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ORIGINAL ARTICLE

Modal Analysis of an 8/6 Pole Switched Reluctance Motor Core with Different Materials and Assembly Method Using FEA

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ABSTRACT – Vibration causes acoustic nuisance, aggravating fatigue etc. Knowing that resonance is caused by amplified deformation when a structure is excited at natural frequency, modal analysis is important to identify the natural frequency and mode of deformation that may be excited in electrical machine. This study analyzes the natural frequency and mode shape of major components in 120v 4-Phase 8/6 Pole Switched Reluctance Motor. The material selected are materials that are commonly employed for electrical machines components. It was found that grey cast iron core has the lowest natural frequency for each mode from 1 to 3. This is mainly due to its lower elasticity modulus (10 times smaller in comparison to other materials). Solid and slinky rotor has a very low first mode natural frequency at tens of Hz, which is very susceptible to mechanically induced excitation vibration.

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INTRODUCTION

Electric motors are the main driver for our industrial development. Many applications use motors ranging from steady state rotating machinery like pumps, turbine generators, compressors to a more dynamic application like electric vehicle and CNC machining. One of the main problems in electrical machine is its vibration. As in any rotating equipment, an electrical machine is sensible to vibration-generating forces. These may include mechanically induced excitation or electromagnetically induced excitation [1].

Vibrations are often related to a natural frequency and resonance. Objects vibrate at certain frequencies due to the periodic exchange of energy between kinetic and potential forms. Resonance occurs when an excitation acts on an object with closely the identical frequency as the object's natural frequency. The result can be large, damaging, and disastrous vibrations.

STATE OF THE ART

Source of vibration

Excessive vibration can cause damages in electric motor in different ways: (1) It can accelerate bearing failure by causing indentations on the bearing raceways at the ball or roller spacing. (2) It can loosen windings and cause mechanical damage to insulation by fracturing, flaking, or eroding of the material. (3) The excessive movement can generate high temperature, and as a result, the lead wires can become brittle. The mechanical causes of the electromagnetic force [1] are primarily the air gap eccentricity between the stator and the rotor. The sources of air gap eccentricity can be divided into four categories: shape deviation, parallel eccentricity, inclined eccentricity, and curved eccentricity. The surface corrugations of the outer rotor circle and inner stator circle will affect the homogeneity of the air gap length. Furthermore, when the stator and rotor are not regular cylinders, their shape deviation can produce air gap eccentricity.

Material selection for rotor core and stator core

It is known that the selection of material and the manufacturing process of the component will influence the natural frequency and mode shape of the components of the machine. Therefore, here we review the materials and manufacturing process that is involved in manufacturing an electric motor.

In practice, the base lamination material used for stators is essentially the same for rotors when it is required to punch the stator and rotor laminations simultaneously with the same die. However, some variances may occur between these two applications [2]. Having the foremost function of a stator is to generate a rotating magnetic field, its lamination material of the stator has higher necessities for electromagnetic properties. Unlike the rotor that is subject to large centrifugal forces as it rotates, the forces acting on the stator are much lower, leading to lesser requirements for mechanical strength properties. Based on these reasons, segmented cores are extensively used in stators for all types of motors but are restricted from use in high-speed rotors due to high centrifugal forces.

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Of all the soft magnetic core materials, the most broadly used materials are known as electrical steels, which are separated into numerous general classes. Among them, a major class is silicon steel, in which silicon is the main alloying element. Alloying the steel with silicon can noticeably increase the volume resistivity of the steel and thereby diminish the eddy-current loss. In addition, silicon can affect the grain structure of the steel and thus gives enhanced core loss by the reduction of the hysteresis loss in non-oriented electrical steels [2].

An alternative material normally used for rotating electric equipment is the nickel alloy due to its high permeability and low core losses. These features make it ideal for motors. However, its cost is significantly higher than silicon steel. Nickel alloys require a very careful annealing cycle. During the annealing process, surface insulation films are formed on the surfaces of the nickel alloy laminations [2].

In some applications that require high flux density without concentration, cobalt alloys be used to make motor laminations. This type of alloys is also used in weight- sensitive applications such as space shuttles and satellites. Usually cobalt alloys contain 48%–50% cobalt and 2% vanadium, making them high tensile strengths. Hence, for some high-speed, large-power motors, silicon steel is no longer applicable due to its low mechanical strengths, and cobalt alloys become an exceptional choice for the lamination material. Like nickel alloys, cobalt alloys require careful annealing after stamping and making oxide coatings on lamination surfaces is a separate process.[2]

Other elements such as manganese and aluminum can also aid lessen core losses due to the different mechanisms from silicon. The addition of these elements into steel will modify the metallurgical grain structure to contribute to lowering of the core loss.[2]

Cold rolled lamination steel is the most cost-effective and most common material for core laminations of low-cost motors. Similar to carbon steel, this material has comparative high core losses. It typically involves annealing after stamping to develop ideal properties and to add oxide coatings on the lamination surfaces.[2]

Method of fabrication for rotor core and stator core

Laminations are the steel portions of the stator and rotor consisting of thin lamination sheets stacked together. These laminations can be stacked "loose", welded, or bonded together depending on the application. Laminations sheets are used instead of a solid piece to reduce eddy current losses [3-4].

A stack of laminations is assembled for a rotor core and stator core. Laminations are often stacked on a mandrel and then compressed under high pressure for obtaining the rigidity of the rotor core in the axial direction. Traditionally, laminations have been bonded using either adhesives or pins. Obviously, these stacking methods require additional operations and thus increase manufacturing costs and production lead time. In last Table 1 Materials applied to the studied components with its properties several decades, several manufacturing processes have been developed to simplify the lamination stacking operation without using adhesives or pins. A simple method is to weld the rotor core when it is compressed. Another process involves interlocking the laminations at their outer tips with a die-punching machine so that corresponding laminations can interlock one another during assembly [2-4].

Using new methods for fabricating rotor cores and stator cores is highly anticipated for both the cost reduction and manufacturing efficiency. One such design is known as the slinky method [5]. With this method, a rotor and stator core are built up from a continuous slotted strip of silicon steel rather than cross-sectional laminations in a conventional manufacturing process. The strip is wound edgewise in a helical configuration by a coiling machine that consists of three flanged rolls. By making the stacked strip to the desired thickness, the rolled core is compressed longitudinally and welded at the outer circumferential surface of the core, avoiding noise caused by vibration. Figure 1 below shows the slinky conventional stacked lamination (left) and the slinky lamination (right).

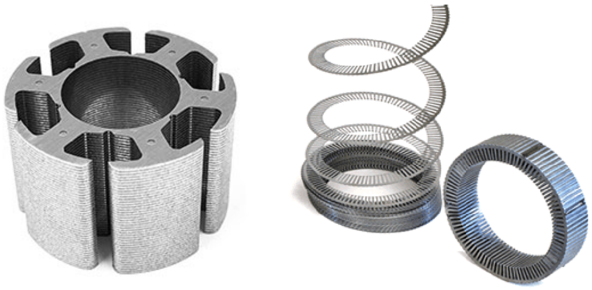

Figure 1. Laminations assembly for core. Left: stacked laminations. Right: Slinky laminations.

Methods for modal analysis

Modal analysis is the process of discovering a system's intrinsic dynamic features, such as natural frequencies, damping factors, and mode shape, and applying them to construct a mathematical model for its dynamic behaviour is known as modal analysis. The information for the characteristics is known as the modal data, and the constructed mathematical model is known as the modal model of the system. The vibration response of a linear time-invariant dynamical system be described as a linear combination of a set of simple harmonic movements termed the natural mode of vibration, according to modal analysis. This notion is similar to representing a complex waveform with a Fourier mixture of sine and cosine waves.

It is known that natural frequency is proportional to the elasticity modulus and inversely proportional to the mass of the object. However, in a non-homogenous and non-isotropic with complex geometry structure like the electrical machine core, finding the natural frequency is not easy. Finite element analysis (FEA) is thus common in finding the natural frequency of complex structure like machine stator and rotor core [6]. SOLIDWORKS® software offers countless types of simulation studies, one of it is frequency study. A body disturbed from its rest position leans to vibrate at certain frequencies called natural, or resonant frequencies. The lowest natural frequency is called the fundamental frequency. For each natural frequency, the body takes a certain shape called mode shape. Frequency analysis calculates the natural frequencies and the associated mode shapes.

In theory, a body has an infinite number of modes. In FEA, there are theoretically as many modes as degrees of freedom (DOFs). In most cases, only a few modes are considered. Excessive response arises if a body is exposed to a dynamic load operating at one of its natural frequencies. This phenomenon is called resonance. Frequency analysis can helps avoid failure due to excessive stresses caused by resonance. It also delivers information to solve dynamic response problems.

METHODOLOGY

Rotor and Stator part of a motor is known as the major parts of any motor, the studies will be done at the stator and rotor parts of the 120v 4-phase 8/6 pole SRM. Figure 2 shows the design and dimension of the SRM machine.

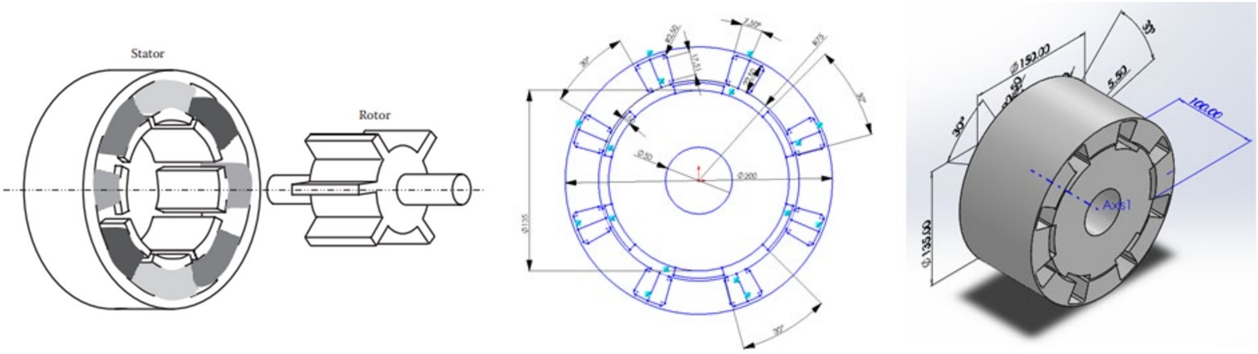

Figure 2. Design and dimensions of the 8/6 pole SRM studied.

The construction of Finite Element Method for computing the natural frequencies of the motor components is performed according to the following steps:

1. Select the model of the components
2. Configure the materials that applied
3. Configure the constrains of the components
4. Create mesh and run the study
5. Study the result in first 3 mode shape

The materials chosen are from the most common materials that are used in electrical machine manufacturing. The list of the material and their mechanical characteristics that may influence the natural frequencies are listed in Table 1 below.

Table 1. Materials for stator and rotor core and its mechanical characteristics.

Material	Carbon Steel	Cobalt Steel	Grey Cast Iron	Aluminium Alloy	Vanadium Permandur
Mass Density (kg/m^3)	7870	8900	7200	2700	8120
Tensile Strength (N/m^2)	4.2e+08	2.35e+08	1.51658e+08	6.89356e+07	1.345e+09
Yield Strength (N/m^2)	3.5e+08	N/A	N/A	2.75742e+07	1.275e+09
Elastic Modulus (N/m^2)	2.05e+11	2.11e+11	6.61781e+10	6.9e+10	2.07e+11
Poisson’s Ratio	0.29	0.31	0.27	0.33	0.31

Thermal Expansion Coefficient (K)	1.17e-05	1.2e-05	1.2e-05	2.4e-05	N/A

The method of fabrication and assembly of the stator and rotor core chosen are solid core, stacked laminations and slinky laminations. The 3D model was developed in Solidworks. The model of the 3 rotor and stator core structure (solid, stacked, and slinky laminations) are shown in the Figure 3 below. They consist of more than 5000 nodes. The frequency study simulation module from Solidworks was used.

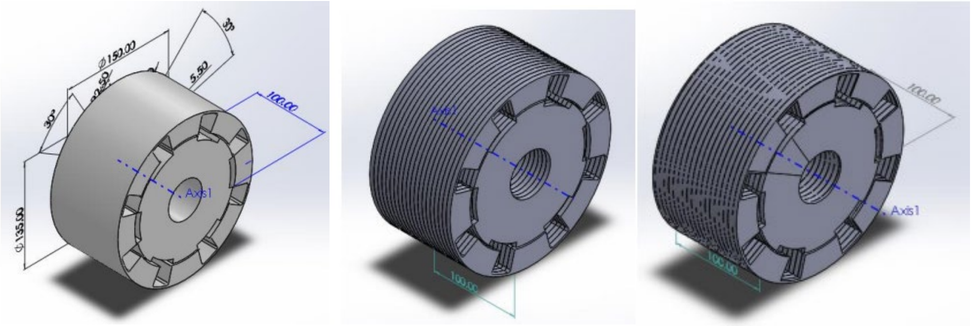

Figure 3. The 3D model of the stator and rotor core. From left to right: Solid rotor, stacked lamination, slinky lamination.

RESULTS AND DISCUSSION

We are observing the first three modes that occurs in each assembly choice (solid, stacked or slinky lamination) for materials selection. The results here will be presented for each assembly choice.

Solid core assembly

Figure 4 shows the mode shape, the natural frequency at which they occur and the resulting deformation of the solid stator core structure. For the stator, the first 3 mode occurs at nearly the same frequency for all materials. The lowest natural frequency is observed for grey cast iron stator core at around 1460 Hz. While other materials stator have higher natural frequency at more than 2400 Hz. The deformation generated is the smallest for Aluminium alloy, with a deformation of 11 micrometers.

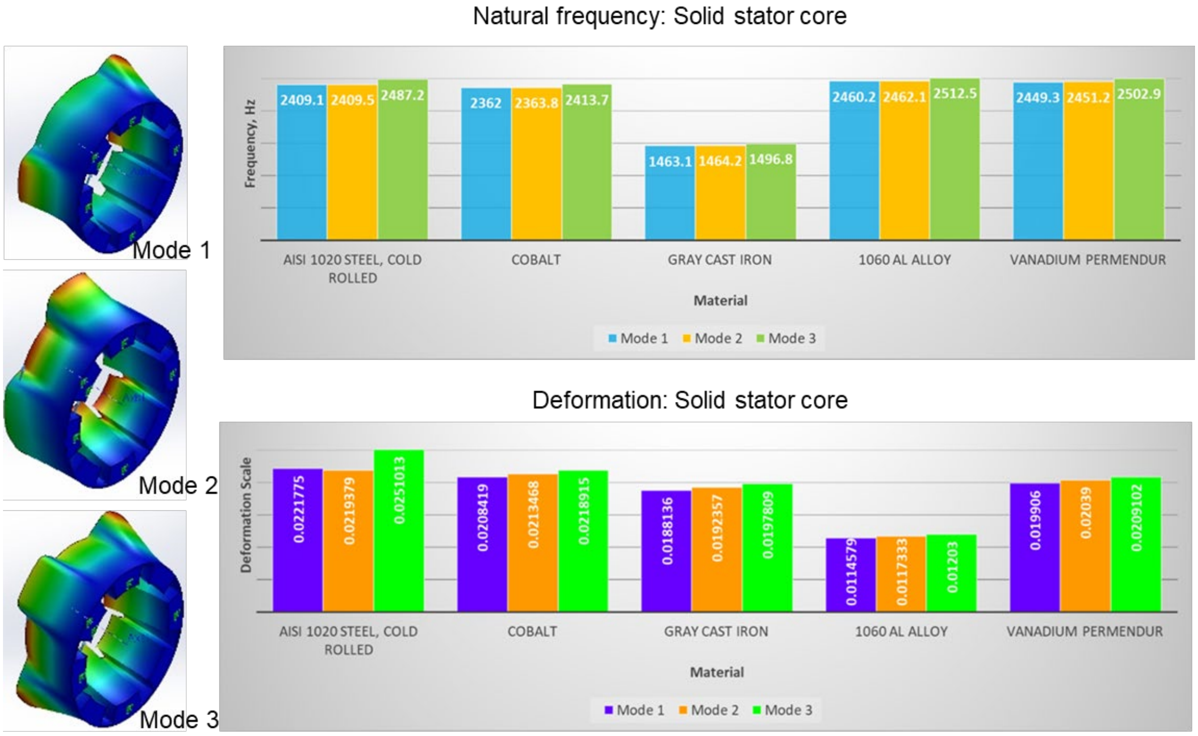

Figure 4. Solid stator core: the first 3 deformation mode shape. The natural frequency and deformation.

Figure 5 on the other hand shows the mode shape, the natural frequency at which they occur and the resulting deformation of the solid rotor core structure. Mode 1 has a remarkably low natural frequency regardless the materials.

The lowest natural frequency occurs for a grey cast iron rotor core at 42 Hz. Mode 2 and 3 occurs at the around the same frequency for all other materials, with all of them occurring at around 10,600 Hz. The most significant deformation is generated by Mode 1 regardless the materials. The order of magnitude of all deformations are at tens of micrometers.

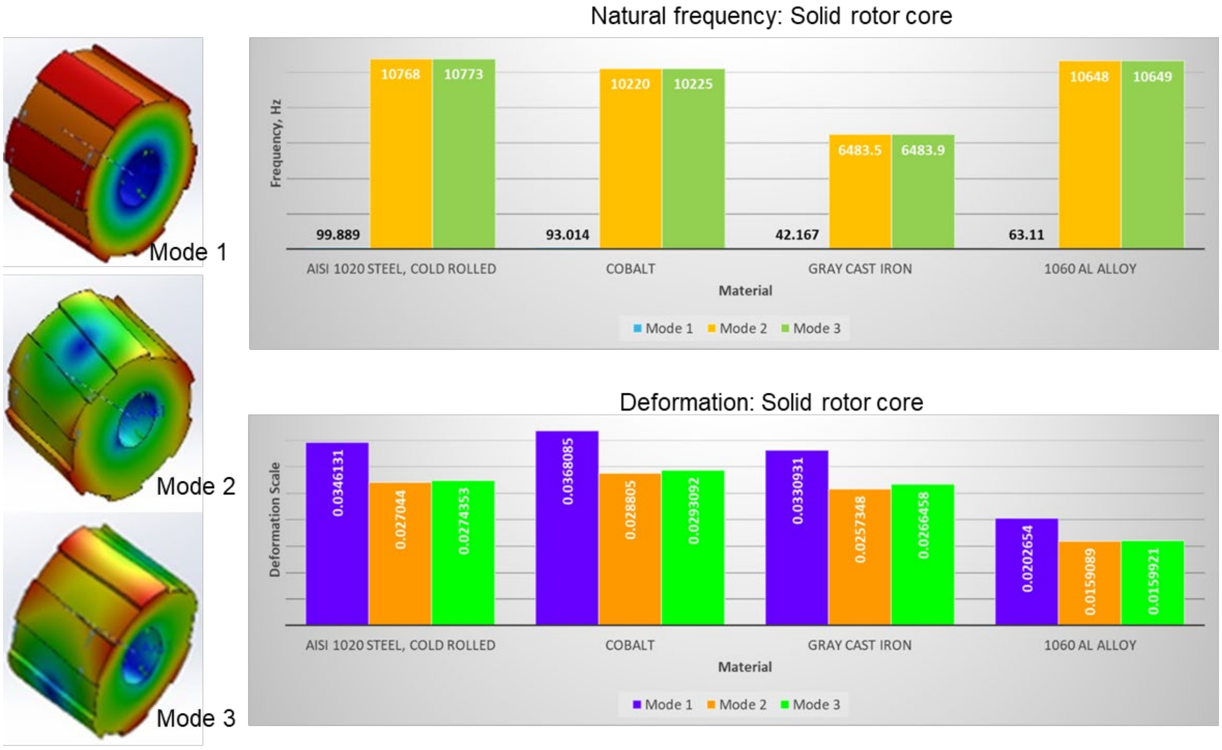

Figure 5. Solid rotor core: the first 3 deformation mode shape. The natural frequency and deformation.

Stacked lamination assembly

Figure 6 shows the mode shape, the natural frequency at which they occur and the resulting deformation of the stacked lamination stator core structure. For the stator, the first 3 mode occurs at around the same frequency for all materials. The

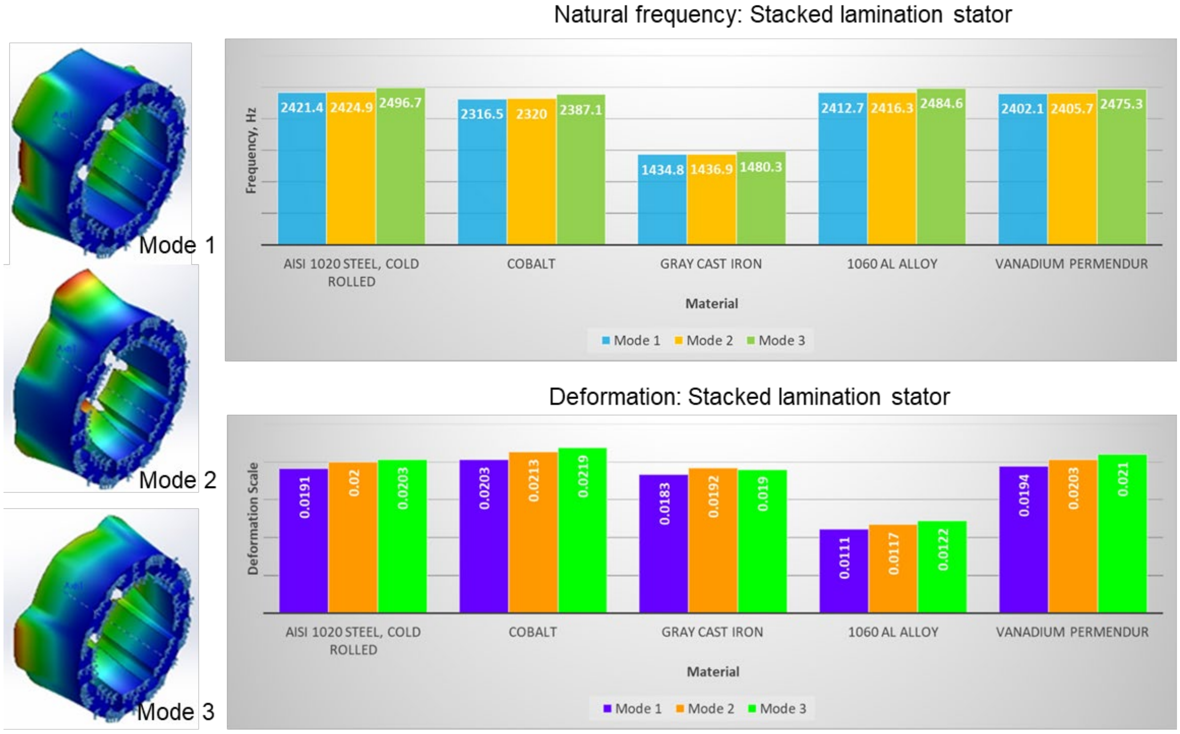

Figure 6. Stacked lamination stator: the first 3 deformation mode shape. The natural frequency and deformation

lowest natural frequency is observed for grey cast iron at around 1400 Hz. All deformation generated at these modes has the same order of magnitude at tens of micrometers.

Figure 7 on the other hand shows the mode shape, the natural frequency at which they occur and the resulting deformation of the stacked laminations rotor core structure. The same observation as in solid core can also be observed here. The first mode occurs at an extremely low frequency which we will consider negligible here. This is reasonable as it is impossible to create an excitation with consistent frequency as low as micro-Hertz mechanically and even electrically. For mode 2 and 3, the natural frequency occurs at around the same frequency, with grey cast iron again having the lowest natural frequency at around 6,500 Hz. The same observation as in the solid core can be made for the deformation generated.

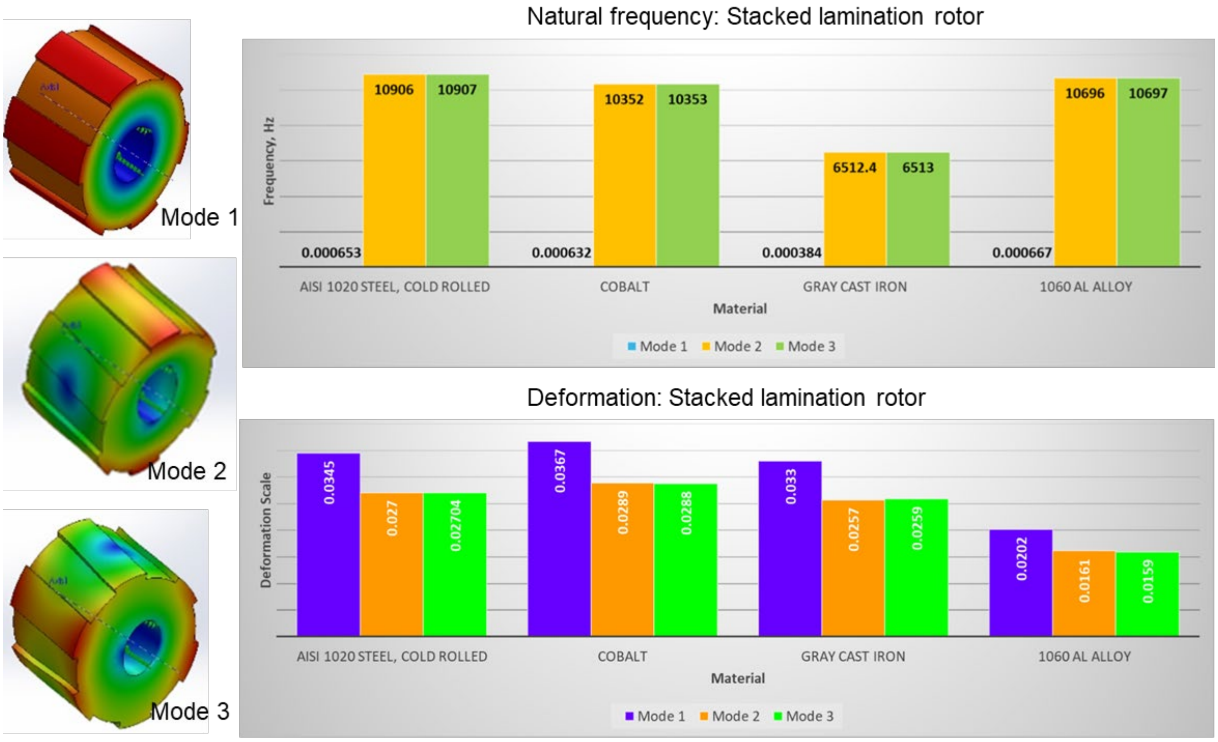

Figure 7. Stacked lamination rotor: the first 3 deformation mode shape. The natural frequency and deformation

Slinky lamination assembly

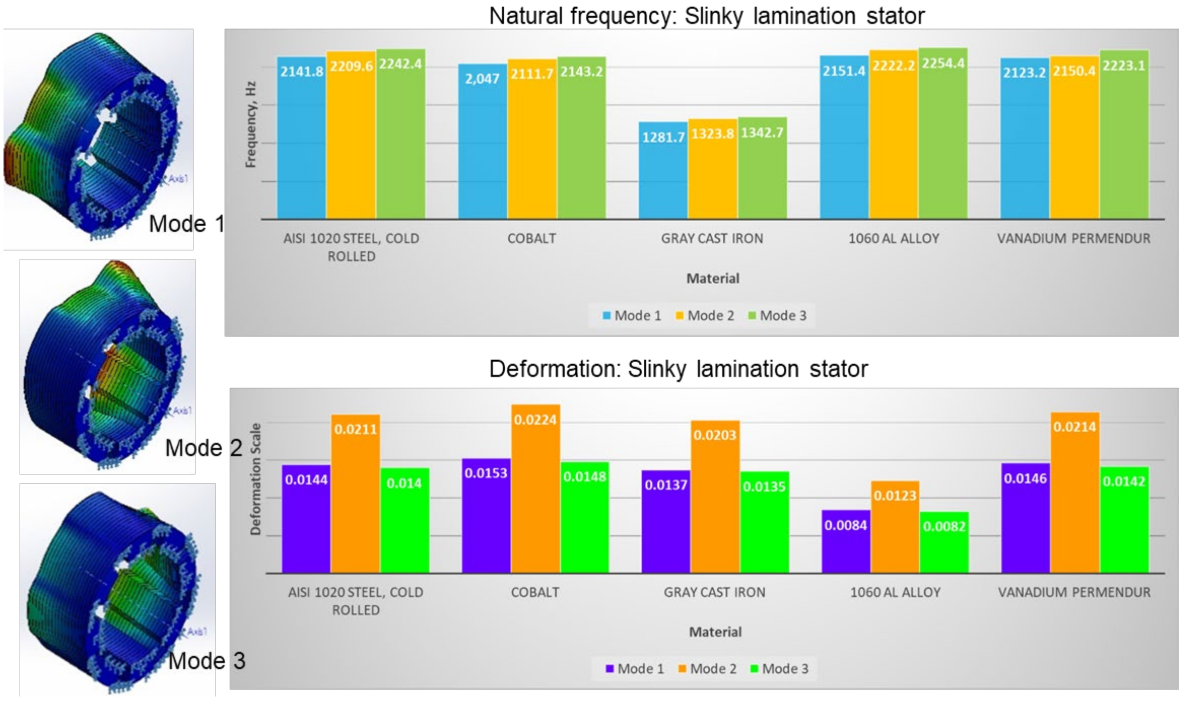

Figure 8. Slinky lamination rotor: the first 3 deformation mode shape. The natural frequency and deformation

Figure 8 shows the mode shape, the natural frequency at which they occur and the resulting deformation of the slinky lamination stator core structure. For the stator, the same trend as in solid and stacked lamination for the natural frequency can be made. However, the deformation generated by mode 2 is significantly higher than the other modes, at around 22 micrometers.

Figure 9 on the other hand shows the mode shape, the natural frequency at which they occur and the resulting deformation of the slinky lamination's rotor core structure. The same remark as in solid lamination structure, where the first mode occurs at tens of Hz. It is however the mode that generates the highest deformation in case of its occurrence.

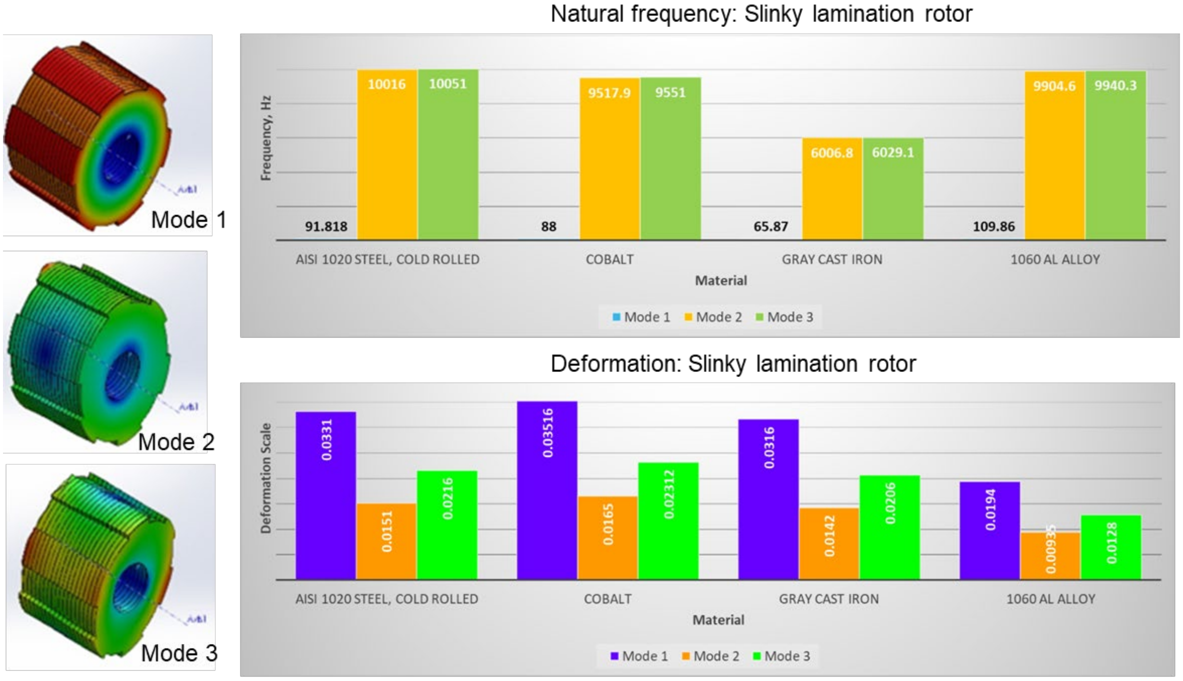

Figure 9. Slinky lamination rotor: the first 3 deformation mode shape. The natural frequency and deformation

CONCLUSION AND PERSPECTIVES

In this study, modal analysis study of an 8/6 pole SRM machine was done under the influence of two variables, namely the materials selection for the core and the assembly methods choices. Different usually employed materials was opted for both stator and rotor core. As for the assembly method, solid core, stacked lamination core and slinky lamination core were considered. Using FEA analysis, it was found that grey cast iron core has the lowest natural frequency for each mode from 1 to 3. This is mainly due to its lower elasticity modulus (10 times smaller in comparison to other materials). Solid and slinky rotor has a very low first mode natural frequency at tens of Hz, which is very susceptible to mechanically induced excitation vibration. The stacked lamination however has an extremely low first mode natural frequency that can be considered negligible. Among the 3 assembly methods, the solid rotor has the lowest natural frequencies.

In perspectives, deciding which natural frequency is risky depends on the excitations, which can come from 2 sources: electromagnetic and external mechanical. The near future study is to do the frequency response study of these stator and rotor core under different relevant excitation, depending on application. From there, the proper choice of material and assembly method can be determined.

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