Efficiency and Electromechanical Resonance in Magnetostrictive Transducers

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Abstract: Analysis of the transduction phenomenon of a Tonpilz Terfenol-D magnetostrictive transducer is presented. Transducer efficiency is discussed from both electroacoustic and scalar energy perspectives. Experimental results are presented which, in agreement with the models, demonstrate that most efficient transducer operation occurs at the frequency of electromechanical resonance, which occurs above the frequency of mechanical resonance.

INTRODUCTION

Analysis of the transduction phenomenon of a Tonpilz Terfenol-D magnetostrictive transducer is presented. Transducer efficiency is discussed using electroacoustic theory. Equations identifying the frequency of most efficient transducer operation are developed in references (1, 2). They show that the frequency separation between resonant frequencies of electrical impedance and admittance functions provides a measure of the efficiency of the system transduction, and present methods for identifying the frequency of most efficient transducer operation. Figures 1 and 2 show measured efficiencies, calculated based on output mechanical power and input electrical power in a magnetostrictive transducer (3). The experimentally observed frequency of maximum efficiency agrees with that predicted using electroacoustics theory.

Two non-intuitive results pertaining to the frequency of transducer maximum efficiency were observed, both analytically and experimentally. Most efficient transducer operation occurs at a frequency above mechanical resonance; mechanical resonance occurs at frequencies slightly above the transducer's electrical impedance resonant frequency, while the frequency of maximum efficiency occurs quite near that of the electrical impedance anti-resonance (electrical admittance resonance). Furthermore, operating conditions which result in an increase in transducer efficiency cause an increase in the difference between the frequency of mechanical resonance and the frequency of highest efficiency. This motivated a comparison with a scalar energy analysis for development of a better, or at least more intuitive, understanding of the mechanisms which might explain this result.

Discussions such as those presented by (4) focus on modeling the transduction process within the magnetostrictive material in terms of elastic and magnetic energy densities within the material. They show that the maximum magnetic energy will be stored in the material when the material is operated under a state of constant stress at the frequency of system resonance, f_R. Conversely, the maximum elastic energy will be stored in the material when operated under a state of constant strain at the anti-resonant frequency, f_{AR}. The maximum fraction of elastic energy which can be transformed to magnetic is identified using the magnetomechanical coupling factor, k^2, which is found from the ratio of the difference in elastic energy at these two states to the maximum elastic energy. Recognizing that the magnitudes of stored elastic energy are proportional to the magnitude of the elastic modulus, and that squares of the resonant frequencies of the system are proportional to the elastic modulus, (4) shows that

$$k^2 = (1 - [f_R / f_{AR}]^2) \tag{1}$$

As f_R decreases relative to f_{AR} (as the frequencies separate), the (magnetomechanical) transduction efficiency increases. As mentioned above and in (3), mechanical resonant frequencies occurs approximately at f_R, while the frequency of maximum efficiency occurs near f_{AR}. Experimental electrical impedance functions shown in Figure 3 illustrate changes in resonant frequencies with changes in efficiency. As drive level increases, both resonant and anti-resonant frequencies shift downward, however resonant frequencies shift more rapidly than anti-resonant frequencies. Thus, as efficiency increases, the separation between frequency of mechanical resonance and that of maximum efficiency increases.

The energy approach to analyzing efficiency emphasizes that the driving mechamism for efficient transduction is the transfer of energy between the mechanical and magnetic states; resonance of this input output relationship provides the most efficient operating conditions. Energy analysis aids in recognizing the distinction between the transducer's mechanical resonance and its electromechanical resonances. Formulas derived using both electroacoustics theory and scalar energy methods indicate the observed trends, that the magnitude of achievable efficiency will be enhanced by separation of electromechanical and mechanical resonances.

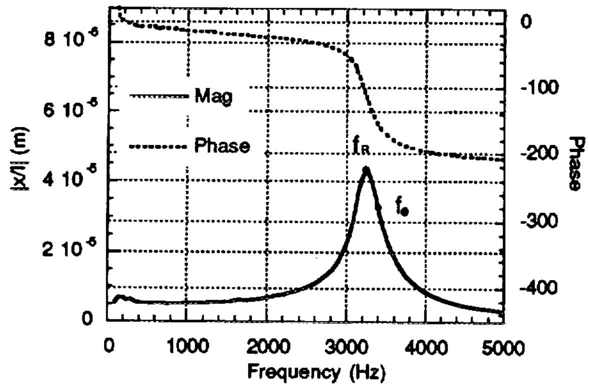

FIGURE 1. Displacement per current calculated from the acceleration output at each frequency. f_R is approximately the frequency of the mechanical resonance, f_E is the frequency of maximum efficiency.

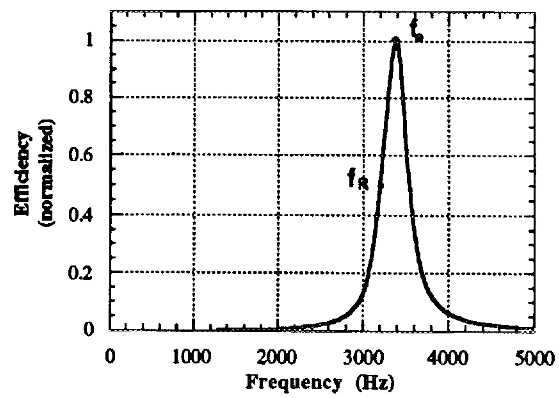

FIGURE 2. Normalized efficiency versus frequency measured as the mechanical output supplied to the load over the electrical input into the drive coil.

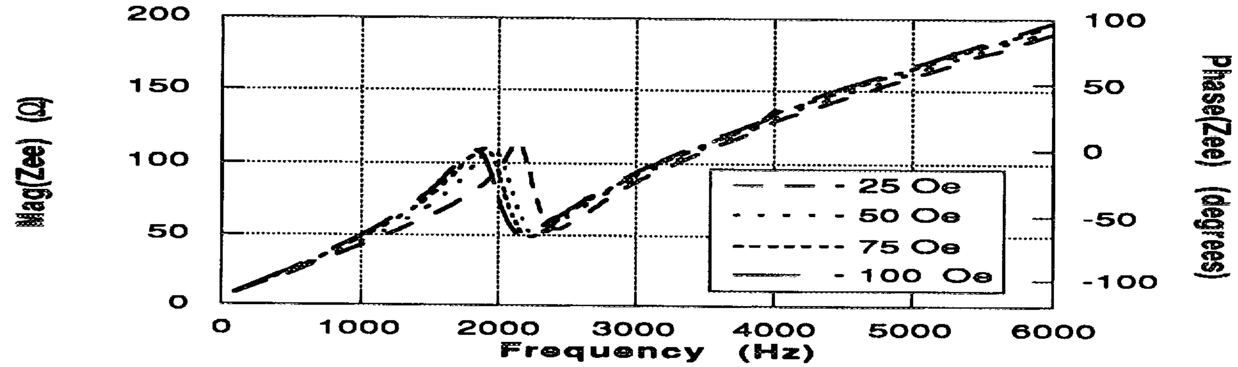

FIGURE 3. Electrical impedance functions reflecting shifts in resonance and anti-resonance frequencies with operating conditions. The frequency of maximum efficiency decreases slowly with the changes in electrical impedance anti-resonant frequencies, while the system mechanical resonance decreases more rapidly with changes in the electrical impedance resonant frequencies.

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