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ANALYTICAL PREDICTION OF NOISE OF MAGNETIC ORIGIN PRODUCED BY PERMANENT MAGNET BRUSHLESS MOTORS

Jacek F. Gieras

University of Technology and Life Sciences
Al. S. Kaliskiego 7, 85-796 Bydgoszcz, Poland
e-mail: jgieras@ieee.org

Summary: Prediction of acoustic noise radiated by electric motors is nowadays important both for machine manufacturers and users. This paper describes an engineering approach to prediction of noise of magnetic origin produced by permanent magnet (PM) brushless motors. The sound power level (SWL) is calculated on the basis of magnetic field analysis in the air gap, radial forces, natural frequencies of the stator-frame system and radiation efficiency coefficient. Accuracy problems encountered in the analytical and numerical noise prediction have been discussed.

Keywords: permanent magnets, brushless motors, noise, magnetic field

1. INTRODUCTION

Although the noise and vibration of induction machines have widely been discussed in many references, e.g. [1-6], significantly less research activity has been observed in vibro-acoustics of permanent magnet (PM) brushless motors, e.g. [7-10].

Noise and vibration produced by electrical machines can be divided into three categories:

– magnetic vibration and noise associated with parasitic effects due to higher space and time harmonics of magnetic field, eccentricity, phase unbalance, slot openings, magnetic saturation, and magnetostrictive expansion of the core laminations;
– mechanical vibration and noise associated with the mechanical assembly, in particular bearings;
– aerodynamic vibration and noise associated with flow of ventilating air through or over the motor.

This paper deals only with the noise of magnetic origin produced by radial magnetic forces due to magnetic flux density waveforms in the air gap. The paper also does no discuss the load induced noise, i.e., noise due to coupling the machine with a mechanical load and due to mounting the machine on foundation or other structure.

2. ENERGY CONVERSION PROCESS

Fig. 1a. shows how the electrical energy is converted into acoustic energy in an electric machine. The input current interacts with the magnetic field producing high-frequency forces that act on the inner stator core surface (Fig. 1b). These forces excite the stator core and frame in the corresponding frequency range and generate mechanical vibration and noise. As a result of vibration, the surface of the stator yoke and frame displaces with frequencies corresponding to the frequencies of forces. The surrounding medium (air) is excited to vibrate too and generates acoustic noise.

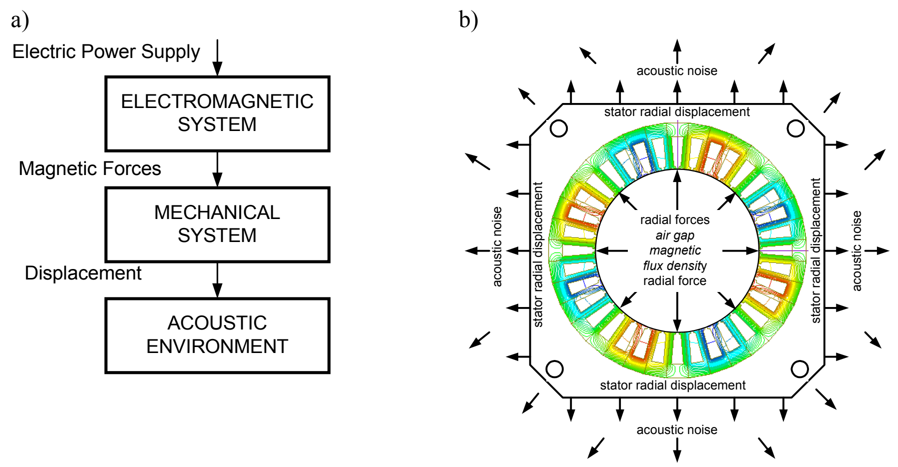

Fig. 1. Generation of vibration and noise in electric machines: (a) conversion of electric energy into acoustic energy; (b) excitation of the stator and frame to vibrate by radial magnetic forces.

The acoustic power radiated from the frame is a very small fraction of the electrical input power. The sound power level (SWL) of 100 dB corresponds to the power of 0.01 W, while 60 dB corresponds to the power of 10^{-6} W. Among other things, this causes a low accuracy of calculation of the SWL.

The stator and frame assembly, as a mechanical system, is characterized by a distributed mass M, damping C and stiffness K. The magnetic force waves excite the mechanical system to generate vibration. The amplitude of vibration is a function of the magnitude and frequency of these forces as well as parameters M, C and K.

3. DETERMINISTIC AND STATISTICAL METHODS OF NOISE PREDICTION

In the *analytical* and *numerical* approach, usually, a *deterministic* method is employed. As shown in Fig. 1a, the magnetic forces acting on a motor structure have to be calculated from the input currents and voltages using an analytical *electromagnetic model* [8, 9] or the FEM model [8, 11]. The vibration characteristics are then determined using a *structural model* normally based on the FEM [7, 8, 11-13]. By using the vibration velocities of the motor structure predicted from the *structural model*, the radiated sound power level can then be calculated on the basis of an *acoustic model*. The acoustic model may be formulated using either the FEM or boundary-element method (BEM). The FEM/BEM, by their nature, are limited to low frequencies.

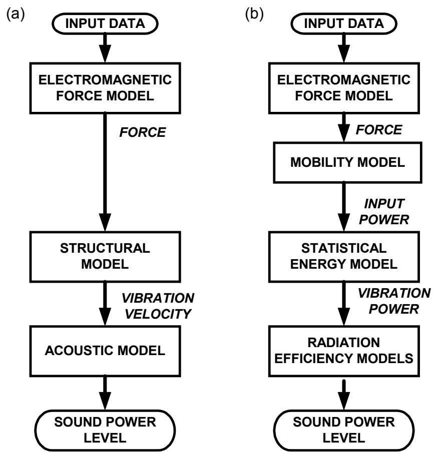

Fig. 2. Flowcharts for noise prediction: (a) deterministic method; (b) statistical method.

A method that is particularly suitable for calculations of noise and vibration at high frequencies is the so-called *statistical energy analysis* (SEA), which has been applied with success to a number of mechanical systems such as ship, car, and aircraft structures [14]. This method was first applied to electrical motors in 1999 [12, 13, 15]. The method basically involves dividing a structure (such as a motor) into a number of subsystems and writing the energy balance equations for each subsystem, thus allowing the statistical distribution of energies over various frequency bands to be determined. The main advantage of the statistical approach (Fig. 2b) is that it does not require all the details to be modeled.

4. ELECTROMAGNETIC SOURCES OF NOISE

Electromagnetic vibration and noise are caused by magnetic flux density waves in the air gap. If the stator produces $b_{1\nu}(\alpha,t) = B_{m\nu}\cos(\nu p\alpha \mp \omega_\nu t + \phi_\nu)$ magnetic flux density wave and rotor produces $b_{2\mu}(\alpha,t) = B_{m\mu}\cos(\mu p\alpha \mp \omega_\mu t + \phi_\mu)$ magnetic flux density wave, then the magnetic pressure on the inner surface of the stator core is:

$$
\begin{aligned}
p_{r\nu\mu} &= \frac{[b_{1\nu}(\alpha,t) + b_{2\mu}(\alpha,t)]^2}{2\mu_0} = \frac{B_{m\nu}^2}{4\mu_0}\left[1 + \cos(2\nu p\alpha \mp 2\omega_\nu t + 2\phi_\nu\right] + \\
&+ \frac{B_{m\nu}B_{m\mu}}{2\mu_0}\left\{\cos\left[p(\nu-\mu)\alpha \mp (\omega_\nu - \omega_\mu)t + (\phi_\nu - \phi_\mu)\right] + \right. \\
&\left. + \cos\left[p(\nu+\mu)\alpha \mp (\omega_\nu + \omega_\mu)t + (\phi_\nu + \phi_\mu)\right]\right\} + \frac{B_{m\mu}^2}{4\mu_0}\left[1 + \cos(2\mu p\alpha + 2\omega_\mu t + 2\phi_\mu\right]
\end{aligned}
\tag{1}
$$

where $B_{m\nu}$ and $B_{m\mu}$ are the amplitudes of the stator and rotor magnetic flux density waves, ω_ν and ω_μ ω are the angular frequencies of the stator and rotor magnetic fields, p is the number of pole pairs, ω_ν and ω_μ are phases of the stator and rotor magnetic flux density waves, ν = 1,5,7,11,13… for three phase machines, and μ = 1,3,5… . The amplitudes of magnetic stress (or magnetic pressure) waves in the air gap are:

$$P_{mr\nu} = \frac{1}{4}\frac{B_{m\nu}^2}{\mu_0}, \quad P_{mr\nu\mu} = \frac{1}{2}\frac{B_{m\nu}B_{m\mu}}{\mu_0} \quad \text{and} \quad P_{mr\mu} = \frac{1}{4}\frac{B_{m\mu}^2}{\mu_0} \tag{2}$$

Their frequencies are $\omega_r = 2\omega_\nu$, $\omega_r = \omega_\nu \mp \omega_\mu$, or $\omega_r = 2\omega_\mu$ orders $r = 2\nu p$ ν, $r = (\nu \mp \mu)p$ or $r = 2\mu p$ μ (r = 0,1,2,3,…) and phases $\phi_r = 2\phi_\nu$, $\phi_r = \phi_\nu \mp \phi_\mu$ or $\phi_r = 2\phi_\mu$. The magnetic stress wave acts in radial directions on the stator core and rotor core active surfaces causing the deformation and, hence, the vibration and noise. Frequencies and orders (circumferential modes) of all fundamental radial magnetic forces are given in Table 1 where f is the frequency of the stator current.

Table 1. Frequencies of radial magnetic forces produced by higher space harmonics ν $\nu > 1$ in PM brushless (synchronous) motors (s_1 is the number of stator slots and m_1 is the number of phases).

Source	Frequency Hz	Order (circumferential mode)
Product of stator space haromics b_ν^2 of the same number ν	$f_r = 2f$	$r = 2\nu p$ $\nu = 2km_1 \pm 1$ $k = 0, 1, 2, 3, \ldots$
Interaction of the rotor magnetic field and slotted core of the stator	$f_r = 2\mu_\lambda f$ where μ_λ = integer $[s_1/p]$	$r = 2(\mu_\lambda p \pm s_1)$
Product of rotor space haromics b_μ^2 of the same number μ	$f_r = 2(1 \pm 2k)f$	$r = 2\mu p = 2p(1 \pm 2k)$ where $\mu = 1 \pm 2k$
Product of stator and rotor space harmonics $b_\nu b_\mu$ — general equations	$f_r = f \pm f_\mu$	$r = (\nu \pm \mu)p$
Product of stator winding and rotor space harmonics $b_\nu b_\mu$ where $\nu = ks_1/p \pm 1$ and $\mu = 2k \pm 1$	$f_r = 2(1+k)f$ $f_r = 2kf$	$r = ks_1 \pm 2p(1+k)$
Product of stator and rotor static eccentricity space harmonics $b_\nu b_\mu$	$f_r = 2(1+k)f$ $f_r = 2kf$	$r = 1$ $r = 2$
Product of stator and rotor dynamic eccentricity space harmonics $b_\nu b_\mu$	$f_r = [2(1+k) \pm 1/p]f$ $f_r = (2k \pm 1/p)f$	$r = 1$ $r = 2$
Product of stator and rotor magnetic saturation space harmonics $b_\nu b_\mu$	$f_r = 2(2+k)f$ $f_r = 2(1+k)f$	$r = ks_1 + 2p(k+2)$ $r = ks_1 + 2p(k+1)$

The magnetomotive force (MMF) space harmonics, time harmonics, slot harmonics, eccentricity harmonics, and saturation harmonics produce parasitic higher harmonic forces and torques. The amplitude of the radial force of the order r is $F_{mr} = \pi D_{in} L_i P_{mr}$ where D_{in} is the stator core inner diameter, L_i is the effective length of the core and P_{mr} is is the amplitude of the radial magnetic pressure according to eqn (2).

The stator – frame (or stator – enclosure) structure is the main radiator for the machine noise. If the frequency of the radial force is close to or equal to any of the natural frequencies of the stator – frame system, a resonance occurs, leading to the stator system deformation, vibration, and acoustic noise.

Magnetostrictive noise of electrical machines with number of poles $2p > 4$ can be neglected due to low frequency $2f$ and high order $r = 2p$ of radial forces. However, radial forces due to the magnetostriction effect can reach about 50% of radial forces produced by the air gap magnetic field.

In inverter fed motors, parasitic oscillating torques are produced due to higher time harmonics in the stator winding currents. These parasitic torques are, in general, greater than oscillating torques produced by space harmonics. Moreover, the voltage ripple of the rectifier is transmitted through the intermediate circuit to the inverter and produces another kind of oscillating torque [3].

5. ENGINEERING APPROACH TO PREDICTION OF NOISE

Although, the analytical and FEM/BEM numerical approaches seem to work well, the time consuming preprocessing and computations can be a drawback to use this approach in engineering practice. On the other hand, it is relatively easy to write a *Mathcad*[1] or *Mathematica*[2] computer program for fast prediction of the SWL spectrum generated by magnetic forces using analytical approach. The accuracy due to physical errors may not be high, but the time of computation is very short and it is easy to prepare and implement the input data set.

The main program consists of the input data file, electromagnetic module, structural module (natural frequencies of the stator system), and acoustic module (Fig. 2a). The following effects can be included: phase current unbalance, higher space harmonics, higher time harmonics, slot openings, slot skew, rotor static eccentricity, rotor dynamic eccentricity, armature reaction, magnetic saturation. An auxiliary program calculates the torque ripple [10], converts the tangential magnetic forces into equivalent radial forces, and transfers radial forces due to the torque ripple to the main program.

The input data file contains the dimensions of the machine and its stator and rotor magnetic circuit, currents (including unbalanced system and higher time harmonics), winding parameters [2], material parameters (specific mass, Young modulus, Poisson's ratio), speed, static and dynamic eccentricity, skew, damping factor as a function of frequency, correction factors; e.g., for the stator systems natural frequencies, maximum force order taken into consideration, minimum threshold magnetic flux density to exclude all magnetic flux density harmonics below the selected margin. The rotor magnetic flux density waveforms are calculated on the basis of MMF waveforms and per-

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1 industry standard technical calculation tool for professionals, educators, and college students

2 fully integrated technical computing environment used by scientists, engineers, analysts, educators, and college students

meances of the air gap. Magnetic forces are calculated on the basis of Maxwell stress tensor. The natural frequencies of the stator system can be approximately evaluated as [9]:

$$f_{mn} \approx \frac{1}{2\pi}\sqrt{\frac{K_m^{(c)} + K_{mn}^{(f)} + K_m^{(w)}}{M_c + M_f + M_w}}\,, \tag{4}$$

where $K_m^{(c)}$ is the lumped stiffness of the stator core for the mth circumferential vibrational mode, $K_{mn}^{(f)}$ is the lumped stiffness of the frame for the mth circumferential and nth axial vibrational mode, $K_m^{(w)}$ is the lumped stiffness of the stator winding for the mth circumferential vibrational mode, M_c is the lumped mass of the stator core, M_f is the lumped mass of the frame, and M_w is the lumped mass of the stator winding. It has been assumed the frame is a circular cylindrical shell with both ends constrained mechanically by end bells.

These values can be corrected with the aid of correction factors obtained, e.g., from the FEM structural package or measurements. Then, using the damping coefficient ς_m which is a function of frequency and radial forces F_{mr}, the amplitudes of radial velocities for the mth circumferential mode are calculated, i.e.

$$A_{mr} = \frac{F_{mr}/[(2\pi f_m)^2 M]}{\sqrt{\left[1-(f_r/f_m)^2\right]^2 + [2\zeta_m(f_r/f_m)]^2}}\,. \tag{5}$$

The damping factor ζ_m affects significantly the accuracy of computation. Detailed research has shown that the damping factor is a nonlinear function of natural frequencies f_m. The radiation efficiency factor σ_m, acoustic impedance Z_0 of the air and radial velocities v_m give the SWL radiated by the m^{th} mode of the machine structure, i.e.

$$\Pi_m = \sigma_m Z_0 S_f v_m^2\,, \tag{6}$$

where $Z_0 = \rho_0 c_0$, $\rho_0 = 1.188$ kg/m^3 is the air density, $c_0 = 344$ m/s is the sound velocity in the air, S_f is the surface of the motor frame and $v_m = 2\pi f_r A_{mr}$ is the spatial averaged mean square velocity of the m^{th} circumferential mode. After performing calculations of SWL for every frequency f_{rk}, where $k = 1,2,3,\ldots$, present in the excitation force spectrum, the SWL spectrum (narrow band noise) can be found. If Π_{mk} is the amplitude of the SWL for the k^{th} harmonic $1 \le k \le k_{\max}$, the overall noise can be found as

$$\Pi = \sqrt{\sum_{k=1}^{k_{\max}} \Pi_{mk}^2} \tag{7}$$

The overall SWL calculated in such a way is lower than that obtained from measurements, because computations include only the noise of magnetic origin (mechanical noise caused by bearings, shaft misalignment, and fan is not taken into account) and usually, the calculation is done for low number of harmonics of magnetic flux density waves.

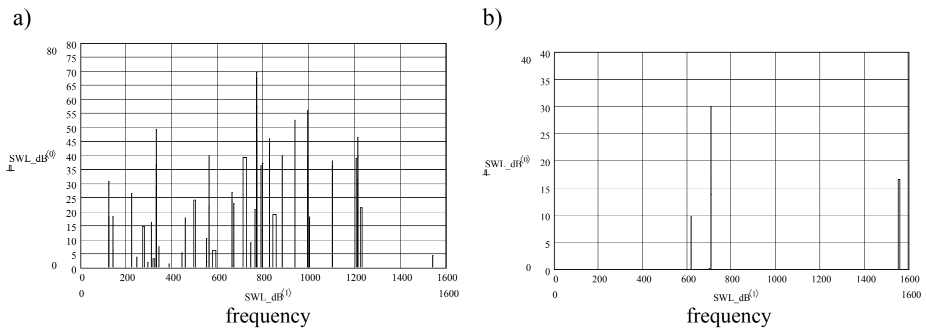

Fig. 3. SWL spectrum of 10-kW, 660-rpm, s_1 = 36-slot PM brushless motors at $\psi\vartheta$ = 4.58°: (a) $2p$ = 10, stator current frequency f = 55 Hz, overall SWL = 70.32 dB; (b) $2p$ = 8, f = 44 Hz, overall SWL = 29.95 dB.

The proper selection of the stator slots s_1 and rotor poles $2p$ is one of the primary factors affecting the noise of magnetic origin of PM brushless motor. For a motor with s_1 = 36 slots and $2p$ = 10 poles the overall SWL at 660 rpm is 70.32 dB or 1.08×10^{-5} W. The SWL spectrum is shown in Fig. 3a. All fundamental frequencies, circumferential modes and SWL obtained from calculations and measurements are listed in Table 2.

Table 2. Calculated key frequencies and modes of SWL at $\psi\vartheta\ \psi$ = 4.58° (frequencies producing noise below 25 dB have been neglected).

SWL, dB		SWL frequency, Hz	SWL frequency equation	mode (order)
calculation	test			
30.8	36.98	121	$(2k + 1/p)f$, $k = 1$	2
26.5	44.38	220	$2kf$, $k = 2$	2
49.14	50.10	330	$2kf$, $k = 3$	2
24.23	41.14	495	$(2k + 1)f$, $k = 4$	2
39.84	28.30	561	$(2k + 1/p)f$, $k = 5$	2
26.67	43.80	660	$2kf$, $k = 6$	2
22.77	36.84	671	$(2k + 1/p)f$, $k = 6$	2
39.14	46.26	715	$(2k + 1)f$, $k = 6$	2
20.85	38.09	759	$(2k - 1/p)f$, $k = 7$	2
69.69	**68.10**	**770**	$2kf$, $k = 7$	**2**
36.46	39.78	781	$(2k + 1/p)$, $k = 7$	2
37.16	34.23	792	$2(k + 1/p)$, $k = 7$	2
45.92	39.20	825	$(2k + 1)f$, $k = 7$	2
39.88	55.42	880	$2kf$, $k = 8$	2
56.02	52.24	990	$2kf$, $k = 9$	2
38.06	43.80	1100	$2kf$, $k = 10$	2
38.9	40.69	1199	$(2k - 1/p)f$, $k = 11$	2
46.64	40.60	1210	$2kf$, $k = 11$	2
70.32	68.73	Owerall SWL		

The predominant amplitude of the SWL = 69.69 dB (calculations) for r = 2 is at $f_r = 2\times7\times55 = 770$ Hz [9]. This force is produced by interaction of the PM rotor field and slotted structure of the stator [9]. The frequency of this force is $f_r = 2\mu_\lambda f$ and order $r = 2 \mid \mu_\lambda p - s_1 \mid$, where $\mu_\lambda = \text{int}\left(\frac{s_1}{p}\right)\mu_\lambda$. If the frequency of this force is close to the natural frequency of the order $r = m = 2$, a large amplitude of the SWL is produced. In the investigated motor the natural frequency $f_{m=2,n=1} = 1044$ Hz and the effect of interaction of the PM rotor field on the stator slotted structure ($f_r = 770$ Hz) is still significant.

If the number of stator slots $s_1 = 36$ remains the same and $2p = 8$, the overall SWL at 660 rpm is reduced to 30 dB (10^{-9} W). The SWL spectrum is shown in Fig. 3b. The predominant amplitude of the SWL = 29.94 dB at $f_r = 2 \times 8 \times 44 = 704$ Hz ($\mu_\lambda = 8$). The amplitude of noise is much smaller than that for $2p = 10$ because the radial force order $r = \mid \mu_\lambda p - s_1 \mid = \mid 8 \times 4 - 36 \mid = 4$ is greater than in the previous case [13]. The natural frequency $f_{m=4,n=1} = 2938$ Hz is much higher than f_r too. The other amplitudes, i.e., 9.55 dB at $f_r = 2 \times 7 \times 44 = 616$ Hz ($k = 7$) and 16.43 dB at:

$$f_r = (2k + 1 + 1/p)f = (2 \times 17 + 1 + 1/4)44 = 1551 \text{ Hz } (k = 17)$$

are also due to magnetic forces of the order $r = 4$ (Fig. 3b).

On the other hand, the 10-pole motor produces lower cogging torque than the 8-pole motor because the least common factor LCM of the number of slots s_1 and poles $2p$ is greater for the 10-pole motor, i.e., LCM (36,8) = 72, LCM (36,10) = 180 [8].

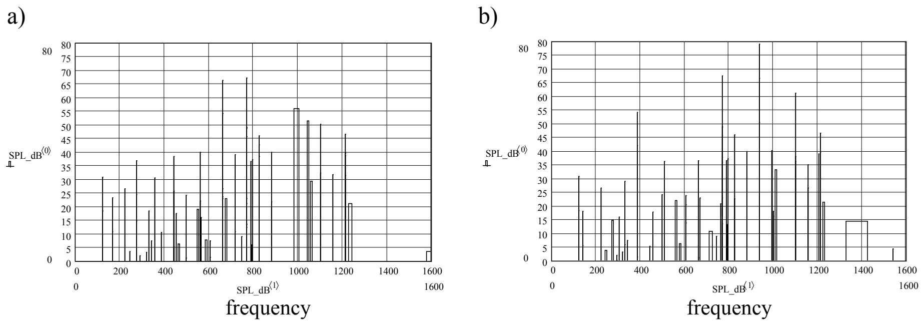

Fig. 4. SWL spectrum of a 10-kW, 660-rpm, $2p = 10$, $s_1 = 36$-slot PM brushless motors at: (a) angle ψψϑ = 5° between the stator current and q-axis; (b) ψψϑ ψ = 4.5°

When the rotational speed increases, the SWL usually increases too. However, this rule is not always true, because while the speed increases the frequencies of low order radial magnetic forces may not match the corresponding natural frequencies of the stator-frame system.

The SWL spectrum of a PM brushless motor is very sensitive to the angle ψϑ between the stator current phasor and the q-axis (EMF phasor). Fig. 4 shows how the SWL spectrum is changed, if the angle ψϑ ψ increases from 4.58° to 5° (see also Fig. 3a) and then decreases to 4.5°.

6. ACCURACY OF NOISE PREDICTION

The results of both analytical and numerical noise prediction may considerably differ from measurements (Fig. 5). Forces that generate vibration and noise are only a small fraction of the main force produced by the interaction of the fundamental current and the fundamental normal component of the magnetic flux density. Approximately only 10^{-10} to 10^{-6} of the electrical input power of a 10 kW motor is converted into acoustic power.

The accuracy of the predicted SWL spectrum depends not only how accurate the model is, but also how accurate the input data are, e.g., level of current unbalance, angle ψ between the stator current and q-axis (Fig. 4), influence of magnetic saturation on the equivalent slot opening, damping factor, elasticity modulus of the slot content (conductors, insulation, encapsulation), higher time harmonics of the input current (inverter-fed motor), etc. All the above input data are difficult to obtain or predict with sufficient accuracy [7, 16].

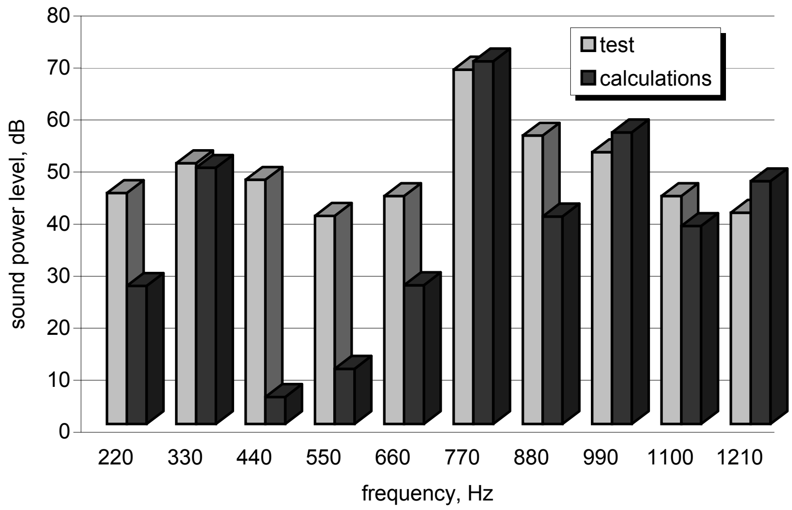

Fig. 5. Comparison of analytically predicted SWL amplitudes with those obtained from measurements for key radial force frequencies $4f$, $6f$, $8f$,…$12f$ of the order r = 2 for a 10 kW, $2p$ = 10, s_1 = 36, f = 55 Hz, $\psi\vartheta$ = 4.58° PM brushless motor.

7. CONCLUSIONS

The accurate prediction of the noise of a PM brushless motor at the early stage of design is much more difficult than electromagnetic, thermal or structural calculations.

Analytical methods of noise prediction of PM brushless motors may be preferred to numerical methods in design calculations, even if their accuracy is not high. The main advantage of analytical methods is easy preparation of the input data file and fast time of computations (seconds, maximum a few minutes).

The most difficult problem in analytical prediction of noise is the accurate calculation of natural frequencies of the stator core-winding-frame system.

The proper selection of the number of stator slots with respect to the number of rotor poles is very important to design a low-noise PM synchronous motor. On the other hand, a low-noise PM synchronous motor may produce a high cogging torque.

The order r (circumferential mode m) of radial magnetic forces increases with the number of poles $2p$. The larger the magnetic force order, the lower the deflection of the stator core which is inversely proportional to the 4^{th} power of the force order [9].

The calculated noise level is usually lower than that obtained from laboratory measurements because calculations may not include all harmonic forces [16].

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OBLICZENIA ANALITYCZNE HAŁASU AKUSTYCZNEGO WYWOŁANEGO POLEM MAGNETYCZNYM W SILNIKACH BEZSZCZOTKOWYCH O MAGNESACH TRWAŁYCH

Streszczenie

Obliczenia hałasu akustycznego generowanego przez silniki elektryczne są obecnie ważnym zagadnieniem zarówno dla producentów jak i użytkowników maszyn elektrycznych. W artykule przedstawiono podejście inżynierskie do obliczeń hałasu wywołanego polem magnetycznym w silnikach bezszczotkowych o magnesach trwałych. Poziom mocy akustycznej (PMA) jest obliczany na podstawie analizy pola magnetycznego w szczelinie powietrznej, sił promieniowych, częstotliwości naturalnych układu stojan-obudowa oraz współczynnika wypromieniowania dźwięku. Przedmiotem dyskusji są zagadnienia dokładności obliczeń na podstawie metod analitycznych oraz numerycznych.

Słowa kluczowe: magnesy trwałe, silniki bezszczotkowe, hałas, pole magnetyczne