ABSTRACT
The purpose of this paper is to introduce TEST and ANALYSIS CORRELATION as applied to Alternating Current (AC) Machines.

Induction motors and the generators often have problems associated with noise and vibration. Consequently, there is need for prediction of noise and vibration during the design of these machines. The Finite Element Modeling (FEM) method is used for the prediction and evaluation of natural frequencies and mode shapes of electrical equipment. However, FEM is often very difficult because of the influence of bolted joints, welded parts, shrink fits, etc. It is usually required to validate and refine FEM results based on using Experimental Modal Analysis (EMA) test results.

1. INTRODUCTION
Vibration and noise of an electrical machine, such as an induction motor or generator, is mainly caused by electromagnetic force of the machine itself, and by centrifugal forces from another prime mover and itself.

During the design and development of such equipment, we investigate vibration and noise caused by the electromagnetic force. However, the initial prediction accuracy is usually not satisfactory. At this time, use of commercial FEM program (I-DEAS) and our own program in order to gain experience in accurately simulating vibration and noise. In order to achieve accurate predictions it is necessary to investigate the following items:
(1) Construct an appropriate FEM modeling
(2) Investigate the influence of bolted joints, weldings, and shrink fits at the model joints using a Building Block Approach (BBA)
(3) Accurate prediction of forces due to the machine's electromagnetic force

2. Vibration and Noise of AC Machines
An example of an Alternating Current (AC) machine is an induction motor. We are currently improving our analysis prediction accuracy, with regard to vibration and noise, prior to the design of this type of machine.

The noise produced by induction motors can be classified into three types: windage noise, mechanical noise, and noise due to electromagnetic force. Each is briefly described below.

(1) Windage Noise

Three principal windage noise generating mechanisms are present:
a) fan generated noise
b) flow generated noise in ducting or cooler pipes
c) Mixing noise at the cooler outlet due to separate air jets and a coalesced air flow system

The remainder of this paper does not explain with windage noise.

(2) Mechanical noise

Mechanical noise sources are a result of unbalance, misalignment, and noise from rolling element bearings.

(3) Electromagnetic noise

Magnetic noise should be minimized as a result of the original design. Magnetic noise is primarily structure-borne.
Structural noise results from the vibration of the stator core or teeth. This noise is transmitted out of the motor by the frame and then is generated as airborne noise from the vibration of the outer surface.

The following process must be considered in trying to decrease the magnetic noise:

a) calculation of the magnetomotive force
b) calculation of vibration in the stator core
c) investigation of transmission of vibration from the stator core to the frame
d) calculation of vibration system around the stator core
e) response due to the vibration
f) analysis of magnetic noise

3. Structure of induction motor

Figure 1 illustrates the structure of an induction motor. This structure has several problems when considering it for Computer-Aided Engineering (CAE) modeling. These problems are noted below:

<table>
<thead>
<tr>
<th>Item no.</th>
<th>Name of parts</th>
<th>Item no.</th>
<th>Name of parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stator core</td>
<td>7</td>
<td>Outer cover</td>
</tr>
<tr>
<td>2</td>
<td>Rotor core</td>
<td>8</td>
<td>Fan</td>
</tr>
<tr>
<td>3</td>
<td>Frame</td>
<td>9</td>
<td>Bearing</td>
</tr>
<tr>
<td>4</td>
<td>Stator winding</td>
<td>10</td>
<td>Shaft</td>
</tr>
<tr>
<td>5</td>
<td>Rotor conductor</td>
<td>11</td>
<td>Terminal box</td>
</tr>
<tr>
<td>6</td>
<td>Bracket</td>
<td>12</td>
<td>Cover</td>
</tr>
</tbody>
</table>

3.1 Bolted joint

Bolted joints were investigated using EMA in order to establish their fundamental characteristics of dynamic behavior. A model of a bolted joint is shown in figure 2.

b) Stator core and shaft

the stator core is shrink-fit onto the shaft
c) Frame

the frame is constructed from some welded plate
d) Stator core

the stator core is laminated silicon steel
e) Stator winding

These problems all present difficulties when using CAE only. Using EMA, we can establish the "fundamental characteristics" for an actual structure. Test and Analysis are thus used in combination to solve the Dynamic problems for this class of electrical machines.

4. Fundamental characteristics

4.1 The fundamental characteristics of bolted joint.

Bolted joints were investigated using EMA in order to establish their fundamental characteristics of dynamic behavior. A model of a bolted joint is shown in figure 2.
The TEST results are used for comparison to FEM results. In this way, we can improve the FEM technique, including that for the bolted joint.

Four bolt sizes (M4, M6, M8, M12) and three pitch sizes (2-pitch 100mm, 3-pitch 50mm, 5-pitch 25mm) were investigated to determine changes of modeling parameters for these bolts.

As individual components, the FEM results agree well with the TEST results. The comparison of the analysis vs. the experimental results is shown in Table 1. (In this case, thin shell elements were used for the FEM.)

The T-bar made by a bolted joint was small change of modal parameters for different bolt size. The change of natural frequency was under 10% for different bolt size and was under 5% for different bolt pitch.

A SYSTEM DYNAMICS ANALYSIS (SDA) program was used for the vibration analysis. One T-bar system was assembled from components (2 plates) and connectors. Another T-bar system was assembled directly using two components. The above two system were then analysis. The following is a summary of the results of the SYSTEM DYNAMIC ANALYSIS.

Table 1 Comparison between Calculated and Measurement (Component only)

<table>
<thead>
<tr>
<th>Mode No.</th>
<th>Measured value (Hz)</th>
<th>Damping ratio (%)</th>
<th>Calculated value (Hz)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>296.1</td>
<td>2.58</td>
<td>296</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>479.2</td>
<td>3.73</td>
<td>474</td>
<td>-1.1</td>
</tr>
<tr>
<td>3</td>
<td>804.3</td>
<td>0.99</td>
<td>816</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Table 2 Comparison between TEST and BBA’s results (Natural frequency)

<table>
<thead>
<tr>
<th>Mode No.</th>
<th>Measured value (Hz)</th>
<th>Calculated value (Hz)</th>
<th>Direct Connect</th>
<th>Spring Connect</th>
<th>optimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>228.5</td>
<td>282.2</td>
<td>229.0</td>
<td>238.0</td>
<td>(+23.5%) +0.2% (+4.2%)</td>
</tr>
<tr>
<td>2</td>
<td>504.6</td>
<td>561.7</td>
<td>423.0</td>
<td>511.0</td>
<td>(+11.3%) -16.2% (+2.1%)</td>
</tr>
<tr>
<td>3</td>
<td>618.6</td>
<td>731.2</td>
<td>561.0</td>
<td>614.0</td>
<td>(+18.2%) -9.3% (-0.7%)</td>
</tr>
<tr>
<td>4</td>
<td>845.3</td>
<td>897.8</td>
<td>717.0</td>
<td>584.0</td>
<td>(+6.2%) (-15.2%) (+1.0%)</td>
</tr>
</tbody>
</table>

(): Error

Figure 3 A typical mode shape of the T-BAR
4.2 The fundamental characteristics of the shrink fits:

In the EMA, the vibrational characteristics of the system include shrink fits. A simple model which includes shrink fits is shown in Figure 4.

Comparing the EMA and FEM results, we can obtain an optimized CAE model which includes shrink fitted parts.

The frame is made of a thin steel plate and some square steel pieces. The structure of the model is to make a shrink fit to a cylindrical CORE in the frame.

Three sets of CORE thickness and interference are used.

The conclusions reached from the analysis were as follows:

1. EMA was used to determine vibrational characteristics of each component and system.

2. The natural frequency of a simple frame and CORE is shown in Table 3. The natural frequency of CORE is greater than that of the frame. The damping ratio of the frame is greater than that of the CORE.

3. In the CAE analysis, the natural frequency accuracy of simple components is influenced by which element is used. In this case, the solid element is the best.

<table>
<thead>
<tr>
<th>Mode No.</th>
<th>Frame</th>
<th>Core1 (t=15)</th>
<th>Core2 (t=25)</th>
<th>Core3 (t=35)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>199.7Hz</td>
<td>1078.5Hz</td>
<td>1954.0Hz</td>
<td>2952.3Hz</td>
</tr>
<tr>
<td></td>
<td>1.81%</td>
<td>0.88%</td>
<td>0.51%</td>
<td>0.32%</td>
</tr>
<tr>
<td>2</td>
<td>401.3</td>
<td>1508.8</td>
<td>2582.3</td>
<td>3645.3</td>
</tr>
<tr>
<td></td>
<td>0.96</td>
<td>0.65</td>
<td>0.39</td>
<td>0.28</td>
</tr>
<tr>
<td>3</td>
<td>568.7</td>
<td>2996.5</td>
<td>5243.3</td>
<td>7569.8</td>
</tr>
<tr>
<td></td>
<td>0.74</td>
<td>0.35</td>
<td>0.19</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Table 3 The results of the TEST

4. In the BBA model, a rigid connection system produces the same mode as the TEST. However, predicted natural frequency is very high when compared with the TEST results.

Using a spring connection system, it is difficult to get good correlation of both the mode and the natural frequency by adjustment of a spring constant only.

4.3 The fundamental characteristics of welded parts:

The vibrational characteristic of the system also include welded parts. These parts were also investigated to determine a CAE modeling technique.

A model structure was made of two steel plates which are fillet-welded to form a T-plate structure.

Good results were obtained by means of using direct connections to connect the individual parts.

Figure 4 The models which include shrink fits
5. **Low-speed Large-capacity Generator**

5.1 Preface

The prime mover of a low-speed diesel power generator was created by redeployment of a low-speed marine-vessel Z-stroke diesel engine. Its revolution speed is 100 to 200 rpm. Employing a low-speed diesel power plant as a prime mover allows the use of low-quality oil for fuel. Notwithstanding the conditions noted above, the thermal efficiency is still high and maintenance parts are interchangeable with common marine engines. Thanks to these outstanding features, and in light of recent oil-relates conditions, the demand for this type of prime mover is expanding world-wide.

During the design of these generators, analysis were made of both the structure and vibration using the CAE methods. Maximum use was made of various data accumulated during past production of low-speed diesel-engine generators. These analysis were useful in solving various problems involving power fluctuations which are peculiar to low-speed dieland power generation. With regard these problems, an analytical approach using detailed dynamic simulation has been applied.

Based on these achievements, a considerable amount of technical knowledge concerning low-speed large-capacity diesel-engine generators, the demand for which is expected to increase in the future, has been accumulated.

5.2 Design

As shown in Figure 5, a low-speed diesel-engine generator usually incorporates a flat construction. This construction is advantageous in increasing the generator’s moment of inertia as a measure taken to eliminate power fluctuations. Furthermore, since low-speed machines of this type tend to be of the multipole type, its rotor diameter automatically becomes the large, flat construction which is generally used.

1. **The stator construction**

The frame of generator is constructed using steel-plate weldings. It is constructed using some side and outside plates and keyposts in order to support the stator core. Because of construction and transportation limitations, the stator is split into two or maybe four sections.

The stator core is constructed of high quality silicon steel laminations.

2. **The rotor construction**

The rotor diameter of the generator is 8-9 meter. The generator’s rim disk and main shaft is jointed by special bolts. The rotor must withstand external vibromotive forces such as pulsating torque, axial excitation forces, etc. These are attributable to the cycle irregularity of diesel engines.

![Figure 5 The Low-Speed Diesel-Engine Generator](image-url)
5.3 Dynamic analysis of stator

An analysis was performed on the stator, to determine whether it will be brought into resonance from the magnetic attractive forces at work. The vibrational simulation analysis has been carried out using a CAE analysis and an EMA.

Two different CAE methods were created based on the goals of the analysis. The two models are first a 2-D, and second a 3-D model. The 3-D model was used to investigate the membrane vibration and the vibration in the axial direction because the frame is a box structure. The 2D-model was used to investigate the mode shape in the radial direction to determine whether the magnetic attractive force, the frequency of which double the power source frequency, is resonant with the stator structure. Comparing the stator's characteristic value of the direction with the frequency of the axial excitation force attributed to the cyclic irregularity of the diesel engine, these two values must be different. The typical mode shape obtained from 3D-dynamic analysis is shown in Figure 6. The mode shape from 2D-analysis is shown in Figure 7.

5.4 The experimental model analysis(EMA)

Magnetic excitation forces are exerted on the stator which deforms it at resonance. The purpose of the EMA of the stator is to measure the damping of the structure from its frequency and mode shape.

The apparatus which was used for the EMA consisted of WCA modal analyzer(Macintosh), impact hammer, electrodynamic velocity pickup and charge amplifier. A list of equipment used is given below:

- Modal analyzer: AD-3600(Macintosh)
- Modal software: WCA/Modal(Zonic), T-DAS
- Force Transducer: PCB Model 208A04
- Charge amplifier: PCB Model 408E09
- Vibration Meter: IMV Model VM-3314A
- Pickup: IMV VP-3314A

The experimental apparatus is shown Figure 9.

The following procedure was implemented to measure the vibration characteristics.

(1) The measurement is carried out after the stator core was fitted to the frame.
The stator was then lefted with crane and measured in that state.
The stator was then put down on the floor, and also measured in that state.

(2) The stator was fixed to the base. The stator is in a standing state. The stator core sets a winding.

Eight points are located on the frame outer surface. The direction of the velocity pickup is radial for each measurement point. This makes a total of eight (8) DOFs.

The frequency response function (FRF) of A-type and B-type are shown in Figure 9. (Note: A-type is with the stator is lefted by the crane. B-type is with the stator placed down on the floor.) The FRF of A-type has clear resonance and anti-resonance points. The B-type FRF is down the level and has divided peaks. The reason for these differences can be attributed to the difference in frame restraint between the upper and lower plates due to the stator being a box structure. The upper plate of the frame is nearly in a free-free state and the lower plate is almost fully restrained. The FRF of A-type was curvefit using multi-degree-of-freedom (MDOF) methods. The first resonance corresponds to the elliptic mode shape. The second corresponds to the triangle mode. The third is a rectangular mode. These mode is shown in Figure 10.

5.5 Verification of FEM model

Using the results of the EMA, the validity of FEM was verified. The FEM's DOF is different than the TEST's DOF. However, by comparing the results of 2D-model with TEST, the natural frequency and the mode shape corresponded well to the TEST.

5.5 Conclusion

The following is a summary of the main conclusions obtained from this example:

(1) Large structures such as Low-speed Large-capacity generators can be excited by using the impact hammer method. The FRF quality obtained using this method is satisfactory.

(2) The stator has elliptic, triangular and rectangular natural modes in the radial direction. The frequency of these modes must be made to avoid corresponding with the magnetic excitation force frequency.

(3) Natural frequencies of a stator can be calculated within about a 5% error using FEM analysis.

6. Acknowledgment

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7. Reference


![Figure 9 The FRF of A-type (Solid line) and B-type (Dashed line) vs. Linear Frequency](image-url)

![Figure 10 The typical modes of the stator](image-url)