on electrical machines.

In motors that utilize permanent magnets (DC motors, stepper motors, synchronous machines), a "cogging torque" occurs in addition to the desired torque. This cogging torque occurs in a no-current state as a result of the variations of magnetic permanence that depend on the position of the ro-