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Research Article

Casimir Force Fluctuation and Torque Tuning in Topological Insulator-Based Micro-Electromechanical Systems

Murtadha Ibrahim[1], Samira Al-Khalil[2], Khalid Al-Shaibani[3]
[1] University of Technology, Iraq
[2] Al-Nahrain University, Iraq
[3] University of Thi-Qar, Iraq

Corresponding Author:

Murtadha Ibrahim,
Department of [Department Name], College of [College Name], University of Technology.
52 Alsinaa Street, Baghdad 10066, Republic of Iraq.
Email: murthada@gmail.com

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Abstract

Casimir interactions increasingly influence the stability of micro-electromechanical systems as device separations approach the nanoscale, yet their force fluctuations and rotational effects remain insufficiently integrated into topological-insulator device design. This study aimed to quantify Casimir force fluctuations, evaluate tunable Casimir torque, and identify mechanically stable operating regimes for topological-insulator-based micro-electromechanical systems. A theoretical-computational framework combined finite-temperature Lifshitz theory, scattering-matrix calculations, fluctuation–dissipation analysis, coupled translational–torsional mechanics, and Monte Carlo uncertainty propagation across 10,000 parameter configurations. Results showed that accepted topological-insulator configurations generated a median torque of 3.84 pN·µm and median torque modulation of 36.8%, while maintaining a lower median normal force than gold-coated references. Stable equilibria occurred in 84.8% of configurations. Separations of 100–250 nm and film thicknesses of 20–60 nm provided the most favorable compromise between torque enhancement and pull-in resistance. Magnetic surface gap and anisotropy increased torque tunability, whereas narrow gaps and elevated temperatures amplified force fluctuations and instability risk. The findings demonstrate that topological surface responses can support controllable, contactless rotational behavior when electromagnetic tunability is evaluated alongside mechanical stability.

Keywords: Casimir force, Casimir torque, Micro-electromechanical systems

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INTRODUCTION

Micro-electromechanical systems (MEMS) have become essential components of modern sensing, actuation, communication, biomedical instrumentation, and precision-control technologies. Continued device miniaturization has reduced the separation between movable components to submicrometer and nanometer scales, where interactions that are negligible in macroscopic systems can strongly influence mechanical behavior. The Casimir effect represents one of the most important interactions within this regime because quantum and thermal fluctuations of the electromagnetic field generate forces between closely separated material boundaries (Scafidi, 2024; Wang, 2025; Q. Yang, 2023). Conventional MEMS analyses often prioritize electrostatic actuation, elastic restoring forces, damping, and surface adhesion, yet the Casimir interaction can alter equilibrium positions, resonance frequencies, pull-in thresholds, and dynamic stability. Its strongly separation-dependent character also means that small variations in gap width, surface condition, or material response may produce disproportionately large changes in device operation.

Casimir interactions are not limited to a constant normal force between ideal metallic plates. Real devices contain dispersive, dissipative, anisotropic, and geometrically complex materials whose electromagnetic responses vary with frequency, temperature, orientation, and surface state (Ishihama, 2024; Lu, 2023; Xu, 2023). Temporal or spatial fluctuations in the Casimir force may introduce force noise, displacement instability, frequency jitter, or transitions between stable and unstable mechanical states. Anisotropic material configurations can also exchange angular momentum through vacuum fluctuations, producing a Casimir torque that tends to rotate one body toward an energetically preferred orientation. Casimir force and torque must therefore be understood as coupled electromechanical quantities rather than as static corrections to classical device behavior. Their manipulation could support contactless torsional actuation, quantum-vacuum springs, low-power switching, and tunable mechanical resonators, while their uncontrolled presence could intensify stiction, angular misalignment, and mechanical failure.

Topological insulators provide a promising material platform for controlling these fluctuation-induced interactions (Bie, 2023; Fang, 2025; Shi, 2024). These materials possess an insulating bulk together with conducting surface states protected by their electronic topology, strong spin–orbit coupling, and spin-momentum locking. Time-reversal symmetry breaking at the surface can produce a topological magnetoelectric response that modifies electromagnetic boundary conditions and, under suitable conditions, changes the magnitude or sign of the Casimir interaction. The optical anisotropy, surface conductivity, chemical potential, film thickness, magnetic gap, and dielectric environment of a topological insulator may offer multiple control parameters unavailable in conventional metallic MEMS. Theoretical studies have predicted attraction–repulsion transitions in some topological-insulator configurations, although these transitions depend sensitively on realistic material properties, temperature, substrate effects, and symmetry-breaking conditions (Grushin et al., 2011; Nie et al., 2013).

The central problem addressed by this study is the insufficient understanding of how Casimir-force fluctuations and Casimir torque jointly affect the dynamics of topological-insulator-based MEMS (H. He, 2025; Pachkawade, 2025; Shen, 2024). Most idealized treatments calculate a mean Casimir force for planar bodies in static equilibrium, whereas practical devices experience mechanical motion, finite temperature, material losses, fabrication imperfections, and environmental disturbances. A mean-force calculation alone cannot determine whether force fluctuations will broaden the displacement distribution, destabilize an equilibrium point, shift a resonant mode, or initiate pull-in. The distinction between average interaction and fluctuating response becomes particularly important near a mechanical instability, where a small stochastic contribution may trigger a large displacement. MEMS design consequently requires a framework capable of connecting fluctuation-induced electromagnetic stresses with measurable mechanical observables.

The angular component of the problem remains equally significant. Casimir torque arises when the electromagnetic response depends on the relative orientation of anisotropic surfaces, crystalline axes, patterned structures, or magnetically modified topological states (Dryagin, 2025; Melzer, 2025; Rowe, 2026). A movable torsional element may rotate toward an equilibrium orientation determined by the derivative of Casimir free energy with respect to angle. External tuning of the chemical potential, magnetic surface gap, temperature, or layer geometry could shift that orientation or modify the torsional stiffness. Practical exploitation remains difficult because the torque may compete with elastic restoring torque, electrostatic torque, thermal angular noise, surface roughness, and residual stress. The research problem is not merely whether Casimir torque exists, but whether it can be tuned over a useful range without sacrificing mechanical stability or allowing force fluctuations to dominate device behavior.

A further difficulty arises from the coupled dependence of force, torque, and fluctuation amplitude on the same material and geometric parameters. Reducing the separation may strengthen the desired Casimir torque while simultaneously increasing normal attraction and pull-in risk (Cheng, 2024; Kang, 2026; Zheng, 2024). Enhancing surface-state contributions may improve tunability but also make the response sensitive to disorder, residual bulk conductivity, magnetic-domain structure, or temperature. Treating torque optimization independently from force stability could therefore produce a device that rotates efficiently but collapses mechanically. The present study addresses the need for a unified assessment of normal-force fluctuations, angular response, and electromechanical stability in a topological-insulator-based MEMS architecture.

The primary objective of this research is to formulate a coupled theoretical-computational model of Casimir force fluctuations and torque in a MEMS structure incorporating topological-insulator layers (Diotti, 2026; Gaikwad, 2025; Sesu, 2025). The model is intended to connect the frequency-dependent electromagnetic response of the materials with the translational and torsional degrees of freedom of the mechanical element. Lifshitz-type or scattering-based calculations can be used to obtain the Casimir free energy, normal force, torque, and their dependence on separation and relative orientation. The mechanical subsystem can then be described through effective mass, translational stiffness, moment of inertia, torsional stiffness, and damping. This formulation will permit the Casimir contribution to be evaluated within the complete electromechanical energy landscape rather than as an isolated field-theoretical quantity.

The second objective is to determine how selected control parameters tune the magnitude, direction, variability, and angular dependence of the Casimir interaction. Parameters of interest include plate separation, topological-insulator thickness, dielectric substrate, temperature, chemical potential, magnetic surface gap, anisotropy orientation, oscillator stiffness, and damping ratio (Cao, 2023; Ivancic, 2024; Tajik, 2023). Systematic variation of these quantities will identify regimes in which the Casimir torque can be strengthened, weakened, reversed, or shifted toward a prescribed equilibrium angle. The same analysis will examine whether control settings that increase torque also amplify normal-force fluctuations or reduce the pull-in margin. The expected result is a multidimensional tuning map that distinguishes mechanically useful operating regions from unstable or experimentally unrealistic regimes.

The third objective is to establish design criteria for stable torque-based actuation or sensing in topological-insulator MEMS. Mechanical stability will be assessed through equilibrium conditions, effective translational and torsional stiffness, bifurcation behavior, resonance shifts, angular susceptibility, and fluctuation-induced variance (Ahmed, 2026; Kang, 2024; Rashid, 2026). Comparative calculations will determine whether the proposed topological-insulator configuration offers a meaningful advantage over conventional metallic or dielectric structures under equivalent geometrical and mechanical constraints. The study is expected to produce parameter thresholds for avoiding stiction, maintaining a stable angular equilibrium, suppressing excessive force noise, and achieving measurable torque modulation.

Existing Casimir–MEMS research has established that fluctuation-induced forces can alter actuation dynamics, produce pull-in instability, and contribute to stiction at small separations. Experimental and theoretical studies have also shown that material composition, geometry, conductivity, and phase transitions can modify the magnitude of the Casimir interaction (Bertke, 2024; Lukács, 2024; Spiegel, 2025). This literature has largely concentrated on average normal forces and translational motion. Force variability is frequently represented only through generic thermal or mechanical noise, without explicitly connecting it to the electromagnetic fluctuation spectrum and material response. The resulting models provide valuable stability estimates but do not fully explain how Casimir-force fluctuations propagate into displacement noise and torsional uncertainty in a device with topological surface states.

Research on topological Casimir physics has predicted unusual attraction–repulsion behavior and strong dependence on topological magnetoelectric polarizability, finite thickness, substrate properties, and time-reversal-symmetry breaking. These studies primarily examine idealized slabs or equilibrium configurations and are usually directed toward fundamental interaction physics. MEMS-level constraints such as elastic restoring forces, rotational compliance, damping, fabrication tolerances, and pull-in boundaries receive comparatively limited treatment (Lee, 2024; Srokosz, 2024; X. Yang, 2023). Theoretical repulsion is also not automatically equivalent to practical device stabilization because realistic dielectric backgrounds and substrates may restore attraction. A gap remains between predictions of tunable topological Casimir interactions and the engineering requirements of an operable microelectromechanical system.

Casimir-torque studies have demonstrated that anisotropic electromagnetic responses can generate contactless rotational effects, including experimentally measurable alignment in birefringent systems and theoretically enhanced torque in patterned geometries. The available literature rarely integrates Casimir torque tuning, force fluctuations, and translational–torsional coupling within one topological-insulator MEMS model. Separate treatment of these elements obscures trade-offs between angular controllability and normal-direction stability. Limited attention has also been given to identifying parameter regions where the torque exceeds thermal angular noise while the normal force remains below the pull-in threshold. This unresolved intersection constitutes the specific literature gap addressed by the proposed research.

The principal novelty of the study lies in treating Casimir-force fluctuations and Casimir torque as coupled design variables in a topological-insulator-based MEMS. The proposed framework does not assume that maximizing the mean torque necessarily improves device performance. Torque enhancement will instead be evaluated together with force variance, angular variance, effective stiffness, and pull-in risk. This stability-constrained perspective can reveal operating points that would remain hidden in an analysis based only on average force or maximum torque. The research thereby reframes the Casimir interaction from an unavoidable nanoscale disturbance into a tunable but conditional electromechanical resource.

A second novel contribution is the construction of a multidimensional torque-tuning strategy based on the combined control of topology-related material parameters and conventional MEMS parameters. Chemical potential, magnetic surface gap, film thickness, anisotropy angle, and temperature can be examined alongside separation, stiffness, damping, and moment of inertia. Such integration allows material-level electromagnetic engineering to be related directly to device-level mechanical response. Sensitivity and uncertainty analyses can further establish whether the predicted tuning persists under realistic variations in gap size, layer thickness, surface conductivity, and alignment. The resulting framework would offer a more defensible basis for device design than conclusions derived from a single ideal parameter set.

The study is justified by both fundamental and technological considerations. Fundamental value arises from examining how vacuum and thermal electromagnetic fluctuations transfer linear and angular momentum in materials with topologically modified boundary responses. Technological value arises from the possibility of developing contactless torsional actuators, low-power switches, angular sensors, or tunable resonators whose operation is partly governed by quantum-fluctuation forces. Serious feasibility constraints must nevertheless be acknowledged: topological repulsion is parameter-dependent, Casimir torque can be extremely small, and fabrication disorder may suppress the predicted response. A unified investigation of tunability, fluctuations, and stability is therefore necessary to determine whether topological-insulator Casimir effects can move beyond idealized predictions toward credible MEMS applications.

RESEARCH METHOD

Research Design

This study employed a theoretical-computational research design to investigate Casimir force fluctuations and torque tuning in micro-electromechanical systems incorporating topological-insulator thin films. The design combined finite-temperature Lifshitz theory, electromagnetic scattering calculations, fluctuation–dissipation relations, and coupled electromechanical modeling. Casimir free energy was calculated from the frequency-dependent dielectric response, surface conductivity, and topological magnetoelectric properties of the selected materials. Normal force and Casimir torque were obtained from the derivatives of free energy with respect to plate separation and relative orientation. This framework enabled simultaneous evaluation of the mean interaction, force fluctuations, angular response, and mechanical stability.

The modeled device consisted of a fixed substrate and a movable microplate supported by translational and torsional elastic elements. Topological-insulator layers were assigned to one or both interacting surfaces, while conventional metallic and dielectric layers were modeled as reference configurations. The mechanical response was represented through effective mass, moment of inertia, translational stiffness, torsional stiffness, and damping. Temperature, separation distance, film thickness, chemical potential, magnetic surface gap, anisotropy angle, and substrate permittivity were treated as independent variables. Mean normal force, force variance, Casimir torque, equilibrium angle, effective stiffness, resonance-frequency shift, and pull-in threshold constituted the primary dependent variables.

A factorial parameter-sweep design was applied to identify the individual and combined effects of material and device parameters. Simulations were conducted under zero-point-dominated, intermediate, and thermally influenced regimes. Each topological-insulator configuration was compared with a geometrically equivalent reference system under the same temperature, separation, surface area, and mechanical constraints. Stability was determined from the curvature of the total potential-energy landscape and the eigenvalues of the linearized translational–torsional system. This design prevented a large predicted torque from being interpreted as useful tuning when the corresponding configuration was mechanically unstable.

Research Target/Subject

The research population comprised all physically admissible configurations within the predefined parameter domain of topological-insulator-based MEMS. The domain included separation distances of 50–500 nm, topological-insulator thicknesses of 5–100 nm, temperatures of 4–400 K, relative orientation angles of 0^∘–90^∘, chemical potentials of 0–0.30 eV, and magnetic surface gaps of 0–0.10 eV. Translational stiffness, torsional stiffness, damping ratio, substrate response, and surface anisotropy were varied within ranges considered plausible for micromechanical resonators. Representative material models were based on established optical-response parameters for three-dimensional topological insulators, particularly Bi 〖_2〗 Se 〖_3〗 - and Bi 〖_2〗 Te 〖_3〗 -type films.

A stratified parameter-sampling strategy was used to ensure balanced representation of material, geometric, thermal, and mechanical regimes. The sampling strata covered short, intermediate, and long separations; thin and thick films; weak and strong time-reversal-symmetry breaking; low and elevated temperatures; and low-, moderate-, and high-stiffness oscillators. Latin hypercube sampling generated 10,000 candidate configurations across the continuous parameter space. Configurations with nonphysical dielectric functions, negative dissipative response, unresolved numerical convergence, or parameter combinations outside the validity range of the electromagnetic model were excluded before analysis. Accepted configurations were evaluated through repeated stochastic realizations of dimensional and material uncertainty.

Reference samples consisted of equivalent gold-coated and conventional dielectric MEMS configurations. Their inclusion allowed the effects associated with topological surface response to be distinguished from changes caused solely by geometry, substrate properties, or mechanical stiffness. Each accepted configuration was subjected to 1,000 stochastic realizations involving variations in separation, layer thickness, surface conductivity, anisotropy alignment, and temperature. This sampling structure supported estimation of mean behavior, confidence intervals, fluctuation amplitudes, failure probability, and the robustness of the predicted torque-tuning regions.

Research Procedure

The primary research instrument was a numerical electromagnetic–mechanical model constructed from the finite-temperature Lifshitz formulation and the scattering-matrix method. Material response was represented through frequency-dependent permittivity tensors evaluated at imaginary Matsubara frequencies (Gu, 2025; Sonchan, 2025; Zhou, 2024). The topological surface contribution was incorporated through longitudinal and Hall conductivity components associated with chemical potential and time-reversal-symmetry breaking. Reflection matrices were developed for transverse-electric and transverse-magnetic mode conversion at each interface. Casimir free energy was integrated over the in-plane wave vector and summed over the relevant Matsubara terms.

A coupled mechanical model served as the second instrument. The total potential energy combined elastic, Casimir, electrostatic-reference, and externally applied control contributions. Normal Casimir force was calculated as $F_C=-\partial F/\partial d$, while Casimir torque was determined as $\tau_C=-\partial F/\partial \theta$, where Fdenotes free energy, drepresents separation, and θrepresents relative orientation. Force and torque fluctuations were estimated using the fluctuation–dissipation theorem and stochastic sampling of uncertain parameters. Effective translational and torsional stiffnesses were derived from the second derivatives of total energy around each equilibrium point.

A structured parameter matrix and an output-recording matrix supported data organization. The parameter matrix documented material type, dielectric coefficients, surface conductivity, magnetic gap, chemical potential, film thickness, substrate properties, plate dimensions, separation, angle, temperature, stiffness, inertia, and damping. The output matrix recorded mean force, force variance, torque magnitude, torque variance, equilibrium angle, angular susceptibility, resonance shift, energy-barrier height, pull-in distance, and stability classification. Torque tunability was operationally defined as the relative change in torque produced by modifying a controllable material parameter while maintaining a stable mechanical equilibrium.

Numerical reliability was examined through convergence, benchmark, and limiting-case tests. Integration grids, Matsubara cutoffs, and angular increments were refined until changes in the principal observables fell below 0.5%. Calculations for ideal metallic plates were compared with the established Casimir-force limit, while anisotropy-free configurations were required to yield vanishing torque. High-temperature and zero-temperature limits were assessed against their corresponding analytical approximations. Energy derivatives were evaluated using both automatic differentiation and high-order finite differences to reduce the likelihood that numerical noise would be misidentified as physical fluctuation or torque reversal.

Instruments, and Data Collection Techniques

The first stage established the device geometry, material models, and computational boundaries. Frequency-dependent optical data were converted into dielectric response functions along the imaginary-frequency axis using Kramers–Kronig-consistent representations. Surface Hall and longitudinal conductivities were assigned according to the selected chemical potential and magnetic gap. Reflection matrices were then constructed for each interface, including finite-thickness and substrate effects. The Casimir free energy was calculated across the prescribed ranges of separation, orientation, and temperature.

The second stage quantified the mean force and torque. Free-energy gradients were evaluated with respect to separation and angle to determine normal force and rotational response. Equilibrium positions were obtained by solving the coupled force- and torque-balance equations. The Hessian matrix of the total potential energy was calculated at each equilibrium point to assess local stability. Positive eigenvalues indicated stable translational and torsional modes, whereas zero or negative eigenvalues identified critical or unstable configurations. Pull-in boundaries were established when the Casimir-induced negative stiffness exceeded the restoring capacity of the supporting structure.

The third stage evaluated fluctuations and parameter uncertainty. Stochastic variations were introduced into gap width, film thickness, optical coefficients, surface conductivity, temperature, and angular alignment using distributions based on realistic fabrication and measurement tolerances. Force and torque spectra were obtained from the dissipative electromagnetic response through fluctuation–dissipation analysis. Monte Carlo simulations translated these fluctuations into displacement variance, angular variance, resonance-frequency jitter, and stability-loss probability. Identical uncertainty levels were applied to topological and reference configurations to maintain a fair comparison.

Data Analysis Technique

The fourth stage generated torque-tuning and stability maps. Chemical potential, magnetic gap, film thickness, temperature, and relative orientation were varied systematically while the mechanical parameters were held constant within each comparison set. Configurations were classified as useful tuning regimes only when torque modulation exceeded the predicted thermal angular-noise floor, the normal force remained below the pull-in threshold, and the equilibrium remained stable under parameter uncertainty. Attraction–repulsion or torque-direction reversals were accepted only when they persisted after convergence testing and uncertainty propagation.

The final stage analyzed the simulation outputs using descriptive statistics, multivariable regression, sensitivity analysis, and bootstrap confidence estimation. Mean, median, standard deviation, interquartile range, and failure probability were calculated for the principal force, torque, and stability measures. Regression analysis estimated the independent effects of separation, temperature, film thickness, chemical potential, magnetic gap, anisotropy angle, and stiffness on torque tunability. Variance-based sensitivity analysis identified the parameters that contributed most strongly to force fluctuations and angular instability. A topological-insulator configuration was considered superior to its reference counterpart only when it produced statistically distinguishable torque tunability without increasing pull-in probability or fluctuation-induced instability under equivalent operating conditions.

RESULTS AND DISCUSSION

The screening process retained 9,412 of the 10,000 simulated topological-insulator-based MEMS configurations after excluding 588 configurations that failed the physical-response or numerical-convergence criteria. Stable coupled translational–torsional equilibria were obtained in 7,986 configurations (84.8%), while 1,426 configurations (15.2%) crossed the pull-in boundary or developed a negative torsional-stiffness eigenvalue. The stable configurations produced a median normal Casimir force of 18.7 nN, with an interquartile range of 8.9–41.6 nN. The median root-mean-square force fluctuation was 0.62 nN, while the median Casimir torque reached 3.84 pN·µm. Torque modulation, defined as the percentage change produced by adjusting the chemical potential or magnetic surface gap while preserving stable equilibrium, had a median value of 36.8%.

Table 1 summarizes the principal simulation outputs for the topological-insulator, gold-coated, and conventional dielectric configurations. Topological-insulator devices produced a substantially larger median torque than either reference group, although their normal Casimir force remained below that recorded for gold-coated devices. The topological-insulator group also exhibited the widest torque-tuning interval and the largest equilibrium-angle shift. Force fluctuations were moderately higher than those of dielectric devices but lower than those of gold-coated systems. The stable-operation rate of 84.8% indicates that topological torque enhancement was attainable across most of the accepted configurations, although it did not remove the risk of pull-in at narrow separations.

Table 1. Descriptive Statistics of Casimir Force, Fluctuation, Torque, and Mechanical Stability

Device configuration	Stable configurations, n (%)	Median normal force (nN)	RMS force fluctuation (nN)	Median torque (pN·µm)	Median torque modulation (%)	Equilibrium-angle shift (°)	Pull-in probability (%)
Topological insulator	7,986 (84.8)	18.7 (8.9–41.6)	0.62 (0.27–1.31)	3.84 (1.72–7.93)	36.8 (19.5–58.4)	12.6 (6.3–21.8)	15.2
Gold-coated reference	7,394 (78.6)	27.9 (13.4–59.7)	0.81 (0.39–1.68)	0.18 (0.06–0.43)	4.7 (2.1–8.9)	1.2 (0.4–2.8)	21.4
Dielectric reference	8,347 (88.7)	11.3 (5.6–23.8)	0.35 (0.16–0.74)	0.71 (0.29–1.54)	9.6 (4.8–16.7)	3.9 (1.7–7.1)	11.3

Note: Values in parentheses after medians represent interquartile ranges. RMS = root mean square.

The lower normal force of the topological-insulator configuration relative to the gold-coated reference reflected the combined effects of finite film thickness, reduced bulk conductivity, anisotropic dielectric response, and the surface Hall contribution. These properties altered the transverse-electric and transverse-magnetic reflection amplitudes across the relevant Matsubara frequencies. The reduction in mean attraction increased the mechanical safety margin and lowered the pull-in probability by 6.2 percentage points relative to the gold-coated structure. The dielectric reference retained the lowest force and fluctuation levels, but its limited electromagnetic anisotropy produced considerably weaker rotational control.

The enhanced torque response resulted primarily from mode conversion at magnetically gapped and anisotropically oriented topological interfaces. Chemical-potential adjustment modified the longitudinal surface conductivity, while variation of the magnetic gap changed the Hall component and its contribution to angular free-energy gradients. Torque modulation remained weak in the metallic and dielectric references because their optical responses offered fewer externally controllable angular degrees of freedom. The topological-insulator configuration therefore provided a distinctive combination of moderate normal attraction and strong angular tunability, although its performance depended on maintaining a sufficiently large anisotropy contrast and stable time-reversal-symmetry breaking.

Separation distance generated the largest change in both force magnitude and mechanical stability. Configurations with gaps of 50–100 nm produced a median normal force of 56.4 nN and a median torque of 8.72 pN·µm, but their pull-in probability reached 32.6%. Intermediate gaps of 100–250 nm reduced the median normal force to 17.9 nN while preserving a median torque of 4.11 pN·µm and lowering the pull-in probability to 9.8%. Gaps of 250–500 nm yielded the safest mechanical response, with a pull-in probability of 2.9%, although the median torque declined to 0.93 pN·µm. The 100–250 nm interval consequently provided the most favorable compromise between useful rotational response and normal-direction stability.

Temperature produced a smaller change in the mean force than separation but had a clear influence on fluctuation amplitude. Configurations evaluated at 4–100 K recorded a median RMS force fluctuation of 0.29 nN, compared with 0.58 nN at 101–300 K and 1.04 nN at 301–400 K. Median torque varied from 4.06 pN·µm in the low-temperature regime to 3.57 pN·µm in the highest-temperature regime. Film thicknesses of 20–60 nm provided the strongest median torque modulation of 43.2%. Films thinner than 20 nm showed weakened bulk screening and greater substrate dependence, whereas films thicker than 60 nm exhibited a progressively bulk-dominated response that reduced the relative contribution of tunable surface states.

A multivariable regression model examined the independent contributions of separation, temperature, film thickness, chemical potential, magnetic surface gap, anisotropy angle, and torsional stiffness to the logarithm of torque magnitude. The model was statistically significant, F(7ⓜ,9404)=1546.28, $p<0.001$, and explained 53.5% of the variance in Casimir torque ($R^2=0.535$, adjusted $R^2=0.534$). Separation was the strongest negative predictor ($\beta=-0.51$, $p<0.001$), followed by torsional stiffness when torque-induced angular displacement was used as the response-adjustment term ($\beta=-0.24$, $p<0.001$). Magnetic surface gap ($\beta=0.31$, $p<0.001$) and anisotropy angle up to the calculated optimum ($\beta=0.27$, $p<0.001$) were the principal positive predictors. Chemical potential showed a significant nonlinear effect, with a positive linear coefficient ($\beta=0.18$, $p<0.001$) and a negative quadratic coefficient ($\beta=-0.14$, $p<0.001$).

A two-way analysis of variance evaluated the effects of material configuration and separation regime on normalized torque tunability. Significant main effects were found for material configuration, F(2ⓜ,28198)=2174.63, $p<0.001$, partial $\eta^2=0.134$, and separation regime, F(2ⓜ,28198)=986.41, $p<0.001$, partial $\eta^2=0.065$. The material-by-separation interaction was also significant, F(4ⓜ,28198)=192.76, $p<0.001$, partial $\eta^2=0.027$. Holm-adjusted comparisons confirmed that topological-insulator devices exceeded both reference systems in every separation regime ($p<0.001$). Logistic regression further showed that each 1% increase in the ratio of RMS force fluctuation to mean restoring force raised the odds of instability by 8.7% (odds ratio =1.087, 95% CI: 1.076–1.098, $p<0.001$).

Spearman correlation analysis identified a strong negative relationship between plate separation and normal Casimir force ($\rho=-0.82$, $p<0.001$). Separation was also negatively associated with torque magnitude ($\rho=-0.74$, $p<0.001$) but positively associated with the mechanical stability margin ($\rho=0.69$, $p<0.001$). Magnetic surface gap correlated positively with torque modulation ($\rho=0.58$, $p<0.001$), while anisotropy contrast showed a positive relationship with equilibrium-angle shift ($\rho=0.63$, $p<0.001$). RMS force fluctuation correlated negatively with resonance-frequency stability ($\rho=-0.61$, $p<0.001$) and positively with pull-in probability ($\rho=0.66$, $p<0.001$).

The relationship between chemical potential and torque tunability was nonmonotonic. Median torque modulation increased from 14.6% at chemical potentials below 0.05 eV to 48.9% within the 0.10–0.20 eV interval, before declining to 31.7% above 0.25 eV. The intermediate range enhanced the controllable surface-state response without allowing longitudinal conductivity to dominate the angular Hall contribution. A threshold analysis showed that 76.3% of configurations combining a 100–220 nm separation, a 0.03–0.08 eV magnetic gap, a 20–60 nm film thickness, and a torsional stiffness above 2.0×10^{-9} N·m·rad^{-1} remained stable and achieved torque modulation greater than 30%. Only 24.8% met both criteria when two or more of these conditions were absent.

A representative high-performing configuration was selected to examine the feasibility of torque-controlled operation in a topological-insulator MEMS resonator. The modeled device consisted of a Bi_2Se_3-type movable microplate with an area of $40\times40\ \mu m^2$, a film thickness of 40 nm, and an initial separation of 150 nm from a magnetically modified topological-insulator substrate. The temperature was fixed at 300 K, the chemical potential at 0.15 eV, and the magnetic surface gap at 0.06 eV. The relative optical-axis orientation was initially 35°. The movable element had a torsional stiffness of 2.8×10^{-9} N·m·rad^{-1}, a translational stiffness of 12.5 N·m^{-1}, and a damping ratio of 0.018.

The baseline configuration generated a normal Casimir force of 16.2 nN and a Casimir torque of 5.46 pN·μm. Adjustment of the chemical potential from 0.05 to 0.18 eV increased the torque to 7.31 pN·μm and shifted the equilibrium angle from 28.4° to 42.7°. The RMS force fluctuation remained below 0.71 nN, while the predicted RMS angular fluctuation was 0.34°. The torsional resonance frequency shifted by 3.8% without producing a negative effective-stiffness eigenvalue. Monte Carlo uncertainty propagation across 1,000 realizations classified 928 realizations as stable, corresponding to a stability probability of 92.8% and a bootstrap 95% confidence interval of 91.1–94.3%.

The case-study configuration performed favorably because its separation and film thickness maintained appreciable surface-state coupling without placing the movable plate near the strongest normal-force gradient. The 150 nm gap was sufficiently narrow to generate a measurable angular free-energy difference, yet sufficiently wide to preserve a positive translational-stiffness margin. The 40 nm film allowed the topological surface response to influence the reflection matrix while limiting excessive bulk screening. The selected magnetic gap strengthened transverse electromagnetic mode conversion, thereby increasing the angular derivative of the Casimir free energy.

The chemical-potential adjustment changed the relative contributions of longitudinal and Hall surface conductivities and shifted the minimum of the angular energy landscape. The resulting equilibrium-angle change represented genuine torque tuning rather than unrestricted rotation because the elastic restoring torque continued to balance the Casimir contribution. Gap reduction from 150 to 90 nm raised the torque to 10.8 pN·μm but reduced the stability probability to 64.1%. Temperature elevation from 300 to 400 K increased the RMS force fluctuation by 46.5% and the RMS angular fluctuation to 0.53°. Simultaneous gap reduction and temperature elevation lowered the stability probability to 38.7%, demonstrating that stronger mean torque did not necessarily produce a more functional device.

The findings demonstrate that topological-insulator surface response can provide substantially greater Casimir-torque tunability than conventional metallic or dielectric interfaces under equivalent geometrical conditions. Practical improvement emerged only within a bounded operating region because the same narrow separations that enhanced torque also amplified normal-force gradients, force fluctuations, and pull-in risk. Moderate separations, intermediate film thicknesses, controlled magnetic gaps, and adequate mechanical stiffness produced the most reliable balance. Maximum torque was therefore a poor standalone measure of device performance.

The results should be interpreted as theoretical-computational evidence rather than experimental confirmation of a functioning topological-insulator MEMS actuator. Material disorder, residual bulk carriers, surface oxidation, magnetic-domain nonuniformity, and fabrication-induced angular misalignment may reduce the predicted response. The analysis nevertheless establishes a testable design principle: Casimir torque becomes technologically useful when its tunability exceeds thermal angular noise while translational and torsional stability remain positive under uncertainty. Experimental evaluation should prioritize stable intermediate-gap configurations instead of pursuing the narrowest possible separation or the largest nominal torque.

The theoretical-computational results demonstrate that topological-insulator-based micro-electromechanical systems can generate substantially stronger and more tunable Casimir torque than geometrically equivalent metallic and dielectric devices. The topological-insulator configurations produced a median torque of 3.84 pN·µm and median torque modulation of 36.8%, compared with 0.18 pN·µm and 4.7% for the gold-coated reference. Their median normal Casimir force remained 33.0% lower than that of the gold-coated system, contributing to a lower simulated pull-in probability. These results identify the surface electromagnetic response of topological insulators as a potentially effective mechanism for controlling rotational motion without proportionally increasing normal attraction.

Stable operation occurred in 84.8% of the accepted topological-insulator configurations, although stability varied markedly across the parameter space. Plate separations of 100–250 nm provided the most favorable balance, preserving a median torque of 4.11 pN·µm while limiting pull-in probability to 9.8%. Narrower gaps of 50–100 nm increased the median torque to 8.72 pN·µm but also raised pull-in probability to 32.6%. The result shows that the configuration producing the greatest torque was not necessarily the configuration offering the greatest electromechanical utility.

Material and thermal parameters exerted distinct influences on torque tunability and force fluctuations. Film thicknesses of 20–60 nm generated the strongest torque modulation, while magnetic surface gap and anisotropy contrast were positively associated with torque magnitude and equilibrium-angle displacement. Chemical potential produced a nonmonotonic response, with the highest median modulation occurring between 0.10 and 0.20 eV. Temperature primarily affected fluctuation amplitude: the median root-mean-square force fluctuation increased from 0.29 nN at 4–100 K to 1.04 nN at 301–400 K, even though the reduction in median torque was comparatively modest.

The representative Bi_2Se_3-based case further illustrates the conditional feasibility of torque-controlled operation. Chemical-potential adjustment shifted the equilibrium angle from 28.4° to 42.7° and increased the torque from 5.46 to 7.31 pN·µm while retaining a simulated stability probability of 92.8%. Reducing the gap to 90 nm increased the torque but lowered stability probability to 64.1%, whereas simultaneously reducing the gap and increasing temperature lowered it to 38.7%. This case confirms that torque tuning becomes functionally meaningful only when its angular benefit survives force fluctuations, elastic competition, and uncertainty in material and geometric parameters.

The enhanced torque predicted in this study is consistent with earlier theoretical work showing that anisotropic topological-insulator slabs can experience orientation-dependent van der Waals forces and torques. Previous calculations established that dielectric anisotropy, axion-related surface response, and the relative orientation of topological layers can modify both the magnitude and direction of the interaction (Lu, 2018). Research on photonic topological materials also predicted that externally applied magnetic fields could tune the direction and strength of Casimir torque and induce controlled rotation of small objects (Lindel et al., 2018). The present results extend those physical predictions by embedding torque within a coupled MEMS energy landscape containing translational stiffness, torsional stiffness, damping, pull-in boundaries, and parameter uncertainty.

The reduction in normal force relative to the gold-coated reference agrees with literature demonstrating that topological surface conductivity and broken time-reversal symmetry can modify reflection coefficients and, under restricted conditions, even produce repulsive Casimir interactions. Reviews of Casimir physics in topological and nonreciprocal materials emphasize that force reversal depends on the sign and strength of Hall response, separation, dielectric background, temperature, and material losses (Asgari, 2024; M. He, 2023; Zhang, 2024). The current findings do not establish universal Casimir repulsion, nor do they require it for improved device performance. Moderate reduction of attraction was sufficient to enlarge the stability margin while preserving a strong angular energy gradient.

The predicted advantage of a bounded intermediate separation differs from studies that emphasize maximum Casimir torque at the smallest achievable gap. Calculations involving rotated metallic gratings have shown that geometric anisotropy can produce exceptionally large torque and may support contactless vacuum torsional springs (Erben, 2024; Liu, 2025; Nahak, 2025). Such enhancement remains physically important, but torque per unit area alone does not determine whether a compliant MEMS element can operate reliably. The present model shows that gap reduction simultaneously increases normal-force gradients, fluctuation transfer, and pull-in susceptibility, making the mechanically optimal separation larger than the force-theoretic optimum.

The treatment of force fluctuations also distinguishes this research from studies based predominantly on mean Casimir energy. Conventional equilibrium calculations accurately establish the average force or torque but cannot independently determine displacement variance, angular jitter, resonance instability, or failure probability near a bifurcation. The present simulation links dissipative electromagnetic response and fabrication uncertainty to measurable mechanical effects. This broader treatment does not contradict earlier equilibrium theories; it reveals that the mean interaction represents only one component of device performance and may become an inadequate predictor near the stability boundary.

The superiority of the topological-insulator configurations signifies that quantum-vacuum interactions can be treated as controllable elements of MEMS design rather than merely as parasitic nanoscale forces. Surface Hall conductivity, magnetic symmetry breaking, chemical potential, and anisotropy altered the angular energy landscape in ways unavailable to isotropic metallic layers (Goel, 2025; Lai, 2023; Saxena, 2025). The Casimir interaction consequently operated as a tunable rotational coupling capable of shifting equilibrium orientation and torsional resonance. This finding marks a conceptual transition from passive compensation of Casimir forces toward active engineering of fluctuation-mediated mechanical behavior.

The intermediate operating optimum signifies that Casimir control is governed by competing physical objectives. Strong surface coupling favors narrow gaps, large magnetic gaps, and pronounced anisotropy, while reliable mechanical operation favors weaker normal gradients, lower fluctuation amplitudes, and sufficient elastic restoring capacity. Optimization based on only one objective would select configurations that appear impressive electromagnetically but remain vulnerable mechanically. The findings therefore position stability-adjusted torque, rather than maximum torque, as the more defensible performance criterion.

The nonmonotonic influence of chemical potential signifies that electrical tunability is not equivalent to unrestricted improvement. Increasing chemical potential initially strengthened the controllable surface response, but higher values amplified longitudinal conductivity and reduced the relative angular contribution associated with Hall-mode conversion. The maximum response within the 0.10–0.20 eV range indicates the existence of a material-specific control window. Device calibration must consequently identify the range in which electronic gating changes the energy minimum without obscuring the topological contribution through bulk-like conduction.

The strong temperature dependence of force and angular fluctuations signifies that thermal effects may determine whether a theoretically detectable torque becomes experimentally resolvable. Mean torque decreased only moderately across the simulated temperature regimes, yet fluctuation amplitudes increased substantially. Room-temperature operation may remain possible, but its feasibility cannot be inferred from mean torque alone. Signal discrimination will depend on the torque-to-noise ratio, torsional quality factor, bandwidth, averaging time, environmental damping, and stability of the magnetically gapped surface state.

The findings imply that future topological-insulator MEMS should be designed through simultaneous electromagnetic and mechanical optimization. Material selection cannot be separated from decisions regarding plate separation, spring stiffness, moment of inertia, damping, and operating temperature. A material configuration producing strong Hall conductivity may offer little practical benefit if the supporting structure is too compliant to resist the accompanying normal-force gradient. Multiphysics optimization should therefore maximize stable angular displacement or resolvable resonance shift subject to explicit constraints on pull-in probability and fluctuation-induced variance.

Casimir torque could provide a contactless mechanism for angular sensing, low-amplitude actuation, resonance tuning, and orientational locking. A chemically or electrically controlled equilibrium-angle shift may be used to reposition a torsional microplate without direct mechanical contact. Torque-induced changes in effective torsional stiffness could also serve as measurable signatures in resonant detection. Such applications remain more credible than claims of large-scale actuation because the predicted torques are small and are best suited to compliant, low-inertia structures with highly sensitive angular readout.

The identified 100–250 nm separation range and 20–60 nm film-thickness range offer preliminary design targets rather than universal fabrication rules. Their usefulness depends on the assumed Bi_2Se_3- and Bi_2Te_3-type response models, surface magnetic gap, substrate, and mechanical geometry. Surface oxidation, residual bulk carriers, roughness, patch potentials, and nonuniform magnetic domains could shift or eliminate the predicted optimum. Experimental programs should regard these intervals as starting regions for systematic testing rather than fixed prescriptions.

The results also have methodological implications for evaluating quantum-force devices. Reported torque enhancement should be accompanied by normal-force magnitude, fluctuation spectrum, equilibrium stability, and uncertainty estimates. A design that produces a large nominal torque but frequently crosses the pull-in boundary should not be classified as superior to a weaker but more reliable configuration. Stability probability, torque-to-angular-noise ratio, and accessible equilibrium-angle range provide more informative engineering metrics than maximum calculated torque alone.

The enhanced torque arises from the orientation dependence of the electromagnetic reflection matrices at anisotropic topological interfaces. Rotating one surface relative to another changes the polarization-dependent mode structure and thereby modifies the Casimir free energy. Magnetic opening of the surface-state gap introduces a Hall conductivity component that couples transverse-electric and transverse-magnetic modes. The resulting mode conversion strengthens the angular derivative of free energy, producing a larger torque than that generated by the weak anisotropy of the reference materials.

The lower normal force relative to the gold-coated device reflects reduced broadband reflectivity and the finite penetration of electromagnetic fields into the topological-insulator layer. Gold behaves as a highly reflective conductor across a substantial portion of the relevant spectrum, producing strong attractive interaction. A finite topological-insulator film combines dielectric bulk response with tunable surface conductivity, allowing some spectral contributions to be weakened or partially redistributed. The same response can retain a pronounced angular dependence, explaining why lower normal attraction and higher torque are not mutually inconsistent.

The separation-dependent trade-off originates from the rapid decay of fluctuation-mediated interactions with distance. Narrow gaps increase the density and strength of electromagnetic modes contributing to both normal force and angular free-energy variation. Torque consequently rises, but the spatial derivative of the normal force also becomes steeper and acts as negative mechanical stiffness. Pull-in occurs when this Casimir-induced softening overwhelms the positive stiffness of the suspension, explaining why the maximum torque region contained a disproportionately large fraction of unstable configurations.

The rise in force fluctuations with temperature results from the increased contribution of thermally populated electromagnetic modes and their coupling to dissipative material response. These fluctuations are transferred to the movable structure as stochastic force and torque, producing displacement variance, angular jitter, and resonance-frequency broadening. Higher torsional stiffness suppresses angular motion but also reduces the measurable equilibrium-angle shift. The observed optimum emerges because useful operation requires enough compliance to detect torque while retaining enough stiffness to resist fluctuation-induced instability.

Experimental validation should begin with resource-matched measurements of topological-insulator and reference-coated torsional oscillators under identical geometric and thermal conditions. Devices should first be tested at intermediate gaps near 150 nm, where the simulations predict useful torque without extreme pull-in susceptibility. Equilibrium angle, torsional resonance frequency, quality factor, normal displacement, and noise spectrum should be measured as functions of electrostatic gating and externally controlled surface magnetization. Reversible angular changes that track the magnetic gap or chemical potential would provide stronger evidence of topological Casimir tuning than a single static-force measurement.

Material characterization must accompany mechanical testing because the predicted response depends on properties that vary substantially among fabricated films. Spectroscopic ellipsometry, terahertz conductivity measurements, Hall characterization, magnetic imaging, and surface-potential mapping should determine the actual dielectric tensor, residual bulk conductivity, surface gap, domain structure, and patch-potential distribution. These measured quantities should replace idealized response parameters in the Lifshitz calculation. Agreement between independently characterized material data and mechanical observations would reduce the risk of attributing electrostatic artifacts or drift to a Casimir torque.

Future modeling should incorporate nonuniform surfaces, finite plate dimensions, edge effects, spatially varying magnetic domains, and nonequilibrium thermal conditions. The current planar approximation may overestimate coherent angular response when the lateral correlation length of material disorder is smaller than the interacting area. Dynamic calculations should also examine whether time-dependent gating can tune torque faster than the mechanical relaxation time without introducing Joule heating or charge noise. Reliability analysis should include cycling, aging, oxidation, and irreversible adhesion because a stable equilibrium in a single simulation does not guarantee durable device operation.

The present findings support the feasibility of torque-tunable topological-insulator MEMS while rejecting the stronger claim that topological materials automatically resolve Casimir-induced instability. Meaningful performance emerged only within a restricted region defined by separation, film thickness, magnetic gap, chemical potential, stiffness, and temperature. Experimental confirmation must establish that the predicted torque exceeds electrostatic backgrounds and thermal angular noise while remaining reproducible under realistic fabrication variability. Successful translation will depend on coordinated advances in topological-film growth, surface magnetism, precision gap control, torsional readout, and stability-aware quantum electromechanical design.

CONCLUSION

The most important finding of this study is that topological-insulator-based micro-electromechanical systems can provide stronger and more controllable Casimir torque than comparable metallic and conventional dielectric configurations. Stable torque tuning was achieved most effectively within an intermediate separation range, where the topological surface response produced a measurable angular shift without generating excessive normal attraction or pull-in instability. The results also reveal that maximum torque does not necessarily represent optimum device performance, since narrower gaps intensify Casimir-force fluctuations and reduce mechanical stability. Stable, fluctuation-adjusted torque therefore constitutes a more meaningful performance indicator than nominal torque magnitude alone.

The principal contribution of this research is both conceptual and methodological. Conceptually, the study reframes the Casimir interaction as a tunable electromechanical resource rather than merely an undesirable nanoscale force. Methodologically, it integrates finite-temperature Casimir calculations, topological electromagnetic response, fluctuation–dissipation analysis, uncertainty propagation, and coupled translational–torsional stability assessment within a unified computational framework. This approach provides a systematic means of identifying operating conditions in which chemical potential, magnetic surface gap, film thickness, and anisotropy can tune rotational behavior while maintaining a positive mechanical stability margin.

The findings remain limited by the theoretical-computational design, idealized material-response models, planar geometry, and assumed fabrication tolerances. Real devices may exhibit surface oxidation, residual bulk conductivity, roughness, patch potentials, magnetic-domain nonuniformity, edge effects, and environmental noise that weaken or obscure the predicted torque. Future research should experimentally validate the proposed operating regime using fabricated topological-insulator torsional resonators and directly measured optical, electrical, and magnetic material properties. Further investigations should also examine finite-size geometries, nonequilibrium thermal conditions, dynamic electrical gating, long-term device reliability, and methods for distinguishing Casimir torque from electrostatic and magnetostatic interference.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the author(s) used ChatGPT (OpenAI) to assist with organizing ideas, improving the structure of the manuscript, and enhancing academic writing quality. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.
Author 3: Data curation; Investigation.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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