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Development of Computational Simulation Tools to Model Weapon Propulsors

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Abstract

The development of computational simulation tools i.e. finite element (FE) models to model weapon propulsors evolves from the need to determine the positive or negative implications for future applications and/or design modifications. The propulsor in this case is an electric motor used in such applications as propelling defense mechanisms like torpedoes and acquiring underwater data. The ability to predict, with a computer model, the vibrational and acoustical signatures allows the user to make modifications specific to these applications as well as for performance enhancement.

Vibration in an electric motor is the result of electromagnetic force interaction between the rotor and stator. This can be modeled by performing a harmonic analysis by means of a computer simulation. The periodic electromagnetic force loads are reduced to their harmonic components by approximating them with a Fourier Series. The harmonic component loads are then applied sequentially to the computer model, and the results are superimposed. This superposition yields the displacements in the motor and the pressures in the fluid field surrounding the motor. In addition, natural frequencies and mode shapes are obtained for the motor both in air and underwater.

Introduction:

The development of computational simulation tools to model weapon propulsors evolves from the need to determine the positive or negative implications for future applications and/or design modifications. Research and development will involve the modeling of an electric motor submerged in fluid to understand the nature of electromechanical vibration and resultant acoustic signature generated.

State of the Art:

Previous work in the area of motor modeling and analysis includes the prediction of acoustic performance of large motors over a wide frequency range. Krott et al [1] created a 2-D finite element (FE) model to obtain the magnetic forces; they were applied to a 3-D structural model to observe its response. This method proved useful for the lower frequency range, and further work is being done by the authors to solidify this method as a standard tool in predicting acoustic performance of large motors over a broader frequency range.

Considerable work has been done on the calculation of the magnetic field with rotor eccentricity in an electric motor by means of an analytical approach with consideration of slotting effects, Kim and Lieu [2], and Kim and Lieu [3]. This approach is compared to and agrees with a corresponding FE model.

Research on magnet geometry and its effects on the vibration of the system concludes that by using the proper magnet shape, the transmission of forces through the stator unit can be reduced, Jang and Lieu [4].

Kolbe, Taegen and Verma [5] worked to determine mechanisms that caused noise and vibration in a motor of variable speed where they needed to consider the multiple resonance frequencies. They compared their theoretical to experimental results and were able to pinpoint the origin of the largest contributor to noise, the radial forces on the stator. They discovered that though the motor was complex they were able to accurately represent its characteristics as well as lower the noise and vibration by increasing the number of phases in the motor.

In all studies excluding the last, analytic results were compared to FE models, however it was not found that the user was able to input various geometries and chose the most suitable design for their purpose. All studies were performed in an atmosphere of air. A parametric FE model for a general motor will be developed. This will include the fluid field, specifically seawater, which will affect the frequencies and mode shapes of the motor; this will be more representative of the actual system.

Background:

This project focuses on the underwater usage of a brushless, permanent magnet electric motor for the Naval Undersea Warfare Center (NUWC). This motor will be used in such applications as propelling defense mechanisms like torpedoes, and acquiring underwater data. The main components of a brushless, permanent magnet motor are the stator and the rotor. Refer to Figure 1 for a schematic of this motor.

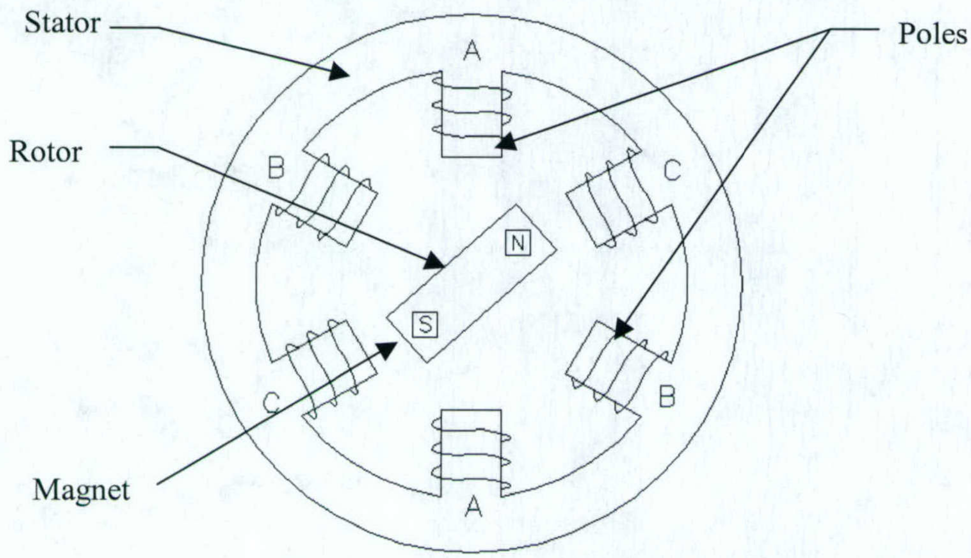

Figure 1. Schematic of Motor.

The pole pairs (A-A, B-B, and C-C) in this schematic are polarized opposite one another at a given time. Only one set is energized at a time. The pole attracts the magnet on the rotor. Once the rotor is attracted the pole reverses polarity and repels the rotor. The adjacent pole is then energized. This cumulatively makes the rotor spin.

The actual motor, refer to Figure 2, studied in this project is a custom made Permanent Magnet DC three-phase motor, it contains a rotor with 26 permanent magnets around its circumference, and 78 poles on the stator unit. Wrapped around these poles are epoxy covered copper wires. This wire acts to polarize each pole in order to attract the permanent magnet rotor. Once the rotor is attracted, and spins a certain angle, the same pole will have its polarity-reversed acting to repel the rotor. Cumulatively the rotor completes a 360-degree revolution. Hence electric energy is converted into shaft or mechanical work. The speed is dependent on the geometry of the rotor and stator (i.e. their diametrical dimensions).

The schematic in Figure 2 does not include the housing unit. The housing unit encases the rotor and stator units. A cooling jacket is not needed, since the housing allows the motor to be cooled while traveling under water. Once the housing is placed over the stator and the end bells are fixed, the motor can be considered a complete system.

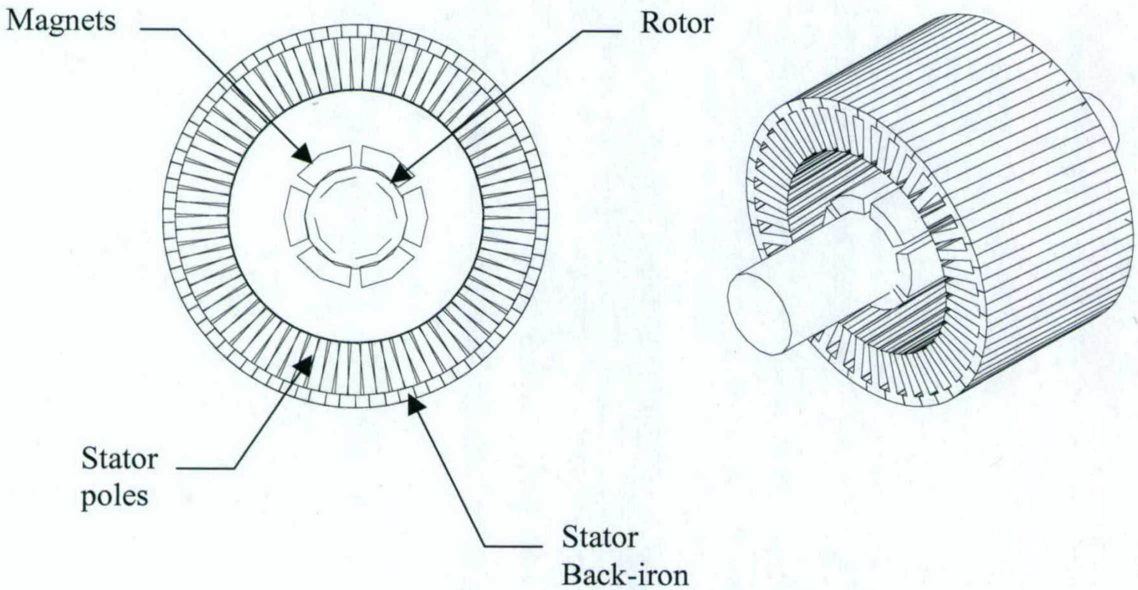

Figure 2. Schematic of the actual motor.

The source of vibration in the electric motor comes from the interaction of the rotor and stator in the form of electromagnetic forces. NUWC provided this project with the radial and tangential electromagnetic force data from a FE model of the electric motor. Figures 3 and 4 show typical radial and tangential force components.

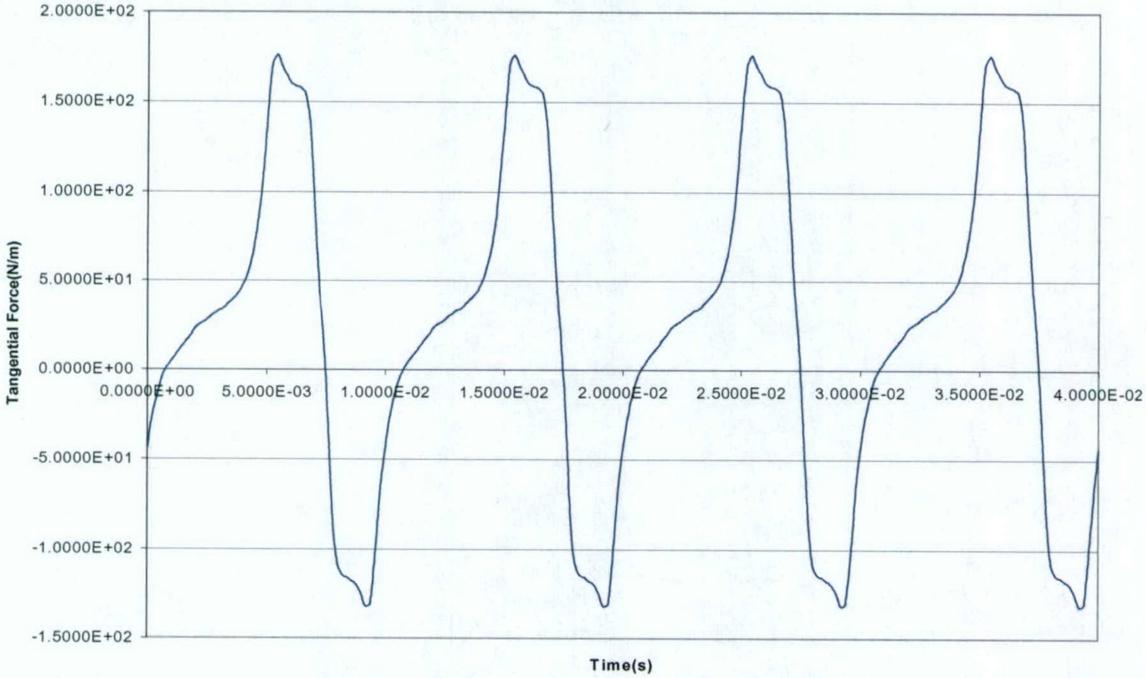

Figure 3. Radial Electromagnetic Force Data.

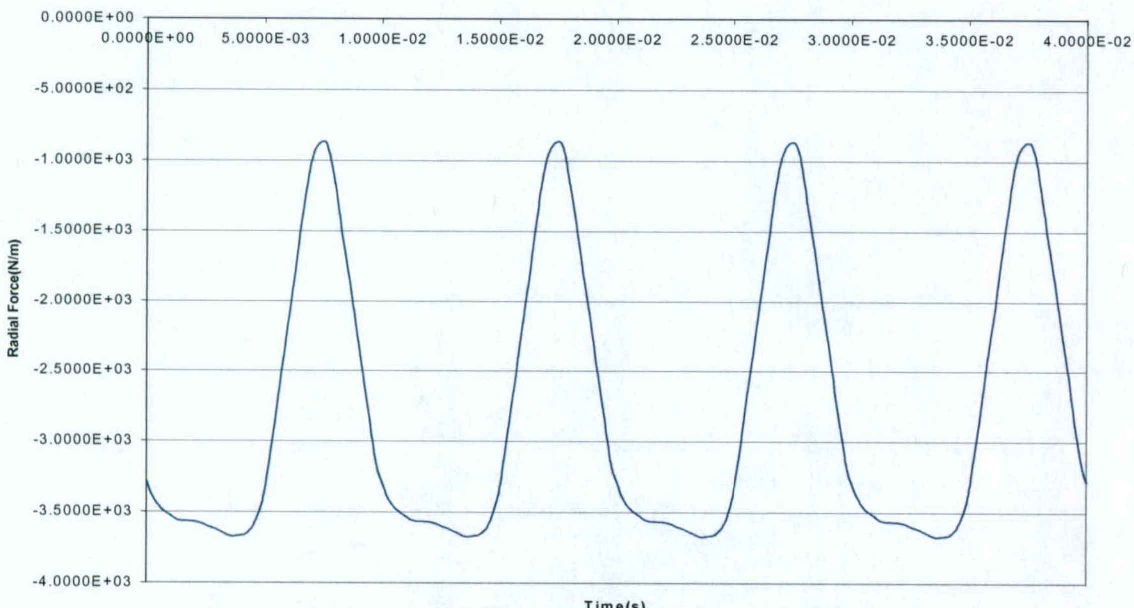

Figure 4. Tangential Electromagnetic Force Data.

Technical Approach:

A FE model of the electric motor was created using the ANSYS program. This program allows the user to obtain information about characteristics particular to their applications such as magnetic force, displacement, velocity, acceleration, stress, mode shape, and natural frequency.

In order to determine the mechanical vibration and acoustic signature generated while the motor was operating, the following steps were required:

Completed Work

Stator Unit:

1. Model the electromagnetic forces on the stator unit as a Fourier Series;
2. Create a FE model of the stator housing unit and fluid field;
3. Determine the natural frequencies of the stator in air and fluid.
4. Apply each harmonic force on the model and sum the corresponding responses to determine the total vibration and acoustic response.

Future Work

Rotor Unit:

1. Find the angular acceleration $\alpha(t)$ due to the electromagnetic forces and load parameters on the rotor unit;
2. Model $\alpha(t)$ as a Fourier Series;
3. Apply $\alpha(t)$ to the rotor model in a similar manner as done for the stator and determine its contribution to the vibration and acoustic response.

Parametric Study for the Complete Motor:

1. Vary the magnetic strength to create an eccentricity in the motor and study the contribution to the mechanical vibration and acoustic signature.

These steps will result in the determination of the vibration characteristics of an electric motor stator and housing unit in a fluid field. A complete parametric model of a generic stator and housing unit in a fluid field will be developed. The user need only input its geometry. The output from the model will be its characteristic vibration and acoustic signature.

The analysis of the stator did not include modeling the rotor. This was due to the verification (performed by NUWC) that the forces transmitted through the bearings were minimal. As shown in figure 5, the bearings were the only point of contact between the stator and the rotor. Therefore replacing the rotor with the electromagnetic forces was an accurate representation of the system.

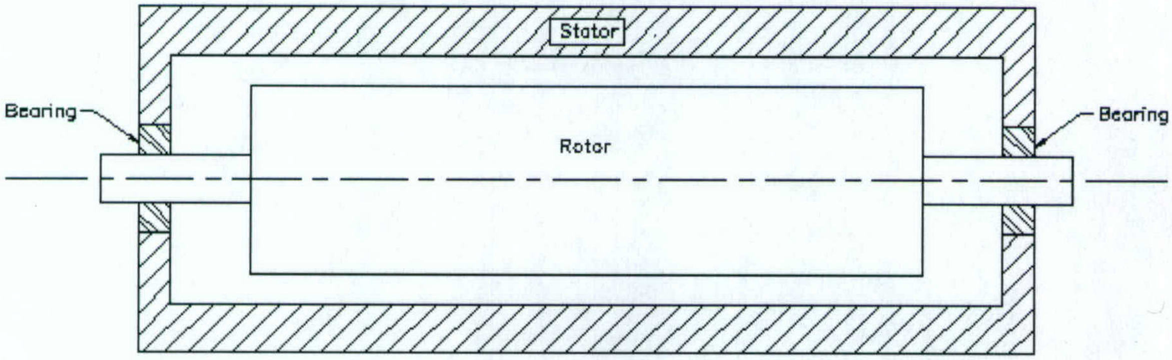

Figure 5. Cross Sectional View of Simplified Motor Schematic

Work on the rotor includes taking the rotor electromagnetic force data and applying it at the center of each magnet in the tangential direction. Assuming that the user of this specific motor application will be connecting loads as direct drive, the load will be kept a user-defined parameter. For a direct drive motor, since there are no mechanical linkages involved, the load parameters are directly reflected back to the motor. The speed of the load is the same as that of the motor, and the friction of the load is what the motor must overcome. Refer to figure 6 for a schematic of a direct drive motor system. Using Newton's Second Law ($\Sigma M_o = I\alpha$), knowing the moment of inertia (taken about the center of the rotor shaft) of the rotor and the load, and the electromagnetic forces, the user will be able to obtain the angular acceleration as a function of time, $\alpha(t)$. Modeling $\alpha(t)$ as a Fourier Series and applying it to the rotor will determine one factor that contributes to the mechanical vibration and acoustic signature of the complete system.

The other factor is the effect of the radial electromagnetic forces. These will also be investigated.

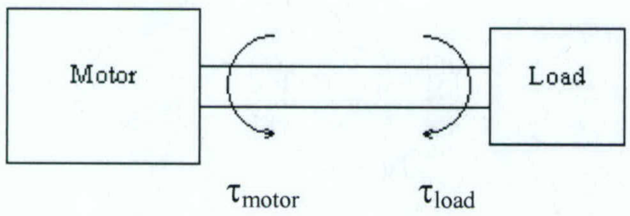

Figure 6. Direct drive motor schematic

The following is the procedure for finding the $\alpha(t)$ of the rotor under user-defined loading conditions.

$\tau_{system} = \tau_{motor} - \tau_{load}$ System torque

$\tau_{motor} = F \cdot r$ Where F are the electromagnetic forces and r is the radius of the rotor.

τ_{load} User defined

$\sum M_{system} = \tau_{system}$

$I_{system} = I_{motor} + I_{load}$ System moment of inertia

From Newton's second law:

$$\alpha(t)_{system} = \frac{\sum M_{system}}{I_{system}}$$

Also, by varying the strength of the rotor magnets (i.e. the coercive force), the user will be able to study the effect on rotor vibration, and its translation through the outer surface of the housing unit, and conversion to pressure in the fluid field. This will be done by decreasing the strength of every other magnet around the circumference of the rotor. A periodic change in strength implies a periodic behavior of the system's vibration. This gives a baseline for correct results. Once these results are obtained, the number of magnets weakened will decrease (still in a periodic pattern) until only one magnet is weaker than the rest. This will simulate eccentricity caused possibly by manufacturing defects or magnet age.

Preliminary Results:

Modal Analysis:

As previously mentioned, the addition of a fluid atmosphere to the motor model was expected to affect the frequencies and mode shapes of the motor system. Performing a modal analysis to obtain the dominant frequencies of the motor helped decide the radius to which the fluid atmosphere should extend in order to simulate an infinite fluid boundary with minimum reflection of pressure waves. The minimum radius for the fluid atmosphere was determined by equation 1.

$$r_{fluid} = r_{motor} + 0.2\lambda \qquad (1)$$

where r denotes the radius of the fluid and motor respectively and $\lambda = \frac{c}{f}$ where c is the speed of sound specific to the fluid type and f is the dominant frequency of the corresponding pressure waves.

Figures 7 and 8 show the entire fluid-loaded stator and housing unit, and a close-up of the stator and housing unit, respectively.

Figure 7. Stator and housing unit with entire fluid atmosphere.

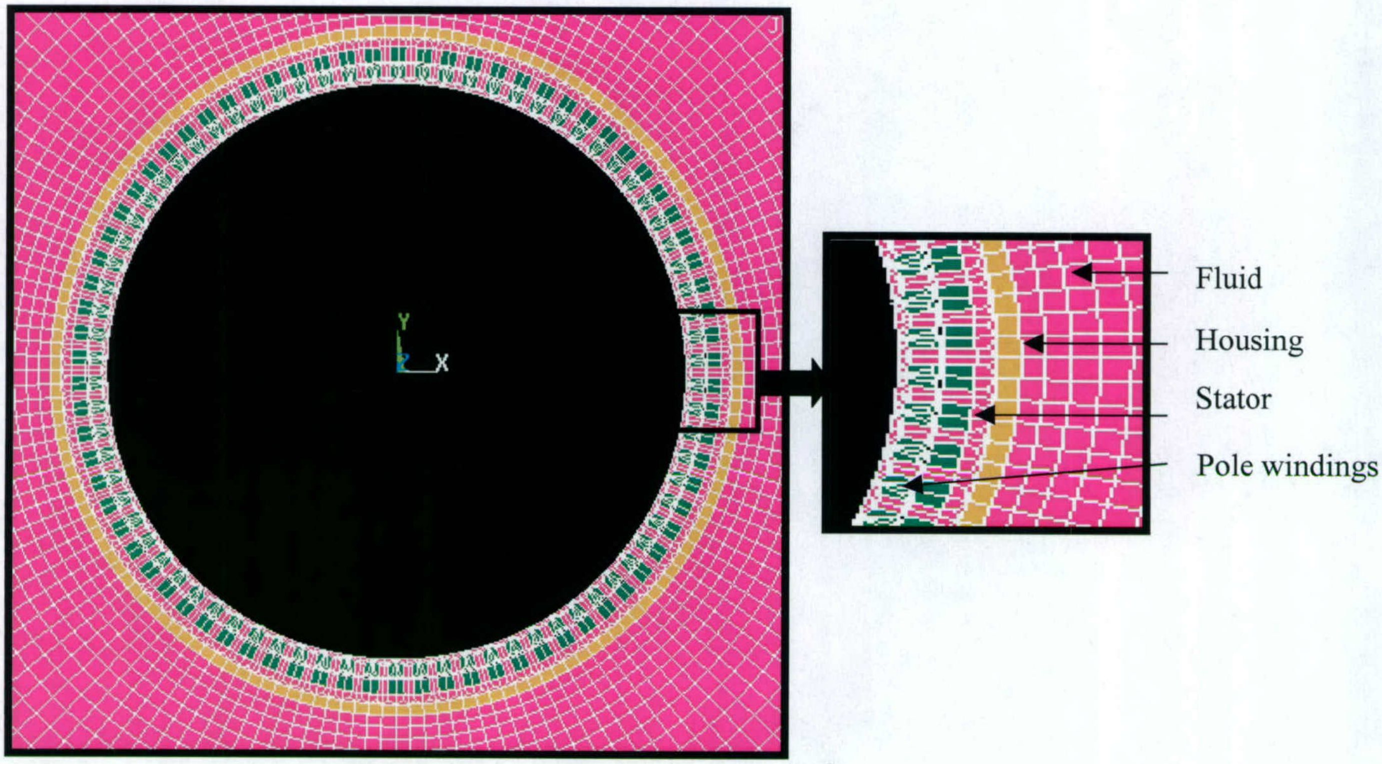

Figure 8. Close-up of stator and housing units enclosed in fluid.

Figures 9-14 show a comparison of the first three modes and their natural frequencies. All models were run with free boundary conditions. The odd numbered figures are the modes with the fluid loading and the even numbered figures are the modes with out fluid loading. Note that the fluid reduces the natural frequencies by 19%, 16% and 13% for modes 1, 2, and 3 respectively.

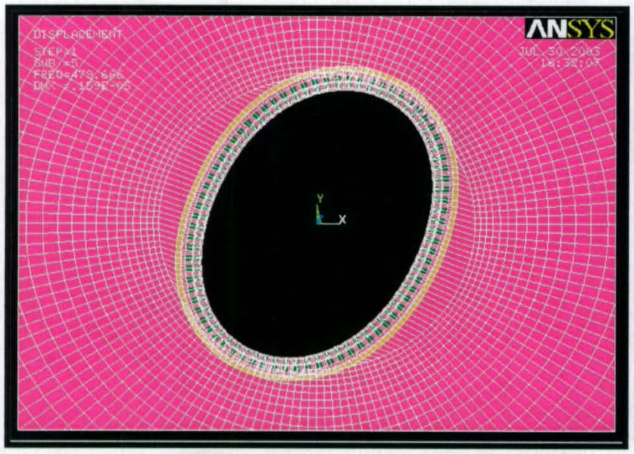

Figure 9. Mode 1 with fluid, 479 Hz.

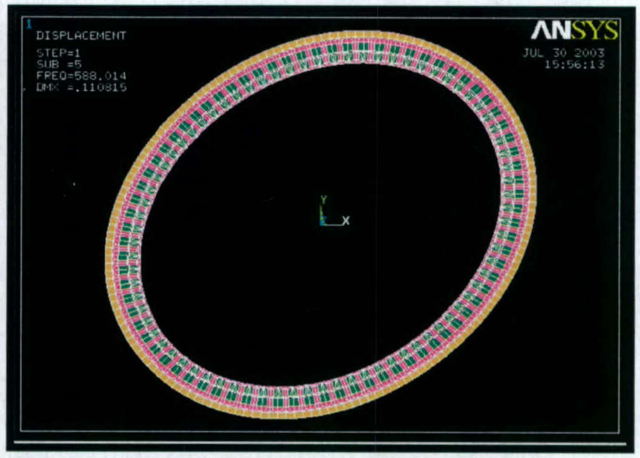

Figure 10. Mode 1 without fluid, 588 Hz.

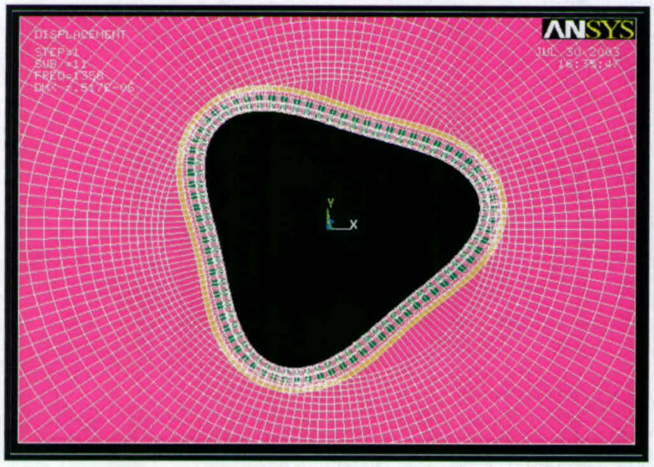

Figure 11. Mode 2 with fluid, 1358 Hz.

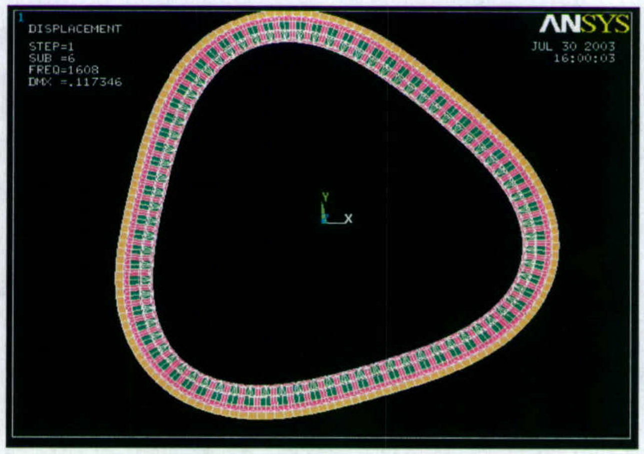

Figure 12. Mode 2 without fluid, 1608 Hz.

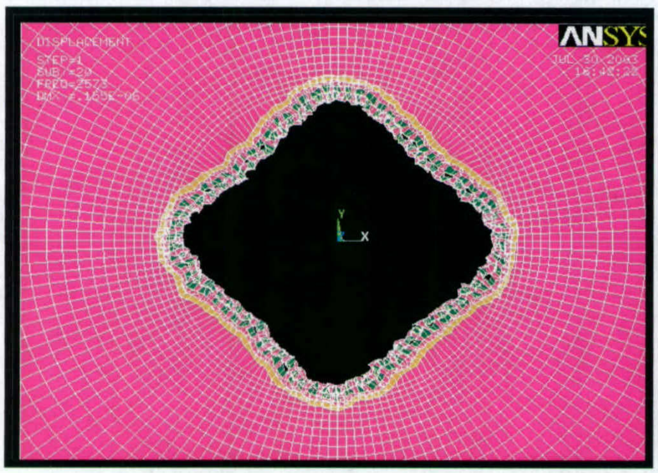

Figure 13. Mode 3 with fluid, 2573 Hz.

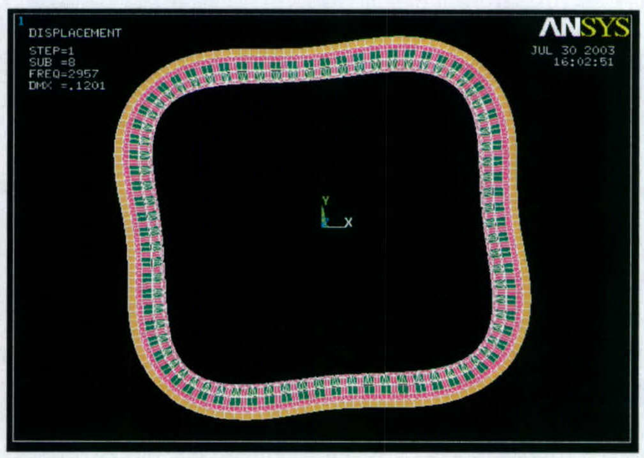

Figure 14. Mode 3 without fluid, 2957 Hz.

Harmonic Analysis:

Next, a harmonic analysis was performed. The electromagnetic force data was approximated by a Fourier Series representation in MathCAD and compared to the FE model force for verification. Figures 15 and 16 show the correlation between the ANSYS FE program and MathCAD respectively. The plots show rotor angle versus force amplitude.

ANSYS Fourier Series

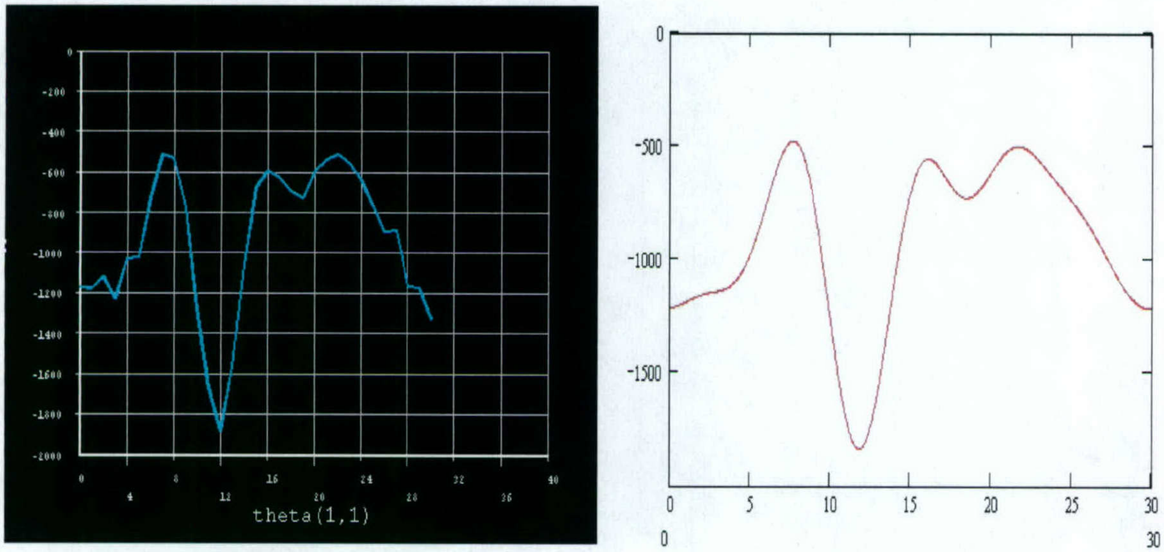

Figure 15. Typical radial force from the magnetic analysis and corresponding Fourier Series approximation used in the harmonic analysis.

ANSYS Fourier Series

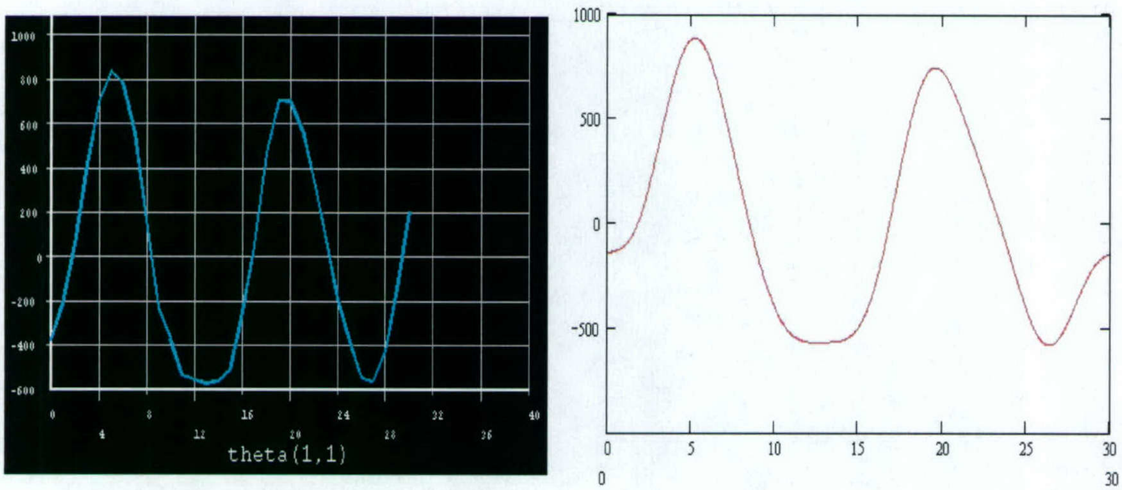

Figure 16. Typical tangential force from the magnetic analysis and corresponding Fourier Series approximation used in the harmonic analysis.

Displacement Results:

Displacements at a point on the housing unit both in the radial and tangential directions were obtained and are shown in figures 17 and 18 respectively. From these figures note that there is an oscillation of approximately 8° which is most likely the affects of the first mode. This oscillation corresponds to a frequency of 560 Hz, close to the first mode frequency of vibration, which is 577Hz. The plots show rotor angle versus displacement amplitude where the order of magnitude is 10^{-4} in.

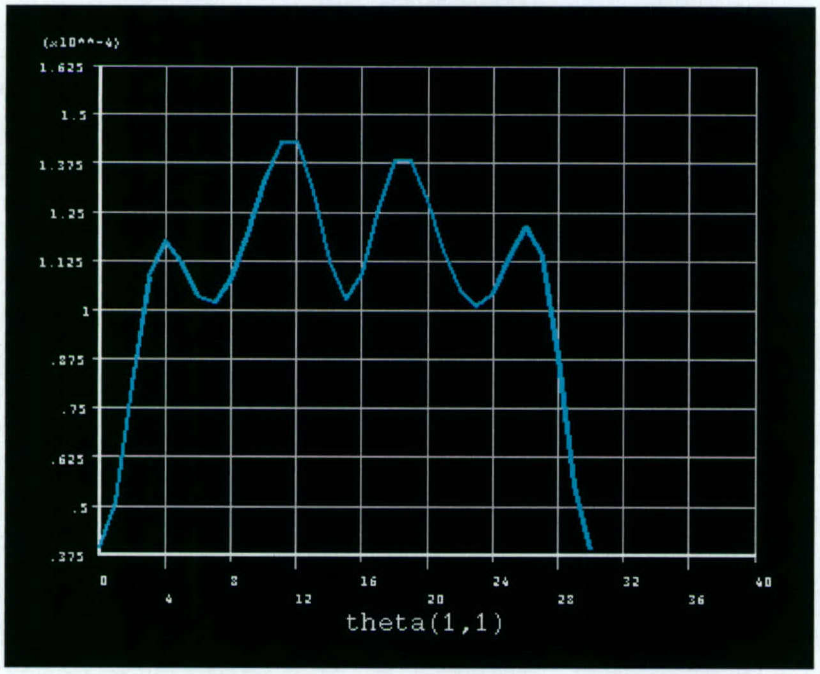

Figure 17. Radial displacement at a point on the housing unit.

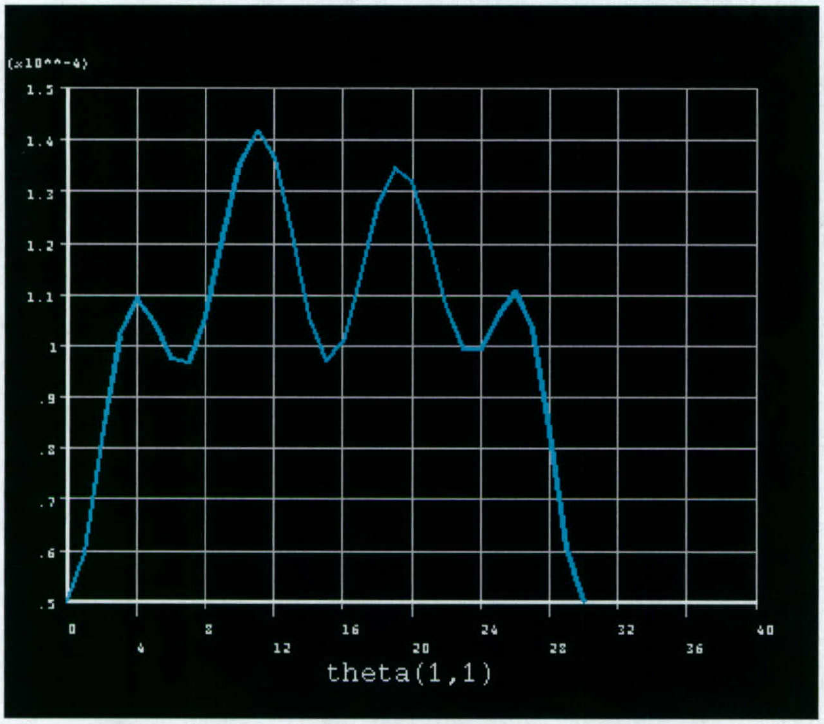

Figure 18. Tangential displacement at a point on the housing unit.

<u>Pressure Results</u>:

Pressure in the fluid atmosphere was calculated in the same way as the displacement, it was approximated as a Fourier Series where the sine and cosine components were the sum of the individual harmonic responses. Figure 19 shows the location in the fluid at which the pressure plot (figure 20) was obtained. The pressure has units of Pa and as you move radially out from the motor the pressure amplitude dies to zero.

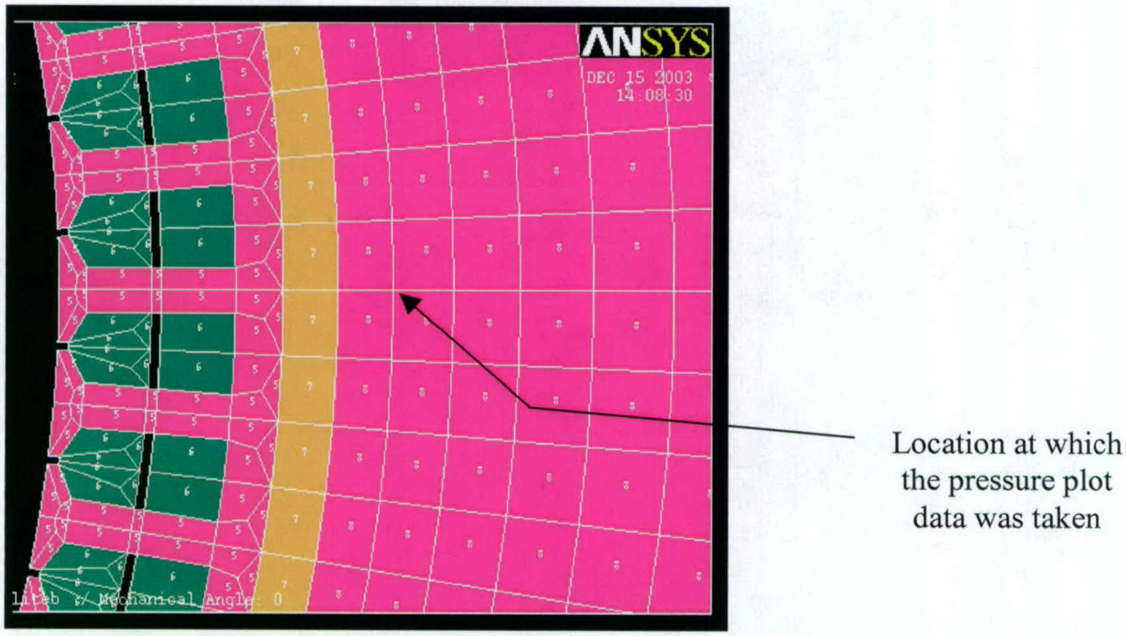

Figure 19. Location in the fluid at which the pressure in the fluid was obtained for figure 20.

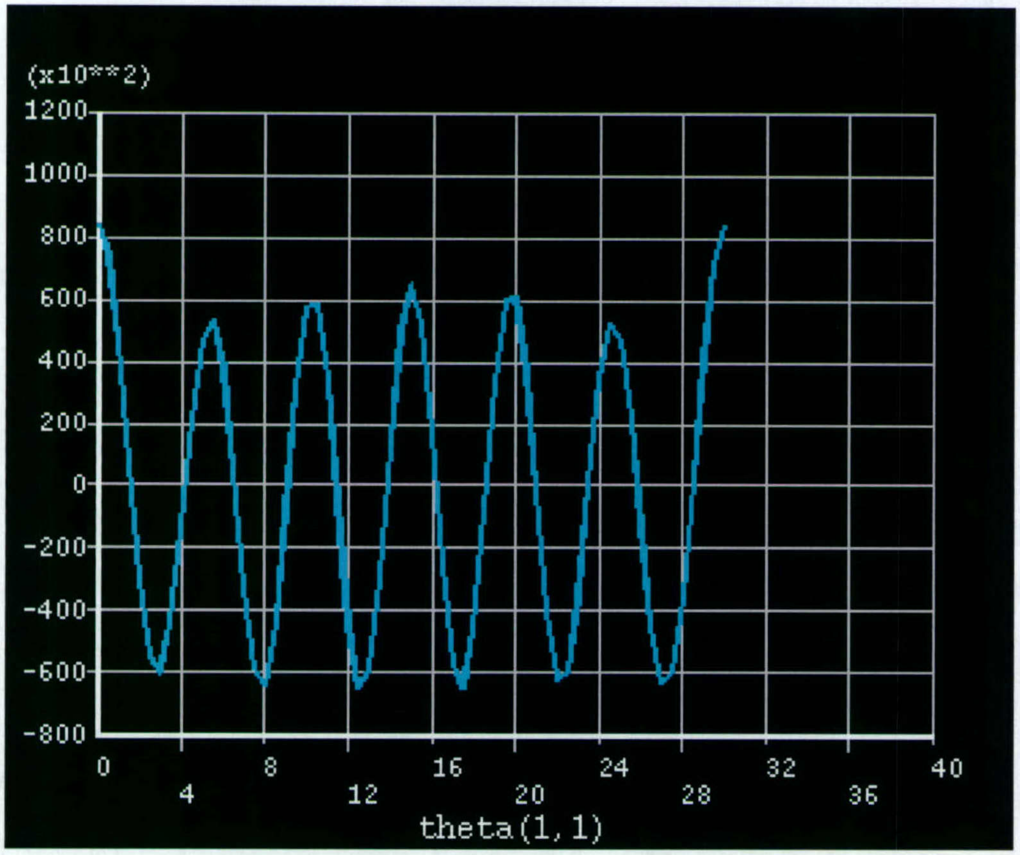

Figure 20. Rotor angle versus pressure (Pa) adjacent to the housing unit.

Statement of Objectives:

Future research on load characteristics experienced by the motor due to specific applications i.e. propelling defense mechanisms like torpedoes, and acquiring underwater data, will allow the development of analyses in the ANSYS program along with some results which can be used as a reference for future applications.

ANSYS is not capable of calculating the moment of inertia, therefore the development of programs that will allow the user to change rotor geometry and obtain this parameter are needed.

Verification of the pressure amplitude obtained in the fluid atmosphere is needed. Since the actual motor is no longer running, it is necessary to develop a theoretical method of obtaining the pressure from a simple cylindrical source (as a simplified model).

References:

[1] Krott, C. P., Neilson, H. C., McConnell, R., Montgomery, S.J., "Finite Element Modeling for Acoustic Analysis of a Full Scale Propulsor Motor," Naval Symposium on Electric Machines, (2000).

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[4] Jang, G.H., Lieu, D.K., " The Effect of Magnet Geometry on Electric Motor Vibration," IEEE Transactions on Magnetics, Volume 27, No. 6, 5202-5204, (1991).

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