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NVH analysis of a 3 phase 12/8 SR motor drive for HEV applications

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Abstract

In this study different noise and vibration measurements on a multi-phase 12/8 switched reluctance (SR) motor for automotive applications are carried out on a test rig and analysed with vibro-acoustic techniques. When evaluating the behaviour of rotating machinery for HEV applications, it is necessary to perform a vibro-acoustic analysis. The reason for this is that these specific noise and vibration contribute significantly to the perceived overall sound quality in the passenger compartment and outside the vehicle. Vibrations or high frequency tonal acoustic noise could be annoying for the passengers or could even cause long term damage. Therefore, the noise and vibration must be deliberately optimized. In case of a SR motor, the radial magnetic force between stator and rotor is a main excitation source to create large deformations of the stator housing, causing serious vibrations and acoustic noise. Measurements and results of simulations in different load conditions are compared. In addition, the dominant vibration modes are verified by modal analysis and operational deflection shapes. The unpleasant tonal acoustic radiation of this electric motor is objectively quantified by noise metrics. Finally, the relationship between the current profiles, radial magnetic forces, and mechanical and acoustic vibrations is investigated to obtain a better insight into the root cause of the vibro-acoustic behaviour of the motor.

Keywords: switched reluctance motor, HEV (hybrid electric vehicles), data acquisition, motor design, noise

1 Introduction

Nowadays, permanent magnet synchronous motors (PMSM) are the motor drive solution for most of the electric and hybrid vehicles. The future uncertainty of availability of rare earth materials, permanent magnet materials, is one of the major drawbacks of this type of electric motor. An alternative is a SR drive. This type of motor has already proven its merits in a wide range of industrial applications which confirms its performance and reliability. From this point, switched Reluctance (SR) motors reflect a very attractive alternative to other electric motor types for automotive traction. Another advantage of the SR motor is its simple design, which yields a cost-effective construction.

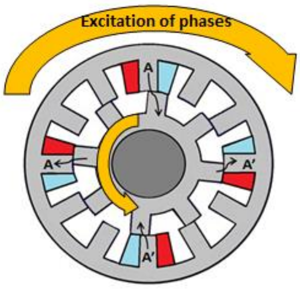
The SR motor suffers, however, from a Noise, Vibration and Harshness (NVH) issue which has caused some concern in the automotive industry.

The noise and vibration produced by SR motors is one of the most crucial problems to be solved before it will find its introduction into the automotive industry. The NVH properties of an SR motor depend on several factors such as machine dimensions, material properties and electromagnetic design. An NVH analysis may bring insight into the relation between these factors and the NVH performance. Therefore, an NVH analysis provides an essential value towards the challenges of designing SR motors in terms of ride comfort and acoustic comfort inside a vehicle.

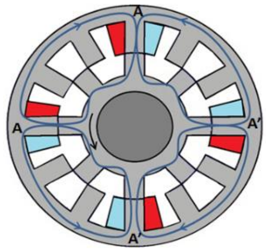
This paper presents the results of a detailed experimental NVH assessment of an SR motor with the aim to establish an understanding of the main noise generation and propagation mechanisms. The paper is outlined as follows. In section 2, the acoustic noise generation process is presented. Next, in section 3, the measurement test setup and the objectives of this research are discussed. Section 4 deals with the vibro-acoustic measurement results. More in detail, a signature time and frequency analysis, a modal analysis, sound metrics and the operational deflection shapes are described for this specific type of electric driveline. Finally, in section 5, some conclusions are drawn.

2 Acoustic noise generation process

A multi-phase SR motor is a type of synchronous machine, but with particular features: field coil is wound around the stator poles, but no coil or magnetic material is presented on the rotor. The motor works by energizing opposite stator poles, thereby generating a magnetic field. This magnetic field forces the rotor poles to rotate to the position of minimum reluctance, aligning them to the closest stator poles. By energizing consecutive stator poles, continuous rotation is generated [1]. Fig. 1 shows the principle for a 12/8 SR motor, which has 12 stator poles and 8 rotor poles. Considering one phase, it can be observed that two main equilibrium position of the rotor exist. The rotor position illustrated in Fig. 1a is called the unaligned position in relation to phase AA'. The position with the smallest magnetic reluctance is called the aligned position (Fig. 1b). Typically, the number of rotor poles is lower than the number of stator poles, which prevents the poles from all aligning at the same time, such that, by switching the poles in an appropriate way a continuous rotary motion can be established.



(a) unaligned position



(b) aligned position

Figure 1: Cross-sections of the analysed 12/8 SR motor and distribution of one coil group

In a 12/8 SR motor, each of the stator phases is activated eight times per revolution. Table 1 compares other configurations, where N_p is the number of poles excited at the same time, N_e the number of electric phases, N_t, the total number of phase excitations per revolution and O the number of times that a phase is excited per revolution:

Table 1: Different SR motor configurations

	8/6	12/8	16/12
N_p	2	4	4
N_e	4	3	4
N_t	24	24	48
O	6	8	12

As shown in Fig. 2, the acoustic noise generation process of an SR motor consists of three steps. Generally, the torque originating from the radial magnetic forces, which are determined by the phase currents, controlled by the switching pattern, plays a dominant role in the noise generation of a SR motor.

In a first step, the phase currents flowing through the stator coils generate time-varying radial forces (Eq. 1) in the air gap between the stator and the rotor poles. The considered radial force F_r is proportional to the square of the phase current i:

$$F_r(\theta, l_g, i) = -\frac{1}{2} i^2 \frac{L(\theta, i)}{l_g} \qquad (1)$$

where $L(\theta, i)$ is the self-inductance of a single phase in function of the rotor position θ and l_g is the air gap length between rotor and stator.

In the second step, these radial forces excite vibrations in the stator which are propagated through the mechanical structure. The largest vibration levels arise when the natural modes of the stator are excited by the pulsating radial magnetic forces (Fig. 3).

In the final step, the deformations of the machine stator and attached components cause air vibrations resulting in pressure differences detectable by the human ear.

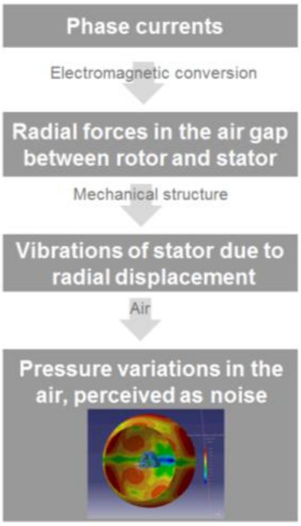


Figure 2: Noise generation process of an SRM

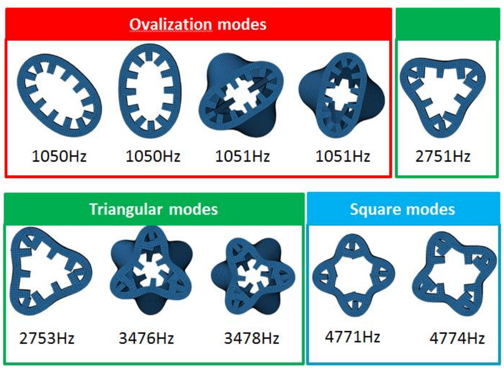


Figure 3: Simulated finite element model of the stator mode shapes [2]

Each type of SR motor has its own unique acoustic and vibration signature which is defined by several factors such as the mechanical design, the electromagnetic design and the excitation pattern of the phase currents. It is expected that a 12/8 SR motor has better NVH properties than the 8/6 configuration. In general, the natural frequencies of the square mode are higher and the 'ovalization' mode is not expected because four poles are excited at the same time resulting in a symmetric distribution. Finally, a lower noise contribution for a 12/8 configuration should be achieved in the most sensitive frequency area of the human ear.

3 Experimental test setup and objectives

Before presenting the vibro-acoustic analysis, this section introduces the reader to the setup and the objectives of the measurements. The setup includes two different machines, a 12/8 SR motor and 110kW squirrel cage induction motor. It concerns a 2-pole induction motor with a modular three-level IGBT converter. A PC-based controller, a programmable powerful target pc, is used to compile graphical block diagram algorithms and run real-time. To satisfy the high performance over the full speed range a field-oriented control (FOC) is implemented to control the induction motor. The SR drive used a conventional control technique, hysteresis current control and is coupled to the induction motor with belts. Fig. 4 shows the principal parts of the test rig setup. The properties of the SR motor are described in Table 2.

Table 2: Properties of the SRM

E-motor dimensions (LxD)	215x256mm
E-motor weight	50kg
E-motor inertia	21087kgmm^2
Nominal continuous power	45kW
Maximum speed	15000 min^{-1}

In total, sixty tri-axial accelerometers were mounted on the jacket and the side panels. Furthermore, four microphones were placed: two in the near-field, two in far-field. An acoustic insulation box was placed around the SR driveline to separate the acoustic motor noise from environmental noise.

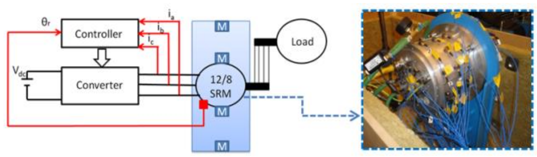


Figure 4: Test rig with a SR drive system coupled to a two-pole induction motor

To measure very accurately the rotational speed, an incremental encoder is used. Its output is measured in 2048 pulses per revolution which give a very detailed rotational speed profile.

The main objective of the measurement campaign is to evaluate a 12/8 SR motor in terms of NVH performance. More specific objectives are i) to verify with the help of operational deflection shapes that the square mode is the first excited mode, ii) to identify the dominant orders in different conditions, iii) to assess the tonality, loudness and sharpness with sound metrics.

An electric motor for vehicle applications should be able to operate in the four quadrants of the speed-torque plane. In this study, motor quadrant I and II (Fig. 5) are considered as they are the most used ones in automotive applications. Quadrant 1 indicates forward motoring since the torque is in the direction of motion. Quadrant 2 indicates forward braking since the torque is opposite to the direction of motion.

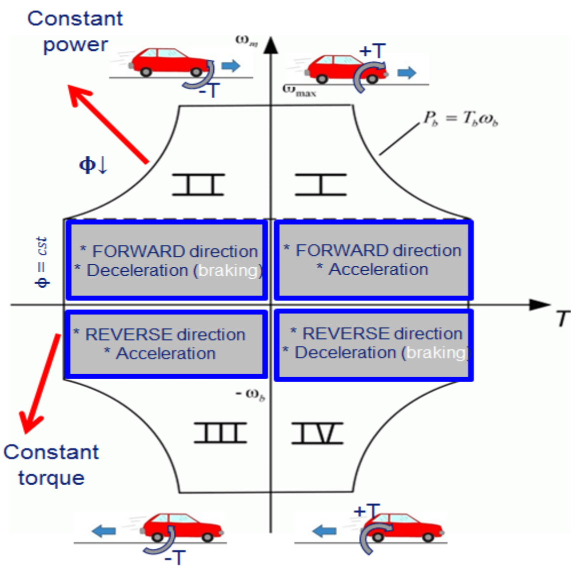


Figure 5: Four quadrant motion control of an electric motor

In both quadrants, different torque levels from 0% to 49% were studied (Fig. 6) for this type of machine.

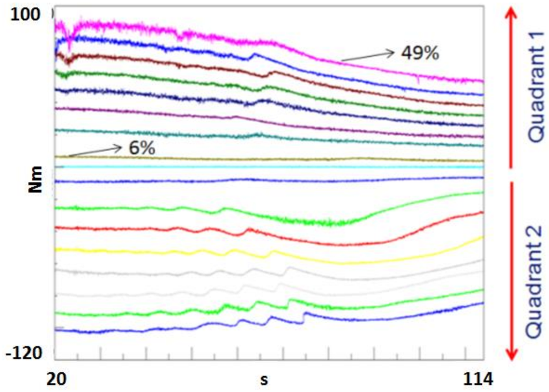


Figure 6: Torque conditions during acceleration and deceleration in forward direction

4 Vibro-acoustic study based on experimental data

In this paragraph, both the results of a modal analysis and operational measurements in a speed range from 0 to 10000 rpm are studied in different load conditions.

4.1 Signature time and frequency analysis

A waterfall 3D-graph is a way to present acoustic noise and vibration data of rotating machines. More in detail, the colour map of frequency spectra shows a dB-level as function of time or rotational speed. It is a suitable tool to examine rotating machinery, like electric drives. Fig. 7 shows a waterfall spectrum of a phase current acquired during a run-up measurement between 0 and 10000 rpm. The corresponding time trace of the current waves is presented in Fig. 8.

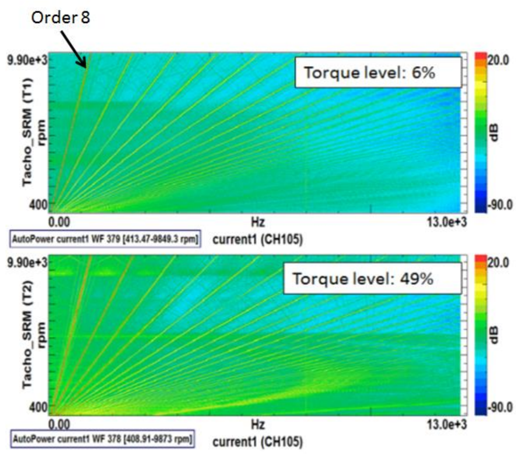


Figure 7: Measured phase current during run-up operation

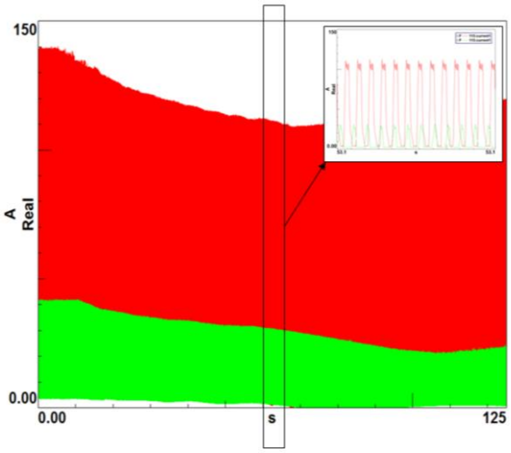


Figure 8: Measured phase current time profile in different load conditions: 6% and 49%.

With this kind of evaluation different characteristics can be examined. The oblique lines in Fig. 7 are motor harmonics, also called orders, which are rotational speed dependent. For the points on these lines, the relation between the frequency and the rotational speed is given by

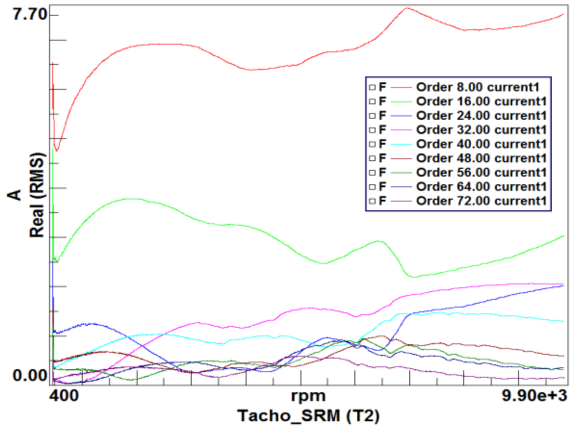
$$f = \frac{h.N.RPM}{60} \qquad (2)$$

where f is the frequency in Hz, N the number of rotor poles and RPM the rotational speed in revolutions per minute. [3] The number of the order h determines the slope of the line. As can be seen in Fig. 7, the 8^{th} order is the most dominant order for a 12/8 SR motor. This is due to the fact that each of the stator phases is activated eight times per revolution in this type of SR motor.

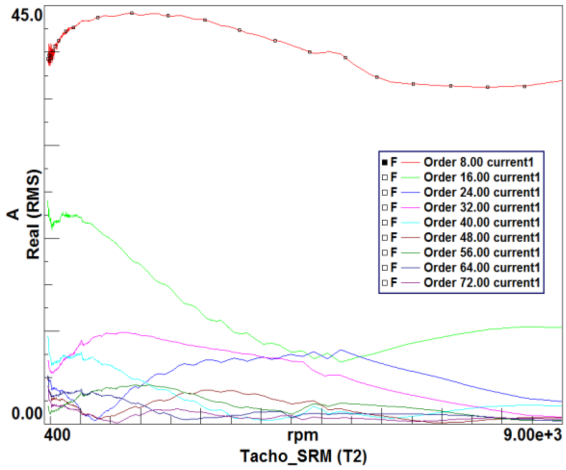
A next step is to go more in detail with an order analysis (Fig. 9) by extracting the orders from the map. An order section allows inspecting the behaviour of single tonal components referring to the rotational speed of the motor itself. In this case the dominant order sections are calculated for torque level of 6% and 49%. As can be seen, the higher the harmonic number, the lower the amplitude for a specific order line is.

Fig. 10a shows a spectrogram of an accelerometer on the stator housing. Three phenomena can be recognized: i) 8^{th} order harmonics, ii) resonances and iii) a kind of inverted C-shape. Fig. 10b shows the corresponding acoustic noise signature in the near-field.

In the proposed accelerometer signal, the resonance close to 6300Hz doesn't lead to increase of the acoustic power near this frequency. The same conclusion can be drawn from the order sections plotted in Fig. 14.



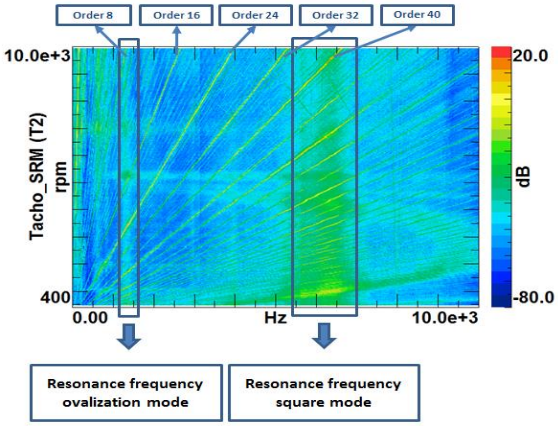
(a) Order sections by a torque level of 6%



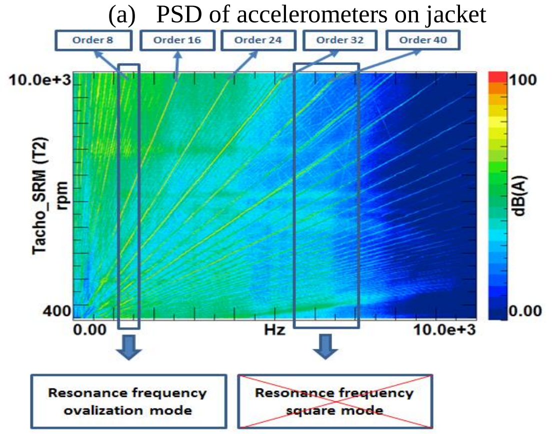
(b) Order sections by a torque level of 49%

Figure 9: Overview order section in different load conditions

In fact, resonances of the stator amplify the excitation forces. The dominant resonance in this application is approximately 6300Hz with a corresponding square mode shape [4]. This is due to the fact that four stator poles are symmetrically loaded in a 12/8 SR motor. Another resonance at 1330Hz, an "ovalization" of the stator should not be excited in a 12/8 SR motor due to symmetry, but it is present probably due to manufacturing tolerances and rotor eccentricity [4].



(a) PSD of accelerometers on jacket



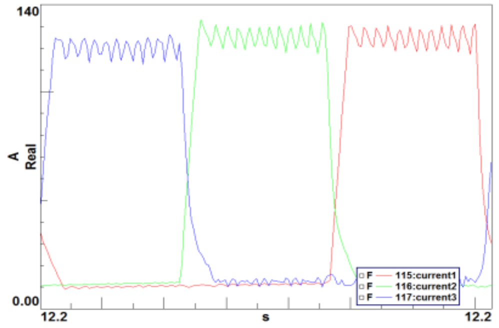
(b) PSD of microphone in near-field

Figure 10: Spectrum analysis in function of the rotational SR motor speed and amplitude

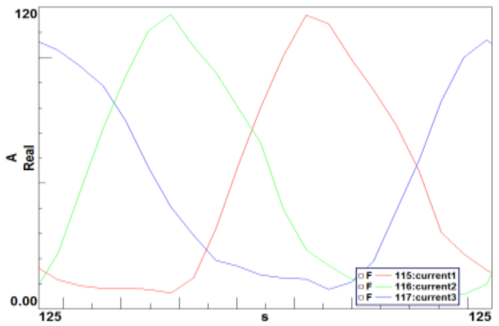
Another phenomenon that can be observed in Fig. 10 is a feature in the form of an inverted C-shape. By analysing it more detailed, this C-shape is mainly related to the phase current commutation process. Principally, at low and intermediate rotational speed a higher content of the current ripple is present (Fig. 11). By reason of a low back electromotive force (EMF), a quite rectangular current pulse with a ripple is present and goes finally through the excited phase coils. At higher speeds, the back EMF increases. Consequently, the current pulse is no longer rectangular but becomes slightly triangular and has a much lower ripple contribution. At the end, it is also reflected in the torque profile which causes noise and vibration. Eq. 3 shows the relation that the electromagnetic torque for one phase of a SR motor is proportional to the current:

$$T = \frac{i^2 dL}{2d\theta} \qquad (3)$$

considering i = the electrical current, L = the motor inductance and θ = the rotor angle.



(a) Current wave form at low speed



(b) Current wave form at higher speed

Figure 11: Current profiles

By removing the ripple on the current signal in the lower speed range the inverted C-shape is disappeared. Fig. 12 shows a part of the time traces for the original current wave form (red) and the modified current wave form without the ripple (blue) at a negative torque condition of - 49%.

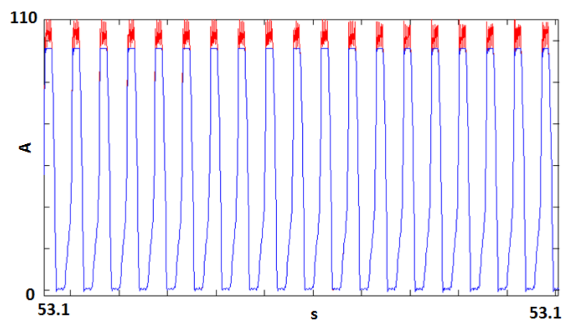


Figure 12: Original current wave with ripple (red) and modified current wave without ripple (blue)

The corresponding waterfall plots are visualized in Fig. 13. It can be noted that the inverted C-shape, has disappeared when the ripple is removed. Consequently, editing the current ripple gives a different content in terms of noise and vibration.

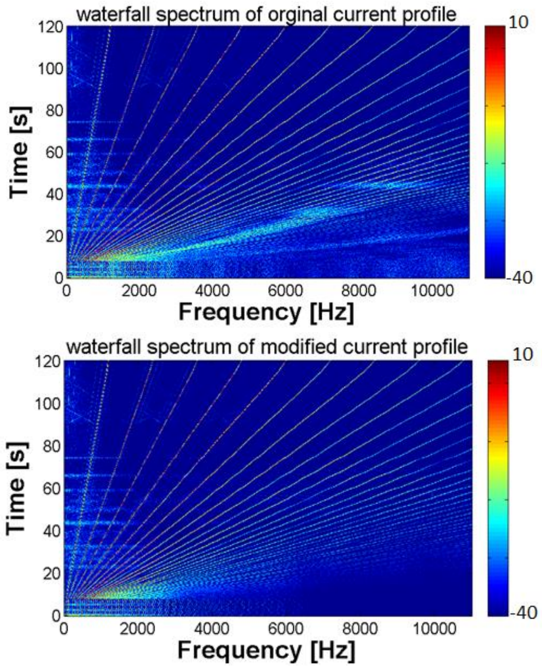


Figure 13: Source of inverted C-shape

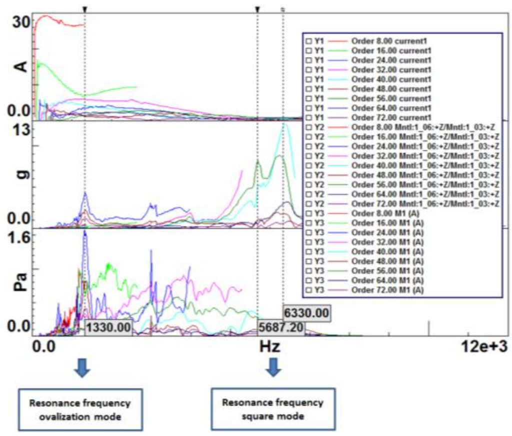


Figure 14: Order sections of phase current (top), accelerometer (middle) and microphone (bottom)

The sound pressure level reaches its maximum when order 24 excites the ‘ovalization’ mode at 1330Hz. Hence, the claim that the ‘ovalization’ mode is not excited in a 12/8 SR motor and therefore does not contribute to the acoustic noise, is not fully consistent with the practice: excitation of the ‘ovalization’ mode is still a major source of acoustic noise (Fig. 14).

To verify the ‘ovalization’ mode shape, a modal analysis is carried out on the 12/8 SR motor. Results can be found in Fig. 15. All measurement conditions should be taken into account. Firstly, the modal analysis is performed on a complete SR motor including, stator, rotor, end shields, cooling water, etc. Secondly, the SR motor was clamped at one side. Consequently, this means that the measured mode frequencies (Fig. 15 and Fig. 16) are a little bit different from the calculated FEM structural mode shapes (Fig. 3) because only the stator housing is there considered in free-free conditions.

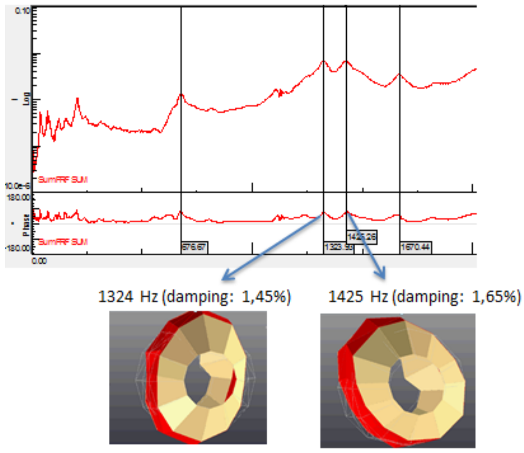


Figure 15: Ovalization modes of mounted 12/8 SRM

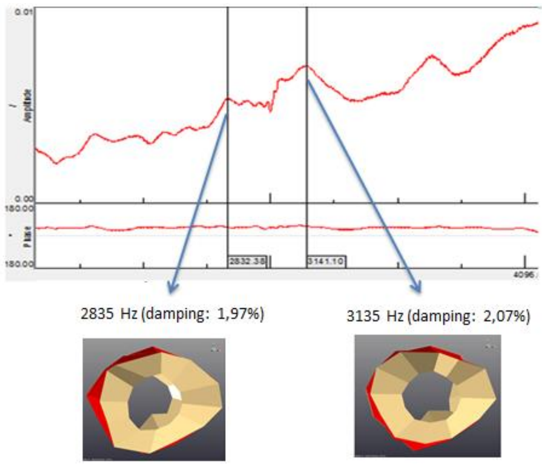


Figure 16: Triangular modes of mounted 12/8 SRM

Two ‘ovalization’ modes are presented (Fig. 15) at 1324Hz and 1425Hz. The ‘ovalization’ mode with out-of-phase of front/back is not presented due to the end shields. Measured resonance frequencies are higher and are more apart than simulated ones due to the end shields and clamping. The triangular modes (Fig. 16) at 2835Hz and 3135Hz are less visible because of the different boundary conditions between the measured and simulated modes. It was not possible to measure the square mode as the sampling frequency was too low during the modal analysis.

Finally, one resonance at 1330Hz in the frequency content of spectrograms in Fig. 10 is confirmed by a modal analysis on the stator housing which visualizes the 'ovalization' mode at this frequency.

4.2 Deflection shapes and time domain animation

During the development process of a new electric motor, several numerical techniques, such as BEM and FEM, can be applied to characterize the dynamic properties. As shown in the discussion of the experiments, the mode shapes play an important role in the vibro-acoustic behaviour of the motor. However, not all modes have equal importance. Furthermore, very often in operational conditions, the deformation of the structure doesn't correspond to a pure mode shape. Operational Deflection Shapes (ODS) can be used to evaluate the contribution of a mode during normal operating conditions. In this paragraph, the mode shapes are analysed in terms of the dominant orders. For lowly damped structures, it can be proven that the form of the ODS highly corresponds to the real (modal) mode. For highly damped structures, the response of a certain frequency will also be contributed by other resonance frequencies. In other words, the resulting ODS will contain in this case different modes.

The virtual reproduction of the mode shapes, carried out by an ODS analysis, is depicted in Fig. 17 and Fig. 18.

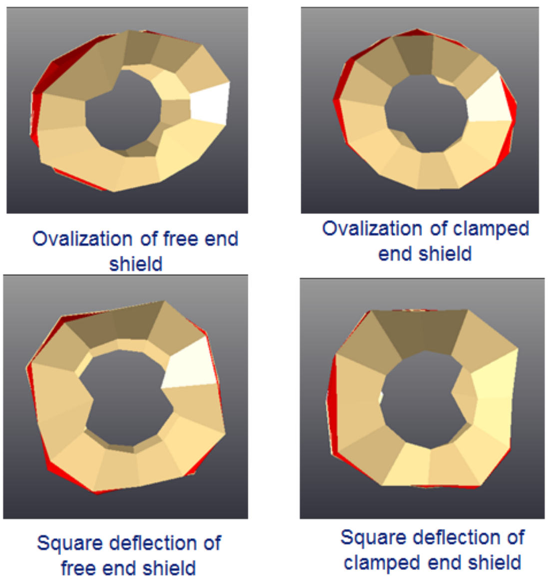


Figure 17: Ovalization (above) at 3370 rpm and square (below) deflection shapes at 5120rpm

The 'ovalization' deflection shape of the housing is visible in all orders at a particular frequency, rpm or time, but best in the 24th order. The 'ovalization' happens at both side panels. Both flanks move in phase with each other. The main difference with the modal analysis is that now the effects of the mechanical structure behaviour and excitation forces are included during operational conditions. The square deflection shape is also visible in all orders, but the best in 56th order. Deflections happen at both side panels but they are less pronounced at the clamped flank, especially at higher speeds (Fig. 18).

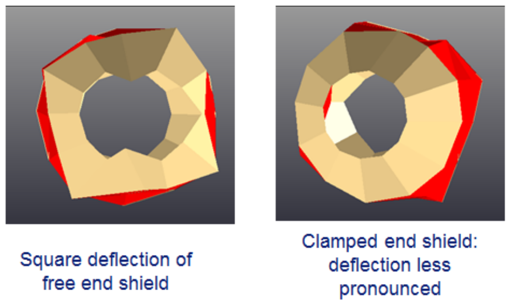


Figure 18: Square deflection shapes at 5960rpm

4.3 Sound Quality Evaluation

Characteristic for electric and hybrid vehicles is that their NVH performance is judged predominantly in noise perception terms rather than in noise levels. This is to a large extent due to the specific noise behaviour of the electric drive systems, causing a higher annoyance than expected from the sound pressure level [5]. The magnetic forces of the SR motor generate a typical tonal and high frequency noise, which is referred as whining noise. This source is the most dominant noise generated by the SR motor. Also other components of the SR motor are producing noise, as the unbalance of the rotor and the power electronics. The tonal and high frequency noise is annoying. This subjective appreciation can be more objectified by Sound Quality metrics. The ones used in this paper are: sharpness, tonality, loudness and Prominence Ratio (PR). These values should be reduced for more pleasant sound in the vehicle.

A first valuable metric is tonality. It is a metric that locates the tonal prominence of the sound. The reference sound for tonality is 1kHz sine tone with a level of 60dB and it is equal to 1 tu (tonality unit). The object of this metric is to evaluate the presence of tonal components in the spectrum of a noisy electric motor like a SR motor. Narrowband noises can also sound like tonal. The smaller the bandwidth is, the more tonal the noise propagates. Fig. 19 shows a reproduction of the tonality during an acceleration from 0 to 10000 rpm. It can be noticed that the higher the torque level of the SR motor is, the higher the tonality of the sound is.

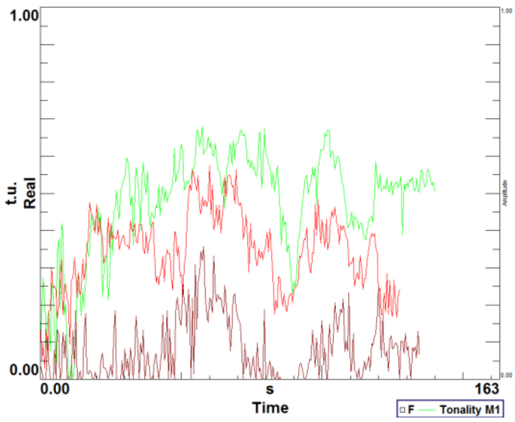


Figure 19: Tonality for an run-up between 0 and 10000rpm with a certain torque level: 0% (brown), 6% (red) and 49% (green)

A feature which is relevant to the agreeableness of the sound of rotational devices is its sharpness. In this way, it is possible to classify sound as shrill (sharp) or 'flat'. The sharpness can be expressed in the unit acum. When switching the SR motor on, a doubling of the sharpness is obtained, as shown in Fig. 20.

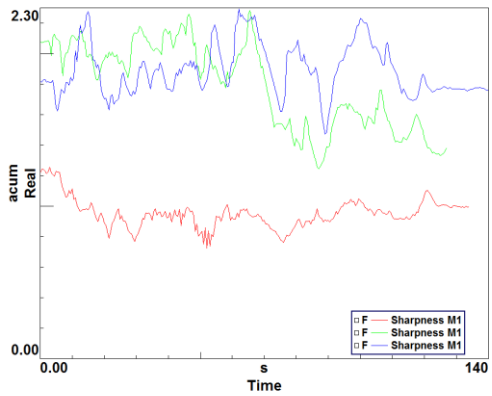


Figure 20: Sharpness for an run-up between 0 and 10000rpm with a certain torque level: 0% (red), 6% (green) and 49% (blue)

The amount of noise coming from one microphone in different load conditions can also be expressed in sones instead of the more familiar decibel (Fig. 21). An advantage is that the sone scale is linear, meaning that doubling the amplitude corresponds to a doubling of the perceived loudness. As a result, it is easier to interpret the sound levels for the different torque levels.

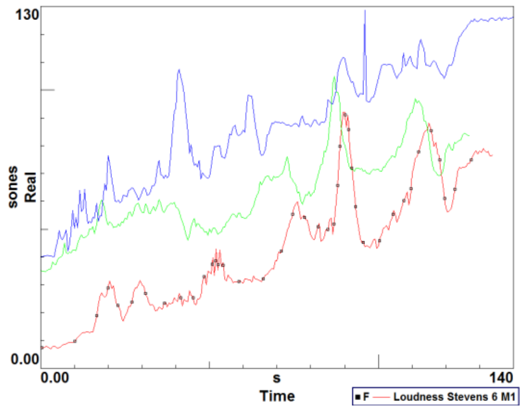


Figure 21: Loudness Stevens during run-up from 0 to 10000rpm with a certain torque level: 0% (red), 6% (green) and 49% (blue).

Fig. 22 shows one example of the 'ovalization' mode confirmation in the acoustic noise based on a prominence ratio sound metric in different load conditions. In the prominence ratio method, a discrete tone nominee is said prominent if the average SPL of the 'critical band' centred on the tone is at least 9dB higher than the average SPL of the contiguous critical bands.

Based on all these objectives techniques, it can be noticed that the torque level has a big effect on the tonality, the loudness and a smaller effect on the sharpness of the sound. In addition, prominence ratio can serve as a detection tool of the various stator mode shapes which are translated in the sound radiation. In this way, noise problems can be detected faster at a particular time, rotational speed and a known frequency which eventually enhances the optimization process of one typical problem.

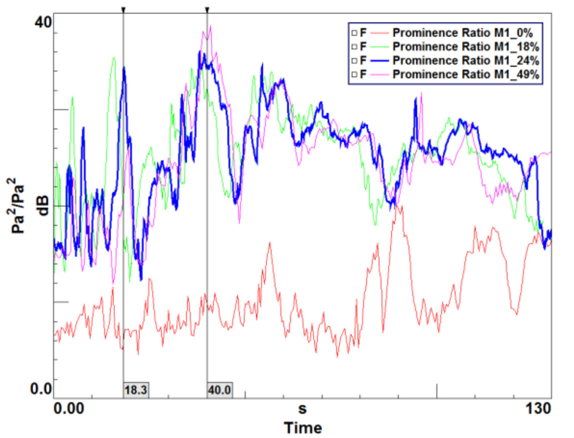


Figure 22a: Sound metric: Prominence ratio

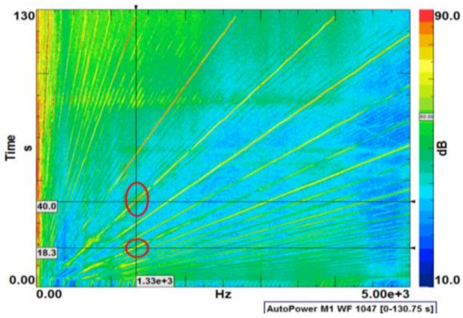


Figure 22b: Frequency content of one microphone near to the SR motor

5 Conclusion

Advanced NVH analytical tools, to analyse the spectral content of noise, current and vibrations in a 12/8 SR motor, have been introduced and applied to test rig measurements. In this way natural modes, harmonic components related to the motor construction and relations between measured signals are identified for a 12/8 SR motor. Finally, all these tools help engineers to obtain insight in the vibro-acoustic behaviour of an SR motor to optimize the NVH characteristics for automotive applications.

Acknowledgments

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