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Full Length Research Paper

Quality factor, static and dynamic responses of miniature galfenol actuator at wide range of temperature

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In this research, galfenol (iron-gallium alloy) is exploited to make a miniature actuator. The relationship between displacement and the applied current is measured. Furthermore, the dynamic behaviors of the actuator in wide range of temperature from cryogenic environment (77 K) to room temperature (RT) are investigated numerically and experimentally. Although, the length of galfenol bar is 10 mm and the maximum strain of annealed galfenol bar is 200 ppm, the large displacements of 37 and 25 µm are achievable at RT and 77 K, respectively when the coil is energized by ±1 A. The natural frequency of this actuator at RT and 77K is 1015 and 1075 Hz, respectively. Furthermore, modal analysis predicts the natural frequency of the actuator by maximum 9% error. Low hysteresis behavior makes this actuator suitable for positioning at both, RT and 77 K. It is also found that the low quality factor of actuator at RT is related to Joule heat dissipation.

Key words: Galfenol (iron-gallium alloy), miniature actuator, cryogenic environment, quality factor, modal analysis.

INTRODUCTION

Cryogenic apparatuses can be traced in a wide range of industrial applications from oil industries to aerospace, transportation and medical devices. For examples, cryogenic control valves for regulating the flow of coolant through the conduit [Elwood and Patterson, 1975], cryosurgical probe for killing the fatal tumors [Yoed et al., 1999], cryogenic pump for pumping liquid helium in high-speed ground transportation systems, and zero-power actuator in next generation space telescopes operates at 30 K can be mentioned as representative applications of cryogenic apparatus [Teter et al., 2000]. However, to increase the performance of this type of equipments especially in the space applications, it is required to make them smaller, lighter and with low power consumption. Yano presented a new mechanical transformer using piezoelectric element [Yano et al., 2008]. Although efficiency of this actuator is high, it needs high voltage power supply and is not suitable for harsh environment. Because of these requirements and conditions, magnetostrictive seems a good candidate for actuator to operate at low temperatures. Among the magnetostrictive materials, only TbDy alloys and galfenol ($Fe_{81.6}$-$Ga_{18.4}$) were used for low temperatures [Teter et al., 2000; Downey and Flatau, 2005). In spite of large strain (9000 ppm) of TbDy alloys at low temperature, this material is expensive, brittle (difficult machining) and it requires a strong applied field of 360 kA/m to saturate. The strain of stress-annealed Galfenol is small (160 to 250 ppm). However, it is strong (large Young's Modulus ≈ 70 to 90 Gpa) [Downey and Flatau, 2005] and has high flux density saturation (1.61 T) [Wun-Fogle et al., 2006]. Furthermore it will be saturated by low magnetic field (30 kA/m) [Ghodsi et al., 2006]. These specifications combined with high ductility (easy machining) promise wide range of industrial applications for recently developed

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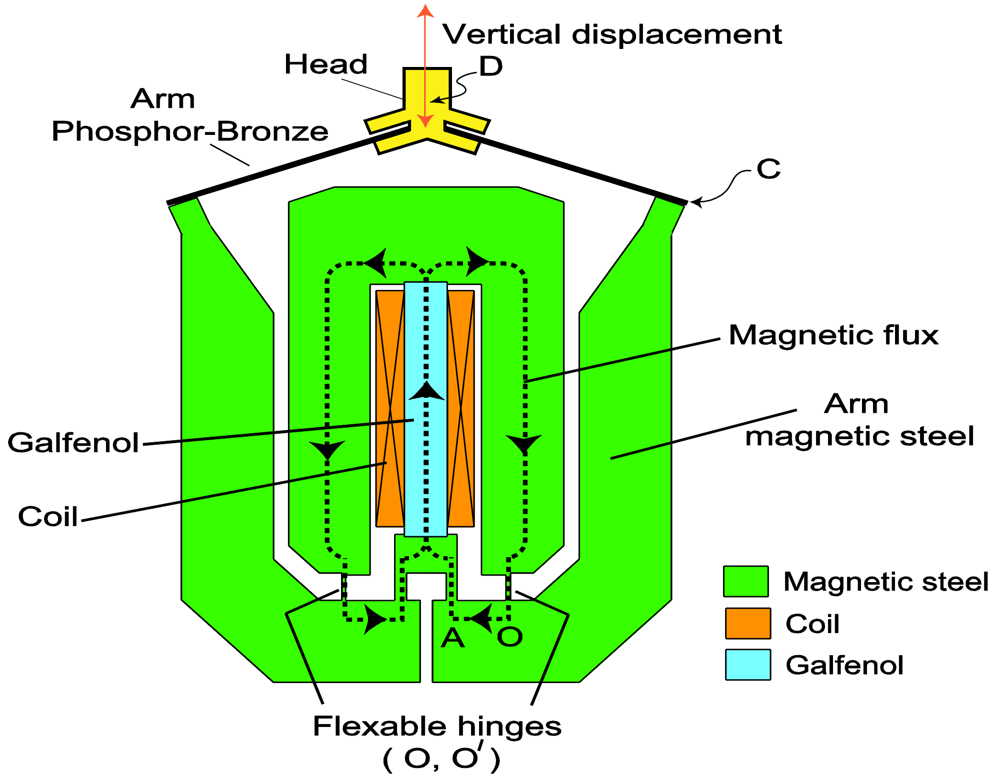


Figure 1. Schematic structure of the actuator.

magnetostrictive material, galfenol.

In this research, galfenol bar is exploited to make a high efficiency miniature actuator. Quality factors, static and dynamic behaviours of the actuator in wide range of temperature from cryogenic environment (77 K) to room temperature (RT) are investigated numerically and experimentally.

PRINCIPLE OF ACTUATOR

Figure 1 shows a schematic configuration of galfenol actuator. This actuator consists of two main parts that make a closed magnetic circuit. The first part is a polycrystalline Galfenol bar and the second part is a magnifying mechanism to amplify strain of the galfenol. To enhance the performance of magnetic circuit, the magnifying mechanism is made of high permeability magnetic steel. The length of galfenol bar is 10 mm and its cross section is square by 0.8 mm width (Figure 2a). The strain of used polycrystalline galfenol bar is 220 ppm [Ueno et al., 2008]. Thickness of magnifying system is 0.8 mm and energized coil is φ = 0.1 mm and 240 turns. Galfenol displacement is transferred to the head by phosphor-bronze spring plate. By energizing the coil, generated magnetic fluxes pass through the galfenol bar and increase its length. As depicted in Figure 1, similar to lever mechanism, the small strain of galfenol is magnified when the arms of actuator rotate around flexure hinges (*O, O′*) and make large vertical displacement by head.

As shown in Figuire 2a, the galfenol bar is expanded at point A when it is energized by coil. Consequently, the position of points *B, C* and D will be changed to *B′, C′* and *D′*, respectively. With the good assumption, CC′ can be assumed as a combination of a horizontal (*CC″*) and a vertical (*C″C′*) displacements (Figure 2b). If *l* be the length of phosphor-bronze arm, *α* is the angle of arm with horizon before excitation, the displacement of point *C* (*CC′*) can be calculated from:

$$C\acute{C} = \frac{OC}{OA} A\acute{A} \qquad (1)$$

for the small displacement, it can assume that *CC″* = *CC′ cos α*. Furthermore, *β* (angle of arm after excitation) and *DD″* can be derived from (2) and (3), respectively.

$$l\,(\cos\alpha - \cos\beta) = CC'' \qquad (2)$$

$$l\,(\sin\alpha - \sin\beta) = DD'' \qquad (3)$$

Therefore *DD′* can be approximated as:

$$DD'' + CC' \sin\alpha = DD' \qquad (4)$$

MODAL ANALYSIS OF ACTUATOR

Since the actuator has complicated structure, numerical analysis is exploited to calculate its natural frequencies at both, RT and 77 K. 3D model of actuator is created based on five areas of *A1* to *A5* (Figure 3a). Areas are extruded and meshed with element SOLID45 in ANSYS software (Figure 3b). To simulate the actuator’s behavior correctly, all degree of freedom in nodes of *A2* and *A3* are considered zero. As shown in Table 1, temperature variation causes changes in Young’s module of actuator parts. Young’s

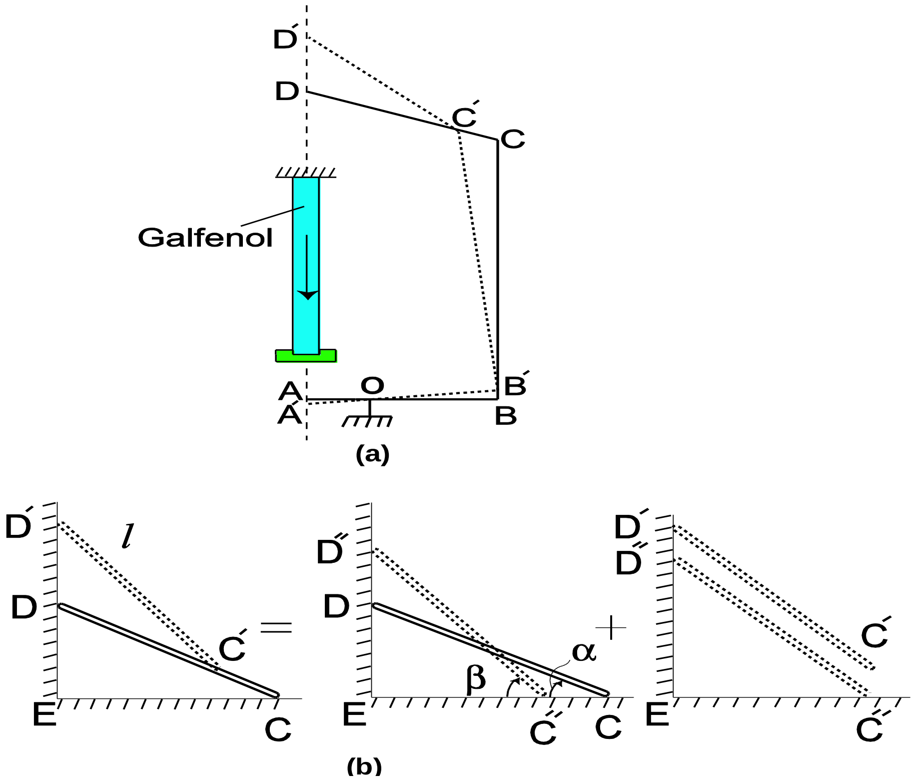


Figure 2. (a) A schematic demonstration of magnifying mechanism; (b) a schematic motion of phosphor-bronze arm.

module, Poison ratio and density of actuation element (Galfenol bar, *A1*), main body (low carbon steel, *A2-A3-A4*) and elastic arm (phosphor-bronze, *A5*) in different temperatures are presented. Figure 3c shows the first longitudinal mode shape of the actuator at RT. Natural frequency of the actuator occurs in the frequencies of 1103 and 1137 Hz at RT and 77 K, respectively.

MANUFACTURING PROCESSES

As was explained previously, the galfenol alloy is ductile and machineable. For precise manufacturing, ultra precision machining seems a good candidate [Ueno et al., 2007]. To achieve this purpose a galfenol plate is bonded by epoxy glue to the brass substrate. Then cutting is done by the small diameter carbide end mill (0.5 mm). Additionally, this machining technique is used for cutting non-magnetic elastic arms (t = 0.1 mm, l = 8 mm, w = 0.8 mm). The magnifying part is a lever mechanism and its stiffness should be high enough to amplify the small displacement of galfenol bar with minimum power loss. Moreover, the material should be magnetic material. Therefore, the material is special grade of magnetic low carbon steel with high permeability. To manufacture the magnifying mechanism and head, wire EDM technique is exploited which is fast and accurate enough.

RESULTS AND DISCUSSION

As shown in Figure 4, the actuators are fixed on brass fixtures. By energizing the coil, a vertical displacement can be realized in the head. Photonic sensor (14.7 μm / V in front slope) is used for vertical displacement measurement. The current is measured by Tektronix TM502A current probe. Figure 4a is the actuator at RT and Figure 4b shows the actuator through the liquid nitrogen (77 K). The displacement of actuator at RT when the coil is energized by a 5 Hz sinusoidal signal with different (1, 0.5, 0.375 and 0.25 A) amplitudes is demonstrated in Figure 5a. Although, the maximum expected displacement of Galfenol bar is 2.2 μm, a large displacement of about 37 μm is achievable when the actuator is energized by ±1 A. It means this actuator can magnify the displacement about 17 times. By applying the currents with different amplitudes, different displacements are achievable. The measurement is repeated when the actuator was cooled by liquid nitrogen (Figure 3b). It is found that in cryogenic condition, the actuator’s displacement is reduced 32 to 50%. Furthermore, the dynamic performance of the actuator is also measured by FFT analyzer (ONO SOKKI CF-5220) at RT and 77 K. As shown in Figure 6, resonance frequencies of the actuator are 1015 and 1075 Hz at RT and 77 K, respectively. In other words, the stiffness of actuator is increased at 77 K. Results show that numerical modal analysis predicts natural frequencies by maximum 9% error.

Therefore, the reduction of static displacement of actuator at 77 K can be inferred from higher stiffness of

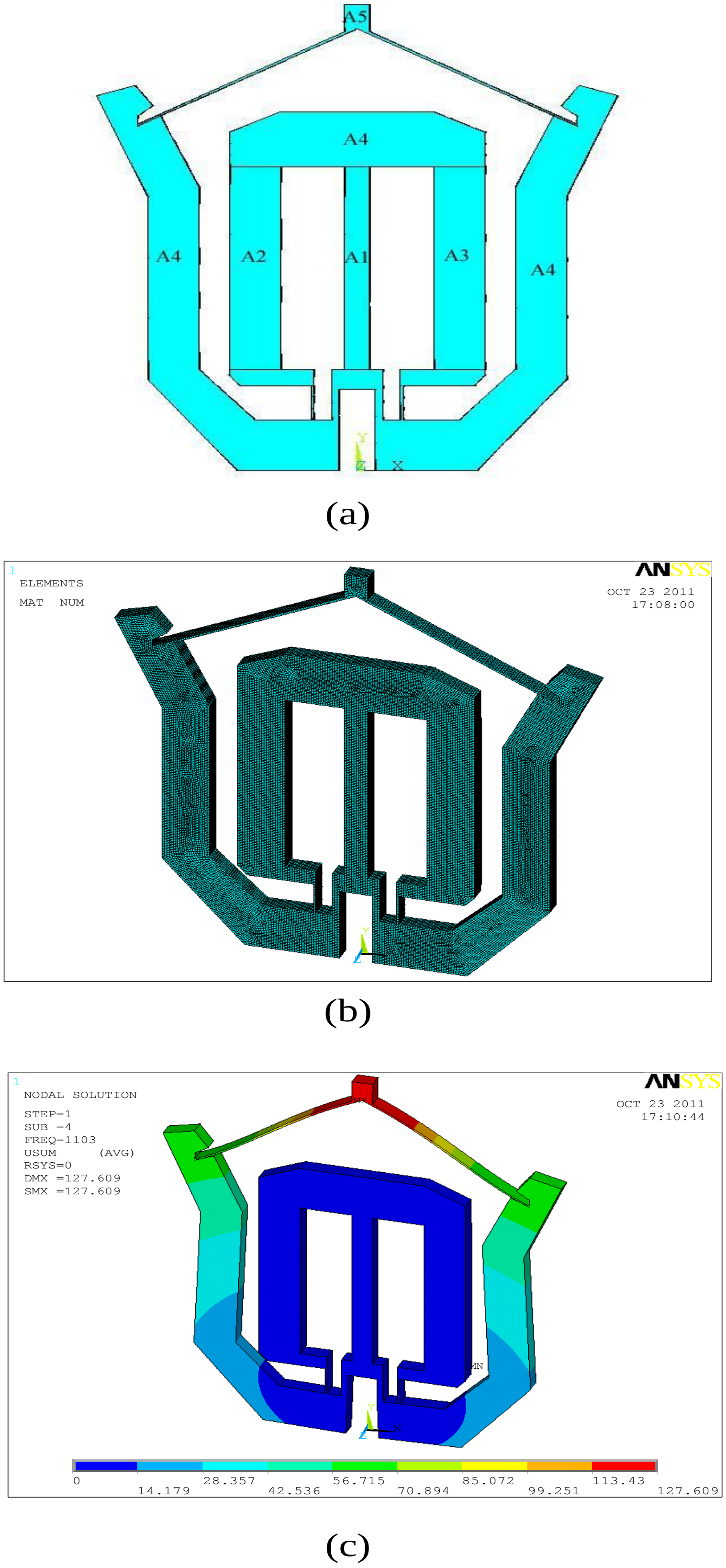
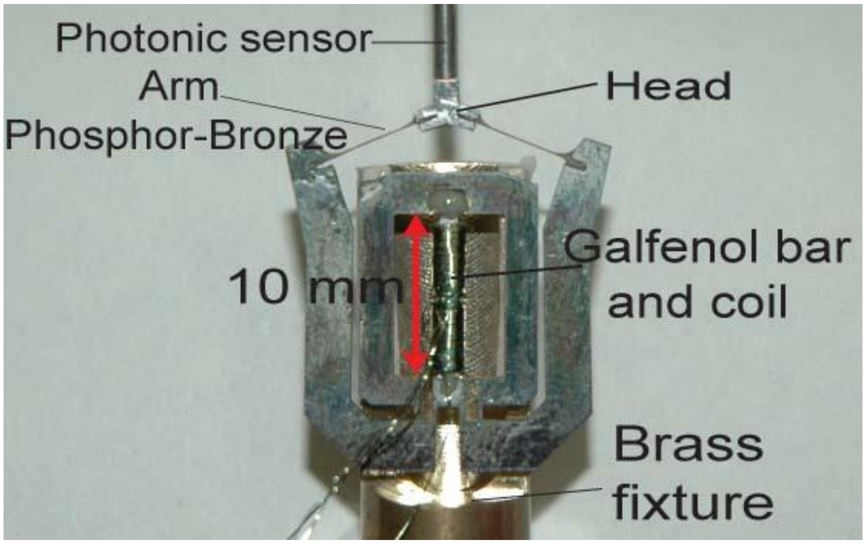


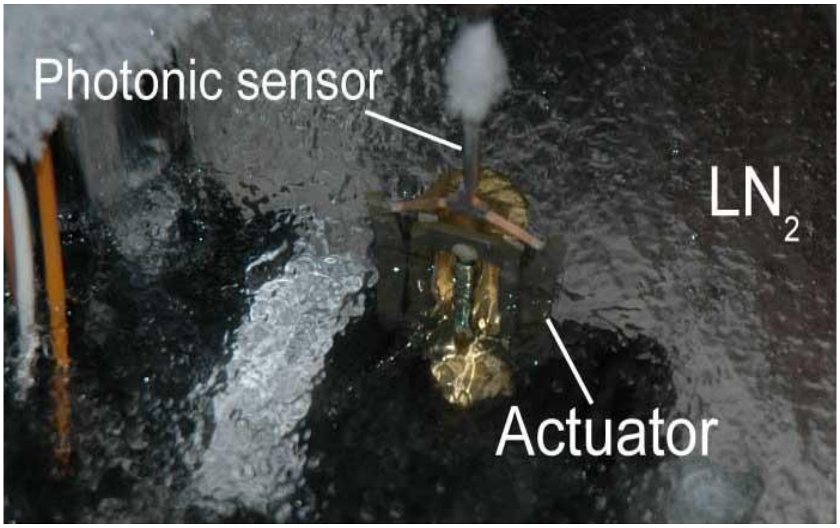
Figure 3. Numerical result of the modal analysis of galfenol actuator, (a) based areas of actuator, (b) 3D meshed actuator (c) first longitudinal mode shape and relative displacement of actuator's head at RT with resonance frequency of 1103 Hz.

Table 1. Physical characteristics of actuator main parts at RT and 77K [American Society of Mechanical Engineers ASME B31.1, 1995].

Material	**Young's module (GPa)**		**Poison ratio**	**Density (kg/m^3)**
	RT	**77K**		
Galfenol (actuation element, *A1*)	65	70	0.44	7970
Low carbon steel (main body, *A2-A3-A4*)	203	216	0.3	7850
Phosphor-bronze (elastic arm, *A5*)	110	116	0.37	8800



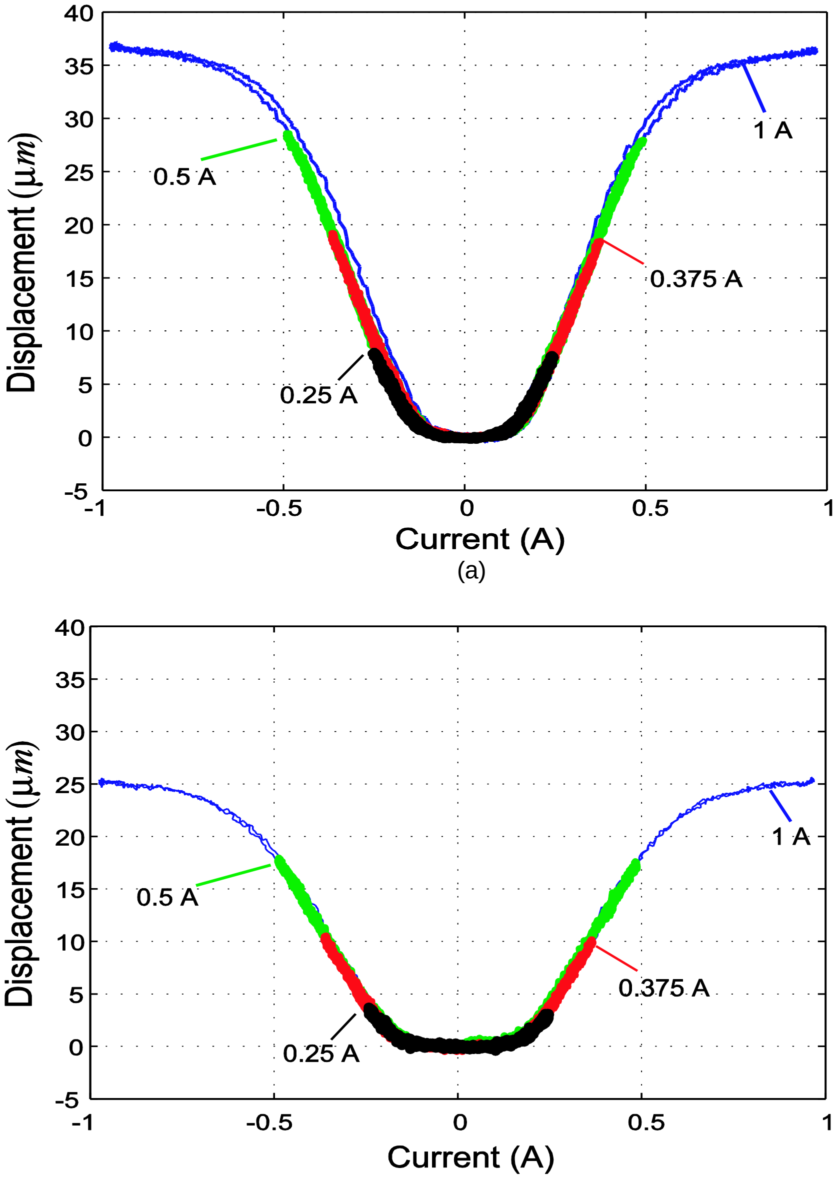
(a)



(b)

Figure 4. (a) Manufactured prototype actuator at RT, and (b) actuator inside liquid nitrogen (77 K).

actuator at 77 K. One of the most significant characteristic of this actuator is large vertical displacement with low hysteresis behavior which makes this actuator suitable for positioning applications. Another important point is the quality factor (*Q*) of the actuator which shows the loss dissipation process in the magnetoelastic transducer or actuator. The quality factor can be defined as [Engdahl, 2000]:



(a)

(b)

Figure 5. (a) Displacement vs, current at RT; (b) at liquid nitrogen (77K).

$$Q = \frac{\text{Stored elastic energy}}{\text{Total energy loss during a peridic cycle } T} \tag{5}$$

Higher value of Q shows lower energy dissipation during a cycle of operation T. The quality factor of actuator can be deduced from resonance curve. Since the damping of the actuator is negligible, the quality factor can be approximated [Engdahl, 2000]:

$$Q = \frac{\omega_{res}}{\omega_1 - \omega_2} \tag{6}$$

where ω_{res} is the resonant frequency of actuator and ω_1-ω_2 is called the bandwidth of the system. If the maximum amplitude of actuator, resonance condition, be assumed M then ω_1 and ω_2 are the frequencies corresponding to the points which the amplitude of actuator is reduced to $M/2^{0.5}$ (half power points). For example, as shown in Figure 7, ω_1 ,ω_{res} and ω_2 for 77 K are 1058, 1075 and1096 Hz, respectively. Therefore, the quality factor at 77K is about 28.3, whereas, this value for RT is 13.5. It means the energy loss at 77 K is about half of the RT. To find out the source of energy dissipation, the impedance of solenoid coil was measured at RT and 77 K (Figure 8). The impedance of coil with Galfenol core at RT is about 4.8 Ω at 1.1 kHz while at 77 K it is reduced to 2 Ω. Since the coil is energized by constant current at both RT and

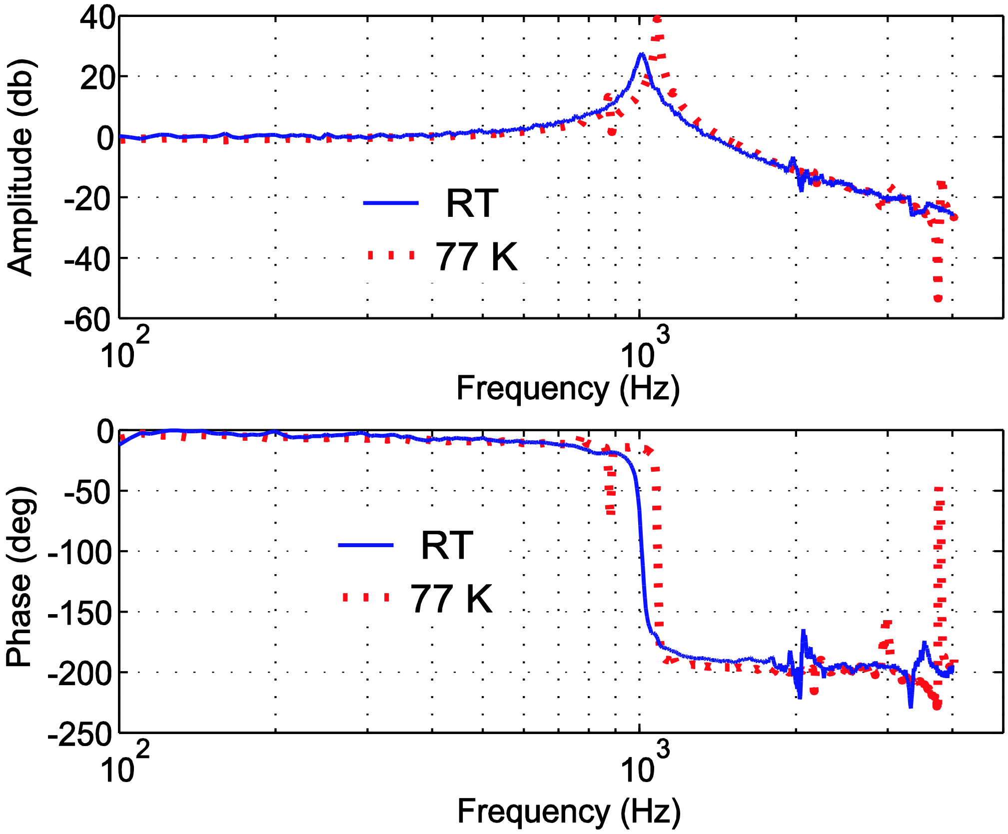


Figure 6. Frequency response of actuator at RT and 77K.

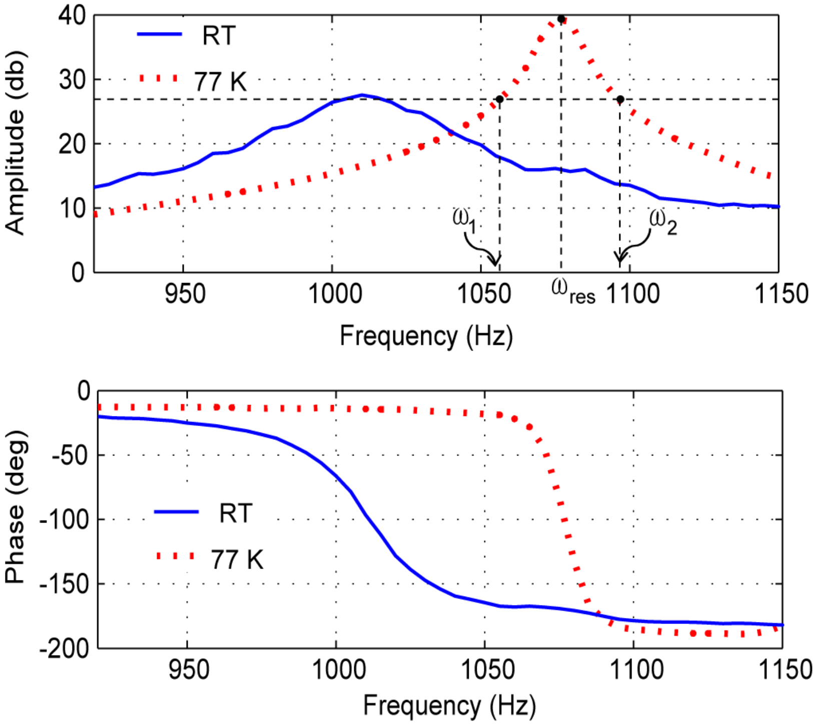


Figure 7. Dynamic behavior of actuator and its bandwidth at RT and 77 K.

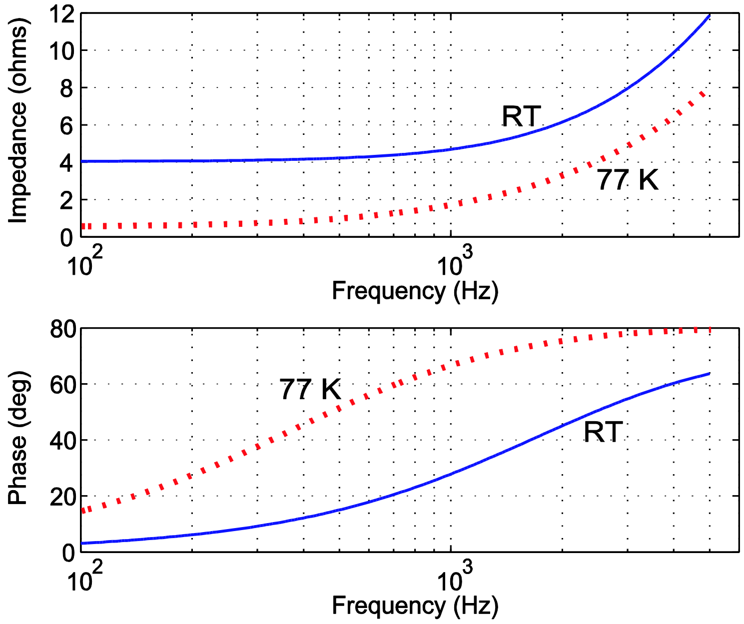


Figure 8. Impedance of actuator's coil at RT and 77 K.

77 K, it seems that lower coil's impedance at 77 K causes less Joule losses and consequently achieving of higher quality factor is predictable.

Conclusions

In this research, a miniature actuator by combining a galfenol bar and a magnifying mechanism has been presented. The actuator consists of two main parts that make a close magnetic circuit. First part is a galfenol bar and second part is a magnifying mechanism to enhance displacement of the actuator. Static and dynamic behaviors of the actuator were investigated numerically and experimentally at both room temperature (RT) and 77 K. The actuator magnified the small displacement of galfenol bar (2.2 μm) and large displacement of 37 and 25 μm were achieved at RT and 77 K, respectively when the coil was energized by ±1A current. Precise positioning was achievable by applying different currents. The frequency resonance of actuator was 1075 Hz at 77 K and 1015 Hz at RT. Experimental results confirmed predicted numerically calculated resonance frequency by maximum 9% error. Since the stiffness of actuator increases at 77 K, the displacement of actuator was reduced 32 to 50% when coil was energized with different current amplitude at 77 K. In addition, at 1.1 kHz, the impedance of the coil at RT was about 2 times of its impedance at 77 K. Then, the Joule heat dissipation was higher at RT which caused higher quality factor of actuator at 77 K compare with RT. Low hysteresis behavior makes this actuator suitable for positioning at both RT and 77 K.

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