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USING FINITE ELEMENT ANALYSIS (FEA) TO ESTIMATE REED FREQUENCY OF VERTICAL MOTORS FOR PUMP APPLICATIONS

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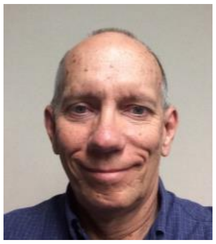

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ABSTRACT

Vertical motor/pump systems that run close to the motor reed frequency may experience significantly high vibration levels, which can damage the motor as well as the entire pump system. These damages can result in costly repairs of the motor/pump, therefore accurate prediction of motor reed frequency will enable a more cost- and performance-effective pump base design and will extend system life. A recent trend has shown that end users are requesting more accurate prediction of motor reed frequency (+/- 10%), enabling better pump base design with less potential for base rework. This study describes the utilization of Finite Element Analysis (FEA) as a tool in the prediction of vertical motor reed frequency and its correlation with extensive bump test results. Preliminary analysis first identified parameters that affect motor reed frequency. It was then followed by sensitivity studies, which further examined the impact of each parameter. One of the critical parameters is the stator core modulus. Because of its laminated structure, the core modulus is not uniform, which has a significant effect on motor reed frequency. The critical parameters were calibrated against existing test data using design of experiments. Lastly, they were used to verify future motor performance. This paper discusses the background behind the analysis, the FEA verification process as well as test validation.

INTRODUCTION

In vertical pump applications, reed frequency is a widely discussed topic because of its effect on the entire pump system. Excessive vibration due to operation near the reed frequency can lead to component failure and eventually system shut down and production losses. Thus, it is important to design the pump system with adequate operating margin away from the reed frequency. To properly design a pump system, one of the key parameters provided by the motor manufacturer is the motor reed frequency on a solid foundation. The pump manufacturer uses this information to design the motor stand for proper structural support and to estimate the pump system frequency.

Weeks before the final motor design, the motor manufacturer has to submit a motor outline drawing with the motor reed frequency. Since the final design is not complete, the motor manufacturer has to rely on empirical calculations along with interpolation of historical test data from similar motor ratings to provide an estimated reed frequency to the customer. For ratings with little test data, alternative methods, such as extrapolation, finite element analysis (FEA)…etc., can be used to obtain the reed frequency.

In the past few years, there has been an increasing demand for accurate (+/- 10%) prediction of motor reed frequency. For large vertical motors with a frequency range from approximately 10 to 30 Hz, this can sometimes be a concern due to the narrow tolerance band, especially for motors with a lower frequency range. This study focuses on methods to accurately predict motor reed frequency on a solid foundation. It will first illustrate approaches to model vertical motors using FEA by examining different parameters and validating FEA results with test data. This study will not only show a systematic approach to determining accurate reed frequency predictions but can also serve as a spring board for further discussions between the pump and motor industries to define requirements that best serve the pump industry's needs.

FUNDAMENTAL UNDERSTANDING

A classical cantilever beam problem can be used to simulate the response of the vertical motor on a solid foundation.

Figure 1: Cantilever Beam with an Excitation Force

The static cantilever beam deflection formula found in Mechanical Engineering textbooks is:

$$\Delta_s = \frac{PL^3}{3EI} \tag{1}$$

Where $\Delta_s = Static\ deflection\ of\ the\ motor\ (in)$
$P = Excitation\ force\ (lbs)$

$L = Distance\ from\ the\ center\ of\ gravity\ (CG)\ to\ the\ mounting\ flange\ (in)$
$E = Equivalent\ Young's\ Modulus\ of\ the\ motor\ (psi)$
$I = The\ effective\ moment\ of\ inertia\ of\ the\ motor\ (in^4)$

Based on the static deflection, one can derive the motor reed frequency using the following equation from National Electrical Manufacturers Association (NEMA) MG 1-2014.

$$f_n = \frac{1}{2\pi}\sqrt{g/\Delta_s} \tag{2}$$

Where $f_n = Resonant\ frequency\ of\ the\ vertical\ motor\ (rpm)$
$g = 1{,}389{,}600\ in/min^2$

The main challenge with Equation (1) is finding the equivalent Young's Modulus and the effective moment of inertia, since unlike a regular beam, a motor does not have homogenous material properties and constant moment of inertia throughout the entire structure. To extract those values and the reed frequency, more detailed modeling and alternative methods, such as FEA, Experimental Modal analysis (EMA)...etc. are required. The FEA technique is the method used for this study.

SIMULATION DEVELOPMENT PROCESS

Figure 2 shows a flowchart that illustrates the entire simulation process.

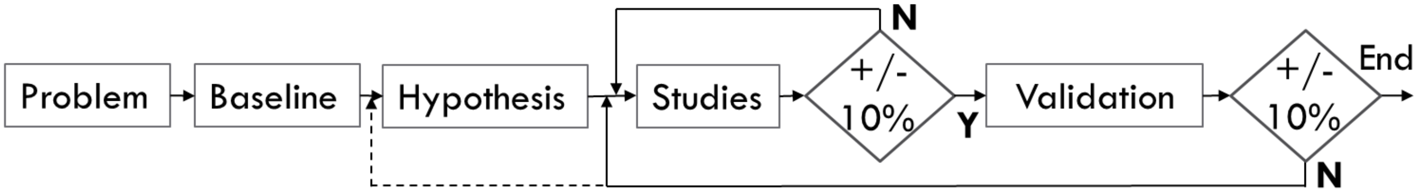

Figure 2: Flowchart of the Process

The "Problem" is to predict the reed frequency to within +/- 10% accuracy. To resolve this problem, it is important to first identify a baseline motor that can be used as a reference. The baseline motor design must have multiple test data points to minimize data variation. The next step is to model the baseline design using FEA, and this is done through a series of hypothesis and studies by identifying parameters of interest and validating results against the test data for accuracy (+/- 10% error). After verifying the baseline FEA model, another round of tests is carried out against additional motor ratings using the same parameters. Throughout the process, multiple iterations are necessary to fine-tune each parameter, and if at any time, the model fails the accuracy comparison, parameters are reevaluated again.

In this study, two baseline designs were selected: 6P 1500 HP and 6P 600 HP. Both ratings have multiple units with test data for each unit.

Parameter Identification for FEA Analysis

Figure 3 shows a breakdown of different potential parameters that were examined during the study.

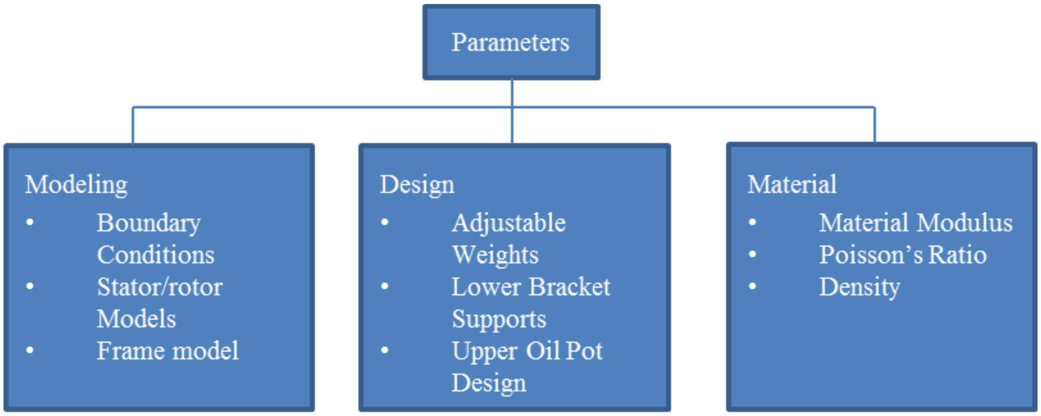

Figure 3: A List of Parameters Studied for the FEA Analysis

Modeling

Modeling focuses on FEA model development and geometry constraints. The goal is to develop a model that adequately represents the actual system. Oversimplification of the model will lead to inaccurate results, but an overly detailed model will require excessive processing time and computer resources. While it is essential to create an acceptable model, it is equally important to provide proper boundary conditions to constrain the model's degrees of freedom. The main boundary condition in this study is the support between the lower bracket and the ground as shown in Figure 4.

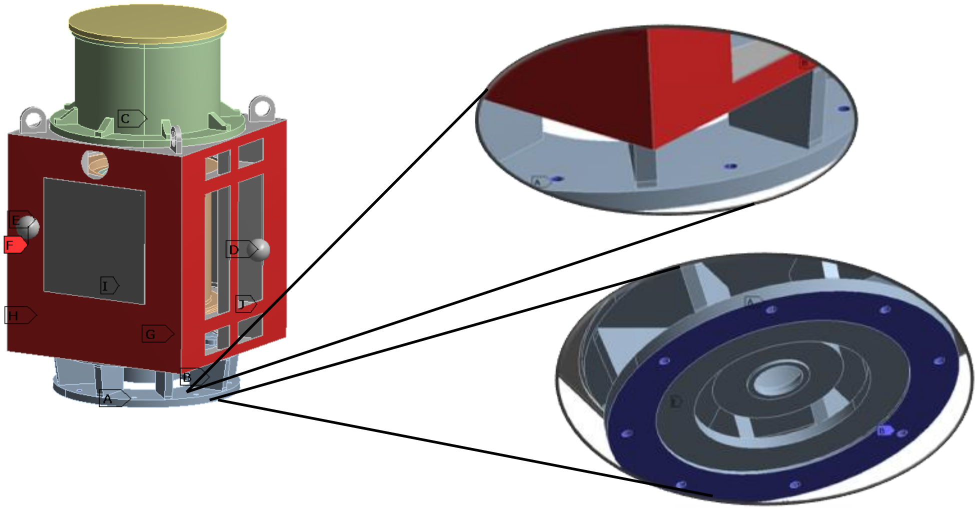

Figure 4: Boundary Conditions for the Motor Lower Bracket

To simulate the contact between the motor bracket flange and the ground, various constraints were tested on the mating surface and the bolt holes in the FEA model.

Design

Design involves comparing the value of different kinds of add-on features and how they perform based on the sensitivity study. Each feature was evaluated to understand the impact on the reed frequency. One of the designs was the use of adjustable weights to shift the center of gravity (CG) of the machine. Another design feature was a modified lower bracket support with slotted cuts (Figure 5). This is a common practice in the field to weaken the stiffness.

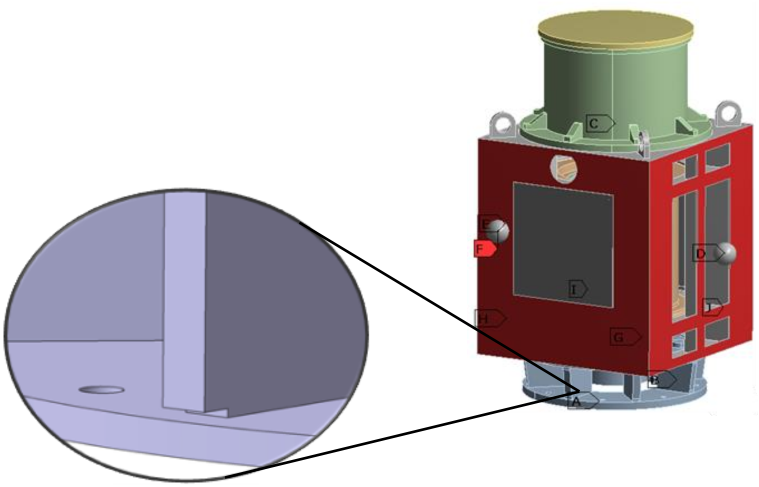

Figure 5: Close-up of the Slotted Cut on the Support Rib for the Bracket

Lastly, the oil pot on the non-drive end of the motor was redesigned to accommodate more mass on top of the motor.

Material

This category pertains to the material properties used in the analysis. Since the stator core occupies a significant mass in a motor, core material properties have a significant role on the motor reed frequency. Tang and other researchers have shown that the frequency is dependent on the material properties (Tang <et al>, 2004).

$$f \propto \sqrt{\frac{E}{\rho}} \tag{3}$$

ρ is the equivalent core density (lb/in^3). In addition, many researchers have shown that because of the laminated core construction, the addition of copper winding and resin impregnation, core modulus is different than regular steel modulus. Figure 6 shows how a core is stacked, copper windings are installed inside the core and core after impregnation.

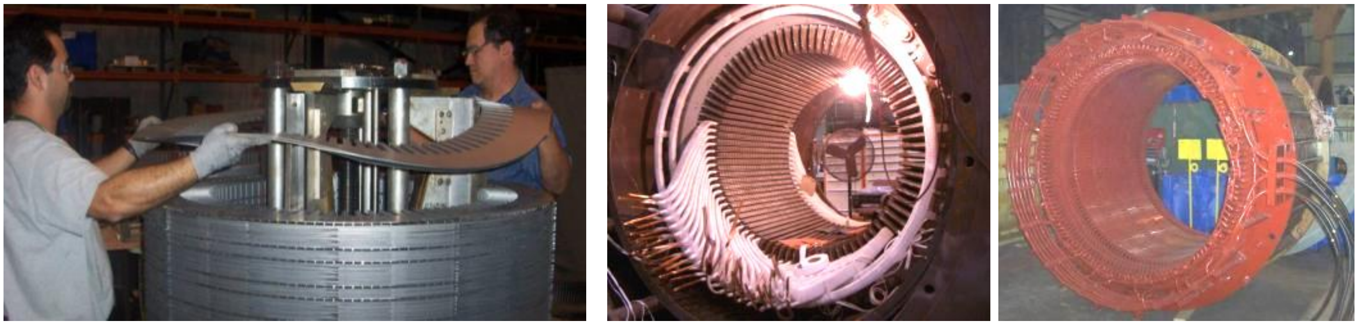

Figure 6: Core Stacking Process (left), Installing Copper Winding inside the Core (center), and Stator Core after Impregnation (right)

For the laminated structure, due to the frictional interface between laminations, the core modulus behaves much differently in the axial direction than in the radial direction. As a result, compared to a solid material, it is more difficult to characterize the modulus of a lamination stack. For smaller cores, some researchers have suggested using an equivalent density and modulus to represent the entire core and copper. For large machines, authors believe that modeling as an anisotropic material is a better representative of the actual machine's characteristics.

Design of Experiment and Sensitivity Studies

Initial analyses involved varying different parameters to study the effect each has on the output. One of the main interests of this study is the material modulus. Below is an example of the design of experiment on the material modulus and the corresponding changes in the output. The table in Figure 7 presents the parametric study of the input variations (Young's modulus, Poisson's ratio and Shear modulus). Certain inputs or a combination of inputs have more effect on the reed frequency (output) than others. This is captured in the corresponding graph in Figure 7.

	E			ν			G		
Case	Ex	Ey	Ez	νxy	νxz	νyz	Gxy	Gxz	Gyz
1	-			-			-		
2	↑		-	-			-		
3	↓		-						
4	-		↑						
5	-		↓						
6	↑		↑						
7	↓		↓						
8	-			↑	-		-		
9				↓	-				
10				-	↑				
11				-	↓				
12				↑	↑				
13				↓	↓				
14	-			-			↑	-	
15							↓	-	
16							-	↑	
17							-	↓	
18							↑	↑	
19							↓	↓	
20	↑		↑	↑	↑		-		
21	↓		↓	↓	↓		-		
22	↑		↑	-			↑	↑	
23	↓		↓	-			↓	↓	
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25	-			↓	↓		↓	↓	
26	↑								
27	↓								

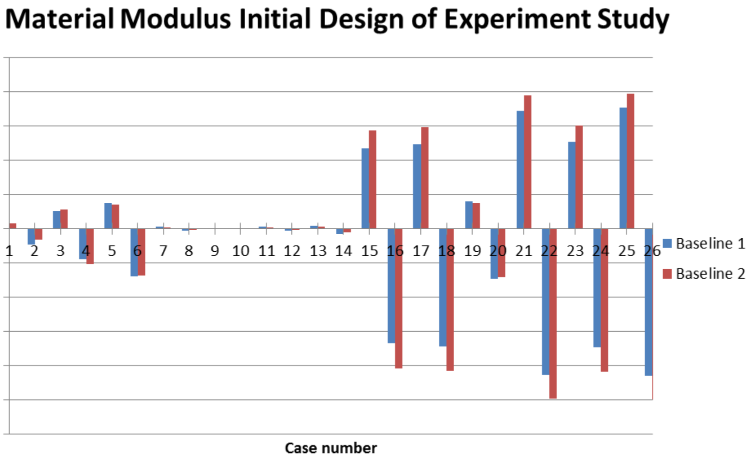

Figure 7: An Example of the Design of Experiment on Material Properties

Throughout the study, it was found that homogenous material properties led to erroneous reed frequency estimation. The same conclusion could not be confirmed for small motors because the study was not carried out for small motors. Ideally, the modulus values should be obtained through rigorous material testing which can be quite expensive as the properties change with geometry. Alternatively, the use of design of experiment allowed to quickly investigate nearly 400 variations of core moduli inside the design space and compared against the baseline designs to find the optimum moduli values.

Similarly, design of experiment was carried out for different design features. These design features were intended for fine tuning purpose, so for some motors where the tolerance frequency band is +/- 2 Hz, even minimum effect on the reed frequency is still valuable. The effect was not relevant for other cases due to various reasons (larger overall tolerance band, lack of shift in the CG...etc.).

Lastly, it was important to investigate different geometric models and boundary condition constraints. The stator model was represented as a solid cylinder. Since stator teeth respond to a much higher frequency, and the reed frequency is considered a low frequency response, stator teeth were not modeled in FEA to minimize model complexity. Stator winding and stator core were modeled separately because the material properties are substantially different. Rotor was modeled both ways as a cylinder and as a point mass. The frame and bearing brackets were simplified to eliminate unnecessary details. Additional accessories, such as coolers and lead boxes, were modeled as point masses. At the end, the FEA model weight was adjusted using equivalent density at the component level to match the tested weight value. Different modeling techniques were attempted to simulate the bolt constraint and the contact surfaces.

After many iterations, at the end of the study, the FEA result came within +/- 10% of the average test result for each baseline.

Table 1: Errors for Baseline Cases

	Error
Baseline 1 (6P 1500 HP)	-8.96 %
Baseline 2 (6P 600 HP)	8.88 %

Validation

With the general FEA analysis procedures established, it was crucial to verify the result for other ratings, in order to ensure the same procedures can be applied to other motors. Over the next several months, different machine ratings were selected, and FEA models were compared against the test data. Bump tests were performed on multiple units using a calibrated hammer and single axis accelerometer. It was very important to perform the test in a consistent manner to minimize variation to the results.

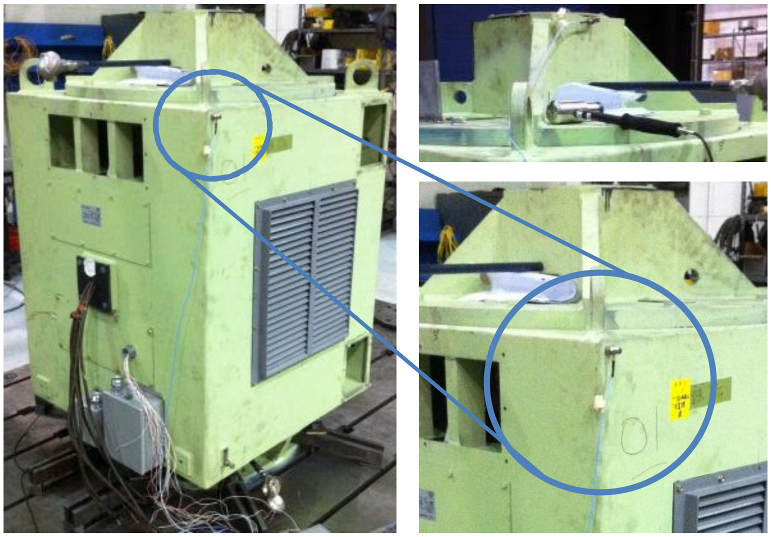

Figure 8: Test Setup and Instruments

In the past, the bump test results for large vertical motors on smaller test floors showed inconsistent test results; an indication that insufficient foundation mass can affect the test results. As a result, all motors for this study were mounted on a large test foundation with a 5-inch steel plate connected to the solid bedrock through a series of steel beams. Additionally, the same personnel and calibrated instruments were used for every test to minimize variability due to test personnel and instruments. Lastly, on certain ratings, tests were performed on multiple units to gather more relevant data. In addition, bump tests were performed on different design features (slotted supports, adjustable weight…etc.) to validate against the FEA results.

Test Results

Figure 9 shows the output error % comparison for baselines and other motor ratings.

Comparison between FEA and Test			
	FEA	Test	Error%
14P 500 HP	22.74	22.61	0.57
6P 1500 HP	20.74	22.79	-8.98
6P 600 HP	29.13	26.76	8.86
14P 500 HP	21.66	21.88	-1.03
4P 2250 HP	18.57	17.50	6.09
6P 500 HP	39.94	36.50	9.42

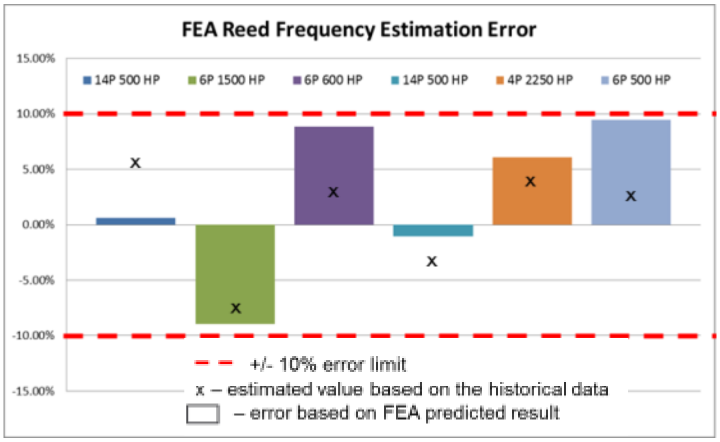

Figure 9: Reed Frequency Error Compared to Test Results.

The “x” is the estimated value based on the historical data, and the bar graph represents the values from FEA results. 0% error means an exact match between test data and FEA result. For these ratings, the frequency varied between 20 to 40 Hz, so tolerance was only +/- 2 to 4 Hz. Both sets of predictions are within +/- 10% of the result. For certain ratings, the results based on historical data are more accurate than the FEA results and vice versa. Since the sample size in this study was relatively small, more test data is needed before identifying the source of error.

For certain particular ratings, the slotted support configuration showed a 1~2 Hz shift, which matched the FEA results. Even though the frequency shift may not seem significant, the flexibility it provides can be very helpful in achieving the customer’s +/- 10% error specification. For adjustable weights, the FEA results showed 0.5 to 1 Hz difference in frequency, compared to 1 to 2 Hz difference from the test data. Since the adjustable weight feature was only implemented in very few motors, the consistency of the result could not be verified. However, the small difference between the FEA and test result showed that the effect was within an acceptable range.

IMPACTS FROM THE STUDY AND FUTURE WORK

Even though, the FEA method has demonstrated reasonable accuracy for certain motor ratings in this study, this method may not be sufficient for motors with a narrower tolerance band. For example, the +/-10% accuracy needed for motors with 15 Hz reed frequency is +/- 1.5 Hz. The FEA method definitely can provide a reasonable estimation, but, to meet the accuracy, motors may require special features to fine tune the frequency during the test. If such a narrow accuracy is not achievable, would a different requirement be defined for motors with low reed frequency? A continuous dialog between the motor and pump manufacturers can help define an acceptable tolerance range and bring about these changes to the requirements. Another way motor manufacturers can help the pump industry is to offer features that allow for frequency adjustment. Features such as a thicker oil pot wall on the non-drive end to support heavier weights, adjustable or removable weights…etc. have the potential to save installation time and cost.

As for future developments, one parameter of interest is the study of core stacking pressure. Higher pressure will increase the friction between laminations, which stiffens the core and increases the core modulus. Material testing can characterize core modulus as a function of stacking pressure. Secondly, future studies should include analysis of higher order modes, i.e. the torsional mode. This mode may provide an insight to torsional vibration. Last but not least, additional comparison against other motor ratings can help refine the FEA model and improve the result.

CONCLUSIONS

One approach to estimate the reed frequency of the vertical motor is FEA method. To satisfy +/- 10% accuracy requirement from the pump manufacturers, one can characterize each parameter systematically to accurately predict the result. For the study, two baseline motors were selected in the study. FEA model for baseline cases were examined first. Each parameter was adjusted to understand the effect individually and in conjunction with other parameters. Afterward, the results were compared against the test data for verification. Both the model and parameters were refined after each iteration. Once the baseline models were verified, they were tested against additional motor ratings for accuracy. In addition, tests involving special features, used for fine-tuning purposes, were also investigated. As a result, the initial goal for the study has been accomplished. One can use FEA method to estimate the reed frequency up to a certain accuracy. For motors requiring a higher degree of accuracy, either more refined models are needed or frequency tuning features have to be used to adjust the frequency during the test. This leads to the discussion about the acceptable tolerance range for vertical motors. Is +/- 10% accuracy appropriate for all machine ratings? To resolve this issue, it is important to understand the pump industry’s needs through continual discussion between industries.

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