



Research Article

A computational modal analysis of graphene and hexagonal boron nitride reinforced polypropylene nanocomposites

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ABSTRACT

One of the shortcomings of Polypropylene (PP) is its moderate damping properties. Because of their improved mechanical properties, PP nanocomposites reinforced with nanomaterials such as graphene (G) and hexagonal boron nitride (hBN) are emerging as potential materials for advanced engineering applications. This study uses computational modal analysis to evaluate the effects of G and hBN reinforcements on the modal parameters of PP nanocomposites such as deformation, mode shapes and frequency etc. A finite element model is created to predict the vibrational behaviour of PP nanocomposites with different thicknesses of G and hBN nanoparticles. The material properties of the PP nanocomposites were determined using ANSYS models, incorporating the contributions of the reinforcements. The inclusion of G and hBN considerably increases stiffness and lowers deformation, resulting in higher natural frequencies and altered mode shapes. The C-channel models of hybrid nanocomposites having neat PP (2.5 mm thick), PP+G+hBN (0.833 mm each), 0.5mm G+1.5mm PP+0.5mm hBN and 0.25mm G +2mm PP+ 0.25mm hBN are examined to check the effect on deformation. One end of the C-channel is fixed, while an excitation force ranging from 100 N to 1000 N is applied to the other end. The findings demonstrate the ability of G and hBN reinforcements to adjust the vibrational performance of PP nanocomposites, making them ideal for use in structural components, aerospace and automotive etc. This computational study establishes the groundwork for experimental validation and further optimization of PP-based nanocomposites for vibration-sensitive applications. This aspect is particularly novel as it opens avenues for future research aimed at improving the vibrational performance of materials.

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INTRODUCTION

Polypropylene (PP) is a thermoplastic with modal properties including tensile strength, density, fatigue resistance, and others. With a density of $\sim 0.90 \text{ g/cm}^3$, polypropylene has an excellent strength to weight ratio and is a good choice for applications that require a lightweight material [1]. Fatigue resistance allows polypropylene to withstand and resist failure from millions of cycles of stress. Like many polymers, polypropylene's vibrational behavior is determined by its molecular structure, and in the case of polypropylene, its crystallinity [2]. As a semi-crystalline polymer, the amorphous regions contribute to lower stiffness and resonant frequencies [3]. The crystalline regions dictate the higher stiffness and resonant frequencies. Among the polymers, polypropylene exhibits a wide range of vibrational behaviors. For this reason, it is a good choice for applications that require a compliant material and for vibration isolation [4]. Graphene is a 2D material with exceptional mechanical and physical properties. It has extremely high natural frequencies and other vibrational modes due to its high stiffness caused by strong covalent π bonds between carbon atoms. Thus, graphene is one of the stiffest materials. [5]. Graphene also displays exceptional strength and elasticity, allowing it to maintain structural integrity under significant deformation. Its low density together with considerable Young's modulus guarantees impressive strength to weight ratio which is useful for those applications where low weight, yet strong materials are needed [6]. Also, the basic damping properties of the graphene are quite small, which allows good energy transfers into mechanical vibrations and is used in sensors and resonators. The modal behavior of graphene might be affected very strongly by the defects, the strains, and environmental effects [7]. Graphene and hBN are nano-sized materials that have beneficial properties and when composites based on polypropylene, which is a thermoplastic polymer, are prepared, a significant improvement in their mechanical, and vibrational properties are expected [8]. The analysis is particularly useful for scenarios where the fabrication of light weight, strong and tough materials is necessary such as for automotive, aerospace, and flexible electronic applications [9]. Hexagonal boron nitride (hBN) has well-known modal properties owing to its two-dimensional atomic layered structure with strong covalent bonds in its hexagonal planes. hBN being an anisotropic material has different vibrational modes when set into motion in different directions [10]. This accounts for high frequency of natural oscillation and good mechanical stability in the material. However, hBN is somewhat poorer in terms of stiffness and is more brittle than graphene. [11]. It has great thermal stability. This means that it doesn't lose its vibration properties when exposed to different temperatures. Also, it's lightweight, and for its size, it can take a lot of stress without breaking, which makes it great for lots of different uses [12]. This material naturally dampens or dissipates vibrational energy. Because of this, it can be used in thermal

management systems and other similar systems that require the dissipation of energy [13]. These modal characteristics make hBN ideal for applications in nanoscale resonators, high-performance composite materials [14].

The modal properties of a structure or system represent its natural behaviours such as oscillations and twirls upon applying external forces in a physics system, engineering or system dynamics [15]. Most of these properties are studied in physics, engineering, and system dynamics. There are fields like structural engineering, mechanical engineering, acoustic and vibration analysis that depend on modal properties [16]. When a system is completely isolated from any external forces, it operates at a certain frequency known as the natural frequency. Structures can also possess an inherent vibration frequency for each of their vibration modes, a feature that is especially critical in engineering. As long as the conditions for resonance remain unchecked, a significant amount of oscillation and consequent damage will ensure [17]. The natural frequency at which a structural member vibrates assumes a definite geometry or deformation pattern called Mode shape. This is the relative movement of points on the structure when the member vibrates in that particular mode. The way the system twists in that mode correlates to the frequencies of that mode and is known as mode shape [18]. When looking at system vibration, certain masses of the system are active in that vibration. The mass of the system that is actively participating in a vibration is referred to as modal mass. Modeling the system as a combination of masses participating in different modes of vibration provides an effective approach to study the dynamic characteristics of the system. Each vibration mode is associated with a stiffness value called modal stiffness. The modal stiffness value is associated with the particular mode and defines the mode's frequency of vibration [19]. How stiffness is distributed affects a structure's modal stiffness. The behavior of the system constrains where the forces of a given mode are acting. Deformation of a structure due to various natural frequencies is known as mode shapes. It is through mode shapes that regions of higher stress and larger displacements in a structure can be determined. Understanding mode shapes is very important during structural analysis and design [20]. The modal analysis helps to understand the vibration behavior of structures and machinery. It includes determination of natural frequencies and mode shapes of structures, identification of various sources of damping, and analysis of influence of various design and material properties on natural frequencies. All these help in designing structures and machinery to withstand loads due to vibration and also to diagnose problems related to excessive vibration. It helps to understand how structures respond to vibrations or dynamic loads, which is essential for design, testing, and diagnosing issues in engineering fields such as mechanical, civil, aerospace [21]. "Experimental methods" is the term for investigations that determine the natural frequencies of real-world systems through physical testing. This method of analysis

is used to address the shortcomings of analytical models and/or simulations [22]. Alternatively, in computational modal analysis, behavior of a structure and estimation of its modal properties is done by means of finite element analysis. Experimental modal analysis measures the natural frequencies and modes of structural vibration. Being inherently experimental in nature, the method is versatile and provides an accurate assessment of a structure's response. On the other hand, computational modal analysis is fast and provides an estimate of natural frequencies over a range of structural designs. This flexibility makes the method an attractive design tool [23]. This method is fast and economic for preliminary studies and design. Using modal analysis, the design team is able to capture and control the vibration behavior of the system and improve the overall performance of the system [24]. Because of their damping properties and low weight, these nanocomposites can be used to create materials to reduce vibration. Further, the use of hBN provides electrical insulation and thermal stability, and the use of graphene provides mechanical strength. As such, these nanocomposites can be used in the creation of flexible electronic devices. Improved mechanical properties of these nanocomposites can be used to create more secure battery and other electronic device casings [25]. Widely recognized for its effectiveness in simulating mechanical properties under various loading conditions [26]. Allows for multiscale modeling, accommodating different material length scales, which is crucial for nanocomposites [27].

By using modal analysis, researcher can better understand and optimize the dynamic properties of PP+G+hBN nanocomposites, enabling the design of more reliable, durable, and lightweight materials for high-performance

applications. No work reported on modal analysis of C-channel for PP+G+hBN composites. In this study, the C-channel models of hybrid nanocomposites with combinations of neat PP (2.5 mm thick), PP+G+hBN (0.833 mm each), 0.5mm G+ 1.5mm PP+ 0.5mm hBN and 0.25mm G+ 2mm PP+ 0.25mm hBN are examined to check the effect on deformation (Table 1).

MATERIALS AND METHODS

Steps for Modal Analysis of PP+G+hBN Nanocomposites:

1. Prepare a CAD model by describing the G and hBN distribution within the PP matrix. Then, create a finite element model of the composite structure, incorporating G and hBN properties with PP in which FEM discretizes the C-channel into smaller elements.
2. Meshing details: Free meshing, Number of sets=100, Nodes= 28996, Elements= 4012.
3. Apply an input force or excitation (100 N, 200 N, 500 N and 1000 N in downward direction) to the composites to induce vibrations with proper boundary conditions in the finite element model as shown in Figure 1.
4. Collect data on natural frequencies, mode shapes, and deformation through ANSYS simulation outputs. Interpret the modal properties and use them to evaluate the system's behaviour under real-life loading conditions to ensure structural integrity or functionality of PP+G+hBN.
5. Following Material properties are added in ANSYS database.

Table 1. Properties of G, hBN, PP [6, 9, 11]

Properties	Graphene (G)	Hexagonal Boron Nitride (hBN)	Polypropylene (PP)
Density (kg/m ³)	2267	2280	910
Elastic Modulus (Pa)	1E+12	1E+12	1.1E+09
Poisson's Ratio (ν)	0.19	0.211	0.42

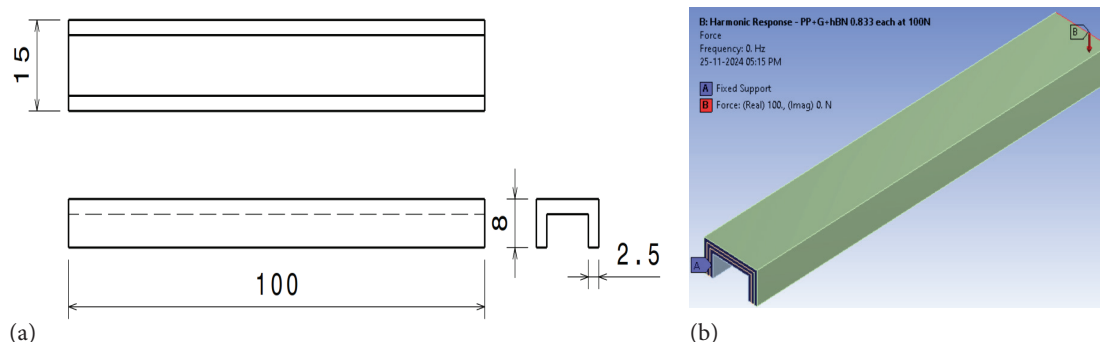


Figure 1. (a) Dimensions of C-channel (b) Boundary conditions.

Table 2. shows all four cases of C-channel nanocomposites, detailing the thicknesses of both the nanomaterials (G and hBN) and Polypropylene (PP) as well as ANSYS model.

The cases are chosen after reviewing studies on PP, G, and hBN. The solid modeling of all above C-channel nanocomposites are performed with the help of modeling software CATIA. CATIA files are exported into the ANSYS to perform modal analysis.

RESULTS AND DISCUSSION

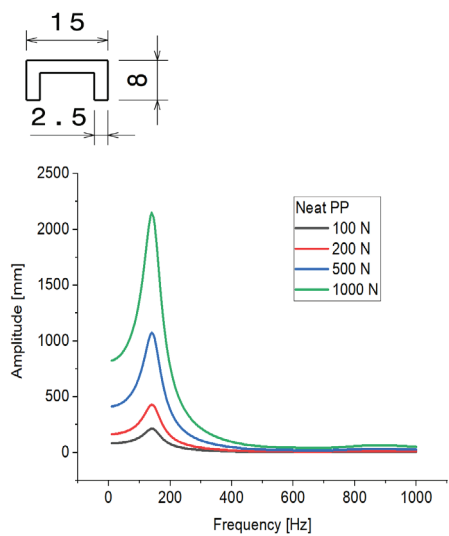
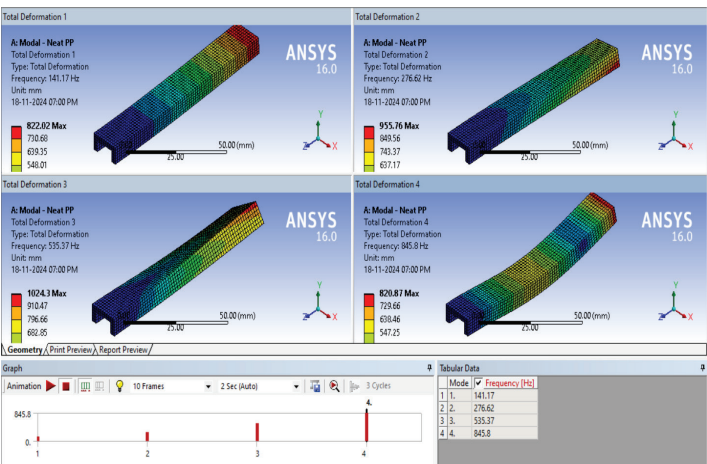
Mode Shapes of Neat PP (2.5 mm thick)

Figure 2 depicts the results of a modal analysis performed on a structural component made of neat Polypropylene (PP) using ANSYS software. The analysis

identifies first four natural frequencies and their corresponding mode shapes, which represent the inherent vibrational characteristics of the material under free vibration. The tabular data indicates the natural frequencies as 141.17 Hz (Mode 1), 276.62 Hz (Mode 2), 535.37 Hz (Mode 3), and 845.8 Hz (Mode 4). These frequencies represent the structure's stiffness and mass distribution, which are crucial characteristics for assessing dynamic performance. The visualised mode forms show various deformation patterns for each frequency. Mode 1 is characterised by fundamental bending deformation, indicating first bending mode of structure. Mode 2 indicates a greater order bending mode characterized by the presence of more nodal points. More complex deformation is possible with Mode 3 introducing the bending and torsional components. A ballpark guess would explain that mode 4, which is associated with

Table 2. Cases of nanocomposites

Dimensions (front view of C-channel)				
ANSYS model of C-channel				
Composite	Case 1 Neat PP (2.5 mm thick)	Case 2 PP+G+hBN (0.833 mm each)	Case 3 0.5mm G + 1.5mm PP+ 0.5mm hBN	Case 4 0.25mm G + 2 mm PP+ 0.25mm hBN



(a) Total deformation (b) Frequency-amplitude curve at different loads for neat PP.

the highest frequency, has sophisticated deformation indicating the presence of higher order vibrational movement. In order to visualize the deformation, the scales have been normalized so that the emphasis is on the mode shapes rather than absolute values of the displacement. These findings help to conceptualise how neat PP would react under dynamic loading, thus allowing it to be considered for use in areas where vibration performance requirements are stringent. Additionally, this work presents a reference for further research on the impact of reinforcements on the modal properties of polypropylene nanocomposites such as graphene and hexagonal boron nitride.

Mode Shapes of PP+G+hBN (0.83 mm each)

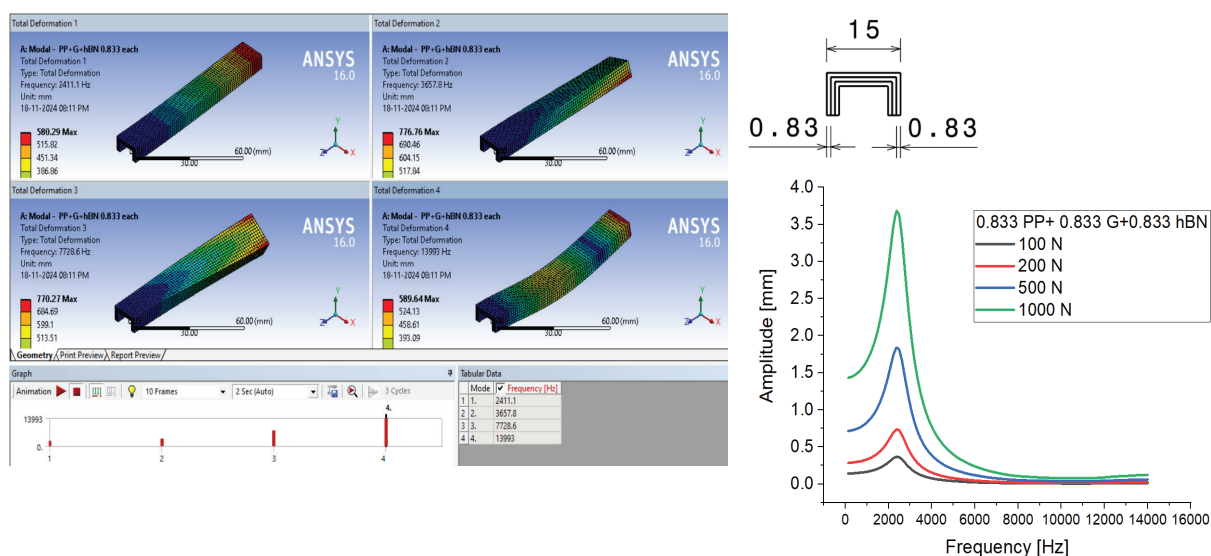
Figure 3 shows the results of a modal analysis of a PP nanocomposite containing equal weights of G and hBN (0.833 mm). The analysis reports the presence of 4 natural frequencies and their corresponding mode shapes. The inclusion of the nanofillers alter the vibration behavior of the composite. The calculated natural frequencies are 2411.1 Hz (Mode 1), 3657.8 Hz (Mode 2), 7782.6 Hz (Mode 3) and 13993 Hz (Mode 4). It is to be noted that presence of uniformly dispersed G and hBN in the PP matrix increase its stiffness and alter its ability to vibrate. As such, the neat PP has relatively low natural frequencies. Mode 1 corresponds to the fundamental bending of the sheet in the out of plane direction and Mode 2 corresponds to a higher order bending of the same sheet in which the bending occurs in the opposite direction compared to Mode 1. Mode 3 is a combination of bending in the out of plane direction and torsion and demonstrates the presence of higher order vibration modes. Mode 4 has a complex mode shape with multiple deformation locations and demonstrates a very high order bending. It should be noted that the high frequency modes and corresponding shapes demonstrate the changes in the

stiffness of the matrix due to the presence of the nanofillers. These outcomes underline the strong influence that G and hBN additions have on the modal characteristics of PP nanocomposites, making them more fit for applications in mechanical engineering structures that are sensitive to vibration. The recorded enhancements in natural frequencies confirm the synergistic effects of the reinforcements in modifying the dynamic properties of the material. The integration of G and hBN transform the fundamental frequency of the PP nanocomposite. Natural frequencies tend to be increased which results in having better performance under dynamic conditions especially in terms of stiffer materials.

Mode Shapes of PP+G+hBN (1.5 mm PP + 0.5 mm G and hBN)

Figure 4 displays the results of a modal analysis for total deformation and frequency vs amplitude curve. This modal analysis illustrates the natural frequencies and mode shapes of a 0.5mm G+1.5mm PP+0.5mm hBN, which is critical for understanding its dynamic behaviour under vibrational loading. The results indicate four different deformation modes (Mode 1 to Mode 4). Each deformation mode is characterized by a corresponding natural frequency and a maximum total deformation value. In mode 1, the frequency is 2127.3 Hz, and the maximum deformation is 647.71 mm. The majority of the deformation occurs at the structure's free end, showing a typical bending mode.

In mode 2, the frequency rises to 3117.1 Hz, with the maximum deformation of 867.81 mm. The deformation pattern indicates a second bending mode or torsional behaviour. 857.48 mm was the highest deformation obtained in mode 3. However, Mode 3 has a rather higher frequency which is 6769.8 Hz as such this mode will entail a more rigid form of bending or torsional modes which will



(a) Total deformation (b) Frequency-amplitude curve at different loads for 0.833 PP+0.833 G+0.833 hBN.

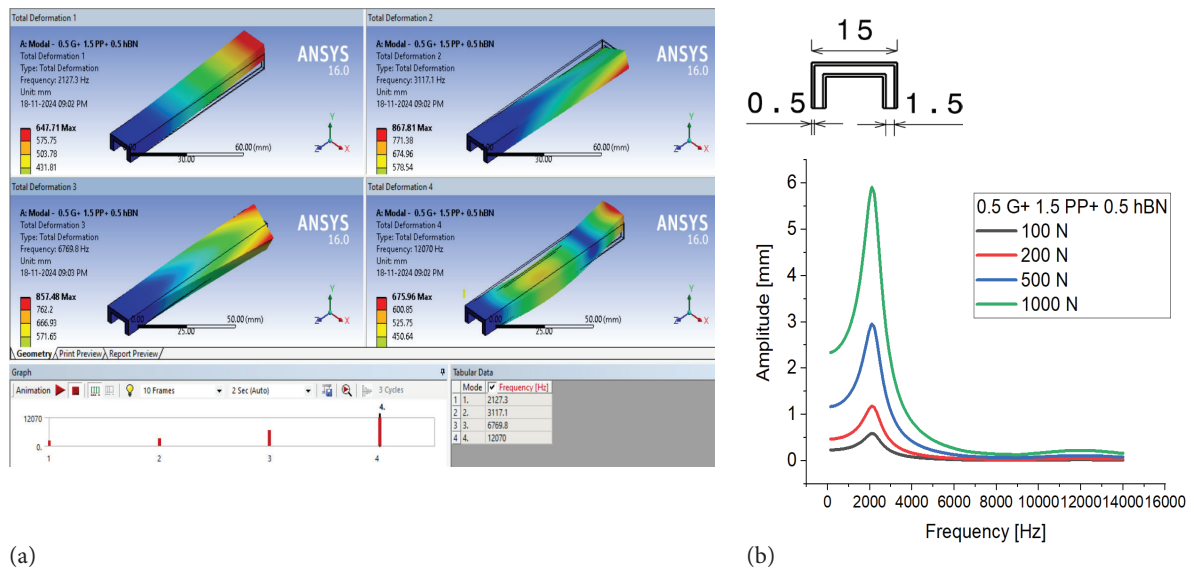


Figure 4. (a) Total deformation (b) Frequency-amplitude at different loads for 0.5 G+1.5 PP+0.5 hBN.

twist but the deformation will be located at certain parts of the structure only. In mode 4, it can be observed that the maximum deformation is 675.96 mm at a frequency of 12070 Hz. This represents a mode of a better degree that has its deformation in more than one region of the structure. The following graph which is beneath the deformation plots gives the frequency of four modes and their development over time. These frequencies are influenced by the material characteristics, the shape as well as the constraints of the model. The research offers valuable information for planning resonance hazards and evaluating the reliability of the construction in the process. In this manner, knowing how a composite behaves at various frequencies helps to

identify weak spots and to improve the material's placement within the composite.

Mode Shapes of PP+G+hBN (2 mm PP+0.25 mm G and hBN)

The results in Figure 5 highlight the gradual increase in frequency and varied deformation patterns, which are critical for monitoring resonance concerns and optimising the structural dynamics of 0.25 mm G + 2mm PP + 0.25mm hBN. The analysis focuses on total deformation for C-channel under different vibration modes and associated frequencies. At mode 1, the natural frequency is 1703.5 Hz, and the maximum deformation is 717.74 mm, indicating that the basic bending mode is localised at the free

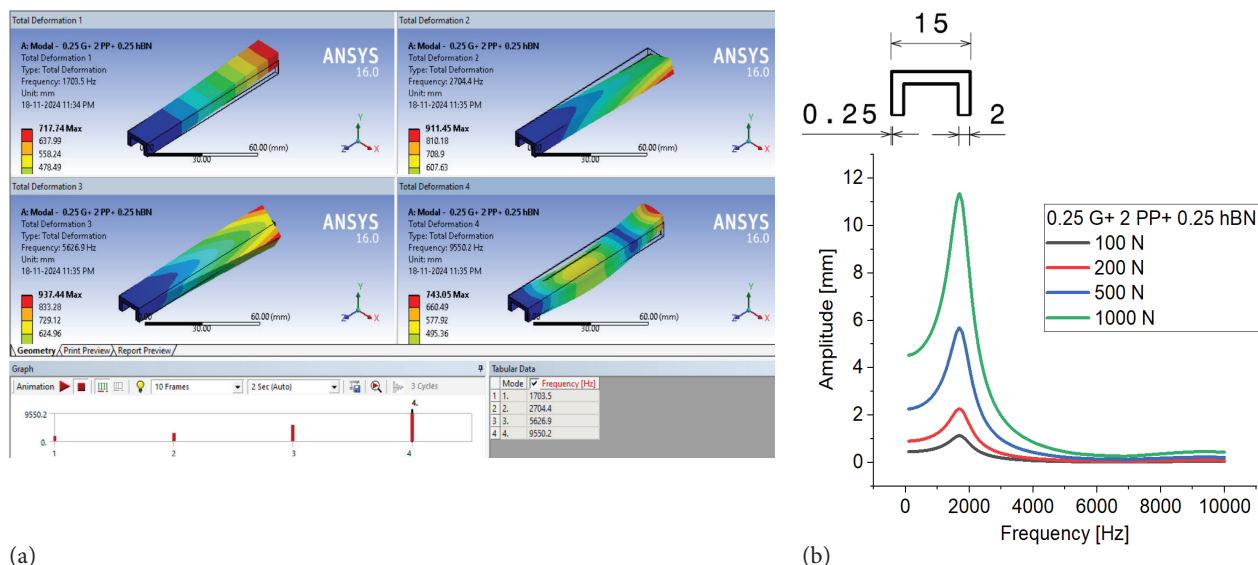


Figure 5. (a) Total deformation (b) Frequency-amplitude at different loads for 0.25 G+ 2 PP+ 0.25 hBN.

end. The frequency rises to 2704.4 Hz, and the maximum deformation is 911.45 mm, indicating bending or torsional behaviour in mode 2. Whereas in mode 3 at 5626.9 Hz, the deformation reaches 937.44 mm, showing more complex structural vibrations. In mode 4, the greatest frequency observed which is 9550.2 Hz, and deformation decreases to 743.05 mm, indicating a scattered mode. The addition of G and hBN influences the damping characteristics. Improved damping can reduce resonance-related issues, enhancing the durability of the PP under the loading. The bonding quality between G and hBN nanofillers and the PP matrix influences the transfer of load, directly impacting stiffness, damping, and overall performance under vibration. A frequency spectrum graph is shown at the bottom which highlights the modal frequencies as distinct peaks, indicating where resonance occurs. Each mode corresponds to one of the peaks.

Comparative Analysis

Figure 6 shows frequency response of polypropylene (PP) nanocomposites with different amounts of graphene (G) and hexagonal boron nitride (hBN). Amplitude (in mm) is shown on the vertical axis against frequency (in Hz). The three reinforcement combinations are: 0.833 mm G + 0.833 mm PP + 0.833 mm hBN, 0.5 mm G + 1.5 mm PP + 0.5 mm hBN, and 0.25 mm G + 2 mm PP + 0.25 mm hBN. The figure shows that each of the constituents exhibit a peak in amplitude, and therefore, resonance. Of the three compositions, the one with 0.833 mm G and 0.833 mm hBN exhibited the lowest amplitude, and therefore, best damping behavior. Thus, this composition of the nanocomposites is expected to have the least tendency to vibrate, among the three compositions. The G + hBN combination of 0.25 mm G + 0.25 mm hBN, which exhibited the highest peak amplitude of all the blends, is followed by 0.5 mm G + 0.5 mm hBN combination that has slightly higher amplitude than the last combination. When the weight fraction of G and hBN increases, it can be seen that the resonant frequency increases, highlighting the stiffening effect of these

reinforcements. Increased concentrations of graphene and hBN add to the stiffness of the material, which results in a higher natural frequency and lower vibrational amplitudes. Such behaviour shows the proper action of G and hBN reinforcements on the dynamics of PP nanocomposites. The results emphasize the importance of balancing the mechanical stiffness and a certain level of damping by optimising the filler percentages in some engineering applications. Mechanical and vibrational properties are related to layer thickness of G and hBN nanofillers in PP.

The graphical representation of Figure 7 shows the phase angle response as a function of frequency for the different concentrations of graphene and hexagonal boron nitride in polypropylene (PP) nanocomposites. These combinations of materials have been analyzed in three material combinations which are outlined as follows; 0.833 mm G + 0.833 mm PP + 0.833 mm hBN, 0.5 mm G + 1.5 mm PP + 0.5 mm hBN and 0.25 mm G + 2 mm PP + 0.25 mm hBN. The phase angle of this system, given in degrees, represents the position of the input and output signals in time relative to each other. The phase angle behaviour shows sizable transitions about certain frequencies that correspond to the resonant and anti-resonant regions of the materials. At the onset, the phase angle stays high and falls as frequency increases which indicates a change from structural to inertial movement. The phase angle drops steeply in the neighbourhood of the resonant frequency and resumes when the frequency exceeds the resonance.

The nanocomposite with 0.833 mm G and 0.833 mm hBN displays a smoother phase transition. This indicates that the nanocomposite exhibits better energy damping. The nanocomposite exhibits frequency independence if the phase transition is smooth. The nanocomposite with 0.25 mm G and 0.25 mm hBN displays an abrupt phase transition. This indicates that the nanocomposite exhibits a lack of control over the vibrational response. The nanocomposite with 0.5 mm G and 0.5 mm hBN displays a phase transition that is smoothed out intermediate between the nanocomposites with 0.833 mm and 0.25 mm layers. This

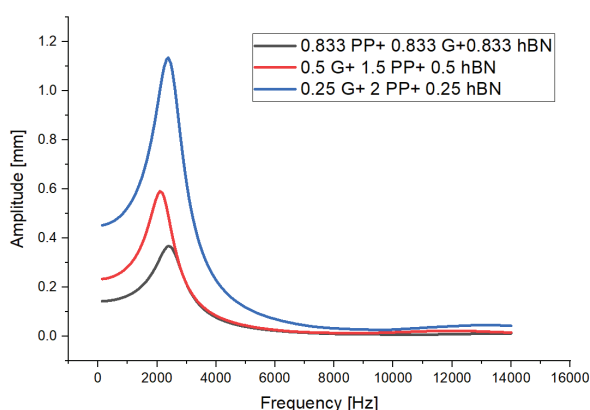


Figure 6. Frequency verses amplitude.

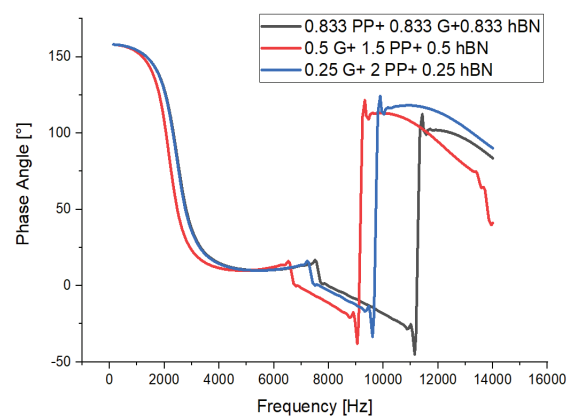


Figure 7. Frequency verses phase angle.

Table 3. Total deformation for all composites at 100 N

C-Channel Composites	Total deformation (Max.) in mm			
	Mode Shape 1	Mode Shape 2	Mode Shape 3	Mode Shape 4
Case 1 Neat PP (2.5 mm thick)	822.02	955.76	1024.3	820.87
Case 2 PP+G+hBN (0.833 mm each)	580.29	776.76	770.27	589.64
Case 3 0.5mm G + 1.5mm PP+ 0.5mm hBN	647.71	867.81	857.48	675.96
Case 4 0.25mm G + 2 mm PP+ 0.25mm hBN	717.74	911.45	937.44	743.05

demonstrates that stiffness and phase stability are interrelated. Vibration sensitive components may benefit from the use of PP nanocomposites.

The Table 3 provides data on the total deformation for different configurations of C-channel composites under a load of 100 N, measured for four distinct mode shapes. The properties of pure PP are studied in contrast with G and hBN based hybrid composites. Case 1 presents 2.5 mm of PP, and it displays the highest amount of deformation of all the cases studied (820.87 mm to 1024.3 mm). As previous cases studied composites, PP displays lower stiffness and strength compared to G and hBN. Case 2 studied 3 (0.833 mm) layers of each of PP, G, and hBN. It displays, as expected, a much stiffer system. The deformation of this case was measured to be 580.29 mm. As seen previously, the hybrid system improves the stiffness and strength of the composite. Case 3, 1.5 mm of PP sandwiched between 0.5 mm G and hBN layers, improved the stiffness of the system, as expected. Case 4 2 mm of PP, 0.25 mm of G and hBN, displays higher deformation than Case 3, and much lower deformation than case 1. As expected, the system becomes stiffer with more reinforcing elements. As previously discussed, the improvement in deformation of the composite is due to the rigid nature of G and hBN. It shows that the addition of G and hBN improves the overall performance of the composites.

CONCLUSION

This modal analysis of graphene (G) and hexagonal boron nitride (hBN) polypropylene (PP) nanocomposites involves understanding how these materials behave under dynamic loads. Adding G and hBN to PP improve its stiffness, strength, and toughness, which affect the modal properties like natural frequencies and mode shapes, also it improves the damping properties of PP, leading to better energy dissipation during vibrations. The total deformation is as follows:

1. Mode shapes 1 to 4 of PP+G+hBN (0.833 mm each): The total deformation is approximately 29.40, 18.72, 24.80 and 28.16 times less than neat PP respectively.
2. Mode shapes 1 to 4 of 0.5mm G + 1.5mm PP+ 0.5mm hBN: The total deformation is approximately 21.20, 9.20, 16.28 and 17.56 times less than neat PP respectively.
3. Mode shapes 1 to 4 of 0.25mm G + 2 mm PP+ 0.25mm hBN: The total deformation is approximately 12.68, 4.63, 8.47 and 9.48 times less than neat PP respectively.

This analysis seems to examine how the structure behaves under vibrational loading, focusing on its natural frequencies and modal shapes. These insights are essential for ensuring the structure can avoid resonance under operational conditions. PP is softer materials often exhibit greater internal damping, which can reduce the amplitude of vibrations and alter the resonance behaviour, though it doesn't directly change the natural frequency. However, PP+G+hBN nanocomposites, being less damped, can sustain vibrations longer and exhibit sharper resonance at their natural frequency. Due to these combinations of nanocomposites, less deformation is found in C-channel of PP+G+hBN in comparison with neat PP.

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared that they have no conflicts of interest.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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APPENDIX

Table 4. Simulation results

Neat PP			0.833 PP+ 0.833 G+0.833 hBN			0.5 G+ 1.5 PP+ 0.5 hBN			0.25 G+ 2 PP+ 0.25 hBN		
Frequency [Hz]	Amplitude [mm]	Phase Angle [°]	Frequency [Hz]	Amplitude [mm]	Phase Angle [°]	Frequency [Hz]	Amplitude [mm]	Phase Angle [°]	Frequency [Hz]	Amplitude [mm]	Phase Angle [°]
10	82.49	158.1	140	0.14339	158.14	140	0.23403	158.12	100	0.45292	158.14
20	83.541	157.81	280	0.14459	157.94	280	0.23651	157.87	200	0.45668	157.94
30	85.351	157.3	420	0.14664	157.61	420	0.24076	157.45	300	0.4631	157.62
40	88.012	156.55	560	0.1496	157.13	560	0.24696	156.84	400	0.47238	157.14
50	91.669	155.5	700	0.15357	156.49	700	0.2554	155.99	500	0.48486	156.49
60	96.534	154.1	840	0.1587	155.64	840	0.26648	154.85	600	0.50101	155.65
70	102.92	152.22	980	0.1652	154.56	980	0.28081	153.37	700	0.52146	154.56
80	111.25	149.71	1120	0.17333	153.19	1120	0.29917	151.42	800	0.5471	153.18
90	122.17	146.3	1260	0.18345	151.45	1260	0.32271	148.84	900	0.57909	151.41
100	136.48	141.58	1400	0.19606	149.23	1400	0.35295	145.39	1000	0.619	149.15
110	155.06	134.9	1540	0.21178	146.37	1540	0.39175	140.68	1100	0.66888	146.21
120	177.98	125.24	1680	0.23141	142.63	1680	0.44082	134.12	1200	0.7312	142.34
130	201.73	111.4	1820	0.25577	137.66	1820	0.4995	124.86	1300	0.80852	137.17
140	214.75	93.055	1960	0.28534	130.97	1960	0.55848	111.9	1400	0.90176	130.15
150	203.68	72.919	2100	0.3189	121.89	2100	0.5912	95.051	1500	1.0054	120.59
160	173.58	55.483	2240	0.35076	109.79	2240	0.56689	76.403	1600	1.0978	107.87
170	140.84	42.588	2380	0.36812	94.687	2380	0.49316	59.393	1700	1.1351	92.251
180	113.64	33.654	2520	0.35748	78.151	2520	0.40811	45.819	1800	1.0803	75.647
190	92.807	27.444	2660	0.32071	62.637	2660	0.33372	36.5	1900	0.95277	59.746
200	77.048	23.012	2800	0.27379	49.869	2800	0.27497	29.83	2000	0.80714	47.616
210	64.991	19.763	2940	0.22959	40.456	2940	0.22971	24.984	2100	0.67462	38.731
220	55.597	17.325	3080	0.19261	33.423	3080	0.19465	21.445	2200	0.56561	32.156
230	48.137	15.462	3220	0.163	28.242	3220	0.16712	18.77	2300	0.47901	27.176
240	42.109	14.02	3360	0.13948	24.276	3360	0.14514	16.705	2400	0.41045	23.413
250	37.159	12.896	3500	0.12067	21.253	3500	0.1273	15.09	2500	0.35561	20.562
260	33.038	12.019	3640	0.10545	18.887	3640	0.11262	13.816	2600	0.31122	18.327
270	29.564	11.337	3780	9.30E-02	17.135	3780	0.10036	12.806	2700	0.2748	16.549
280	26.603	10.817	3920	8.27E-02	15.629	3920	9.00E-02	12.004	2800	0.24453	15.121
290	24.056	10.431	4060	7.40E-02	14.407	4060	8.12E-02	11.373	2900	0.21909	13.965
300	21.845	10.16	4200	6.67E-02	13.411	4200	7.36E-02	10.883	3000	0.19747	13.025
310	19.912	9.9899	4340	6.04E-02	12.598	4340	6.70E-02	10.514	3100	0.17892	12.26
320	18.21	9.9109	4480	5.49E-02	11.937	4480	6.12E-02	10.248	3200	0.16287	11.641
330	16.703	9.9153	4620	5.02E-02	11.403	4620	5.61E-02	10.074	3300	0.14886	11.143
340	15.36	9.9982	4760	4.60E-02	10.977	4760	5.15E-02	9.984	3400	0.13656	10.751
350	14.158	10.156	4900	4.23E-02	10.646	4900	4.75E-02	9.9708	3500	0.12568	10.449
360	13.076	10.388	5040	3.90E-02	10.397	5040	4.39E-02	10.03	3600	0.116	10.228
370	12.1	10.693	5180	3.61E-02	10.223	5180	4.06E-02	10.16	3700	0.10735	10.08
380	11.214	11.073	5320	3.35E-02	10.116	5320	3.77E-02	10.357	3800	9.96E-02	9.9979
390	10.409	11.53	5460	3.11E-02	10.071	5460	3.50E-02	10.623	3900	9.26E-02	9.9785
400	9.6742	12.068	5600	2.90E-02	10.085	5600	3.26E-02	10.958	4000	8.62E-02	10.018
410	9.0017	12.69	5740	2.70E-02	10.155	5740	3.04E-02	11.363	4100	8.04E-02	10.114
420	8.385	13.403	5880	2.53E-02	10.279	5880	2.84E-02	11.842	4200	7.52E-02	10.265
430	7.8181	14.213	6020	2.36E-02	10.457	6020	2.65E-02	12.399	4300	7.03E-02	10.471
440	7.2963	15.129	6160	2.21E-02	10.562	6160	2.48E-02	13.038	4400	6.59E-02	10.733
450	6.8452	7.7364	6300	2.08E-02	10.832	6300	2.32E-02	13.765	4500	6.18E-02	11.05

Table 4. Simulation results

Neat PP			0.833 PP+ 0.833 G+0.833 hBN			0.5 G+ 1.5 PP+ 0.5 hBN			0.25 G+ 2 PP+ 0.25 hBN		
Frequency [Hz]	Amplitude [mm]	Phase Angle [°]	Frequency [Hz]	Amplitude [mm]	Phase Angle [°]	Frequency [Hz]	Amplitude [mm]	Phase Angle [°]	Frequency [Hz]	Amplitude [mm]	Phase Angle [°]
460	6.4831	4.985	6440	1.95E-02	11.155	6440	2.17E-02	14.072	4600	5.81E-02	11.425
470	6.1697	3.0531	6580	1.83E-02	11.531	6580	2.04E-02	14.945	4700	5.46E-02	11.86
480	5.8956	0.99805	6720	1.73E-02	11.964	6720	1.95E-02	14.051	4800	5.14E-02	12.358
490	5.6542	-0.66918	6860	1.62E-02	12.668	6860	1.87E-02	0.25127	4900	4.84E-02	12.921
500	5.4408	-2.424	7000	1.53E-02	13.245	7000	1.79E-02	-1.4621	5000	4.56E-02	13.555
510	5.2522	-3.7712	7140	1.45E-02	13.394	7140	1.73E-02	-2.7616	5100	4.30E-02	14.264
520	5.085	-5.1912	7280	1.36E-02	14.065	7280	1.67E-02	-4.1288	5200	4.06E-02	15.054
530	4.9369	-6.6806	7420	1.29E-02	14.808	7420	1.62E-02	-5.5621	5300	3.88E-02	1.8887
540	4.8059	-8.2363	7560	1.22E-02	15.627	7560	1.57E-02	-7.0598	5400	3.73E-02	0.77739
550	4.6901	-9.8549	7700	1.17E-02	2.6376	7700	1.53E-02	-8.1308	5500	3.59E-02	-0.39578
560	4.5883	-11.052	7840	1.13E-02	1.5787	7840	1.50E-02	-9.7564	5600	3.47E-02	-1.6298
570	4.4992	-12.796	7980	1.08E-02	-2.76E-02	7980	1.47E-02	-10.951	5700	3.36E-02	-2.9232
580	4.4217	-14.12	8120	1.05E-02	-1.2089	8120	1.44E-02	-12.703	5800	3.26E-02	-4.274
590	4.3545	-15.508	8260	1.02E-02	-2.4456	8260	1.41E-02	-14.024	5900	3.17E-02	-5.6801
600	4.2976	-17.442	8400	9.85E-03	-3.7352	8400	1.39E-02	-15.902	6000	3.09E-02	-6.6445
610	4.2497	-18.963	8540	9.58E-03	-4.5874	8540	1.38E-02	-17.356	6100	3.02E-02	-8.1595
620	4.2101	-20.555	8680	9.33E-03	-5.9792	8680	1.36E-02	-18.876	6200	2.95E-02	-9.7243
630	4.1785	-22.219	8820	9.11E-03	-7.4174	8820	1.35E-02	-20.467	6300	2.90E-02	-10.848
640	4.1542	-23.959	8960	8.91E-03	-8.4166	8960	1.34E-02	-22.131	6400	2.84E-02	-12.022
650	4.1368	-25.778	9100	8.73E-03	-9.4582	9100	1.33E-02	-23.871	6500	2.80E-02	-13.745
660	4.1258	-27.681	9240	8.57E-03	-11.039	9240	1.37E-02	110.36	6600	2.76E-02	-15.026
670	4.1207	-29.672	9380	8.42E-03	-12.176	9380	1.42E-02	111.39	6700	2.73E-02	-16.36
680	4.1209	-31.755	9520	8.30E-03	-13.358	9520	1.48E-02	112.17	6800	2.70E-02	-17.749
690	4.1265	-33.48	9660	8.18E-03	-14.587	9660	1.53E-02	112.71	6900	2.67E-02	-19.195
700	4.1365	-35.769	9800	8.08E-03	-16.351	9800	1.59E-02	113.03	7000	2.70E-02	113.13
710	4.1502	-38.166	9940	7.99E-03	-17.676	9940	1.65E-02	113.14	7100	2.79E-02	114.42
720	4.195	88.202	10080	7.92E-03	-19.052	10080	1.70E-02	113.05	7200	2.88E-02	115.51
730	4.3773	88.526	10220	7.86E-03	-20.477	10220	1.76E-02	112.75	7300	2.97E-02	116.39
740	4.5653	88.537	10360	7.80E-03	-21.956	10360	1.82E-02	112.27	7400	3.07E-02	117.09
750	4.7572	88.249	10500	7.76E-03	-23.01	10500	1.87E-02	111.6	7500	3.17E-02	117.61
760	4.9508	87.674	10640	7.73E-03	-24.602	10640	1.93E-02	110.75	7600	3.27E-02	117.97
770	5.1438	86.825	10780	7.71E-03	-26.253	10780	1.98E-02	109.72	7700	3.37E-02	118.17
780	5.3335	85.715	10920	7.69E-03	-27.965	10920	2.03E-02	108.52	7800	3.47E-02	118.22
790	5.5171	84.36	11060	7.69E-03	-29.739	11060	2.08E-02	107.15	7900	3.57E-02	118.12
800	5.6915	82.776	11200	7.69E-03	-31.11	11200	2.12E-02	105.63	8000	3.67E-02	117.88
810	5.8535	80.98	11340	7.75E-03	100.92	11340	2.16E-02	103.95	8100	3.76E-02	117.5
820	5.9998	78.993	11480	8.02E-03	101.51	11480	2.19E-02	102.13	8200	3.86E-02	116.99
830	6.1273	76.839	11620	8.30E-03	101.89	11620	2.22E-02	100.18	8300	3.96E-02	116.34
840	6.2333	74.544	11760	8.58E-03	102.09	11760	2.24E-02	98.122	8400	4.05E-02	115.56
850	6.3156	71.958	11900	8.87E-03	102.09	11900	2.25E-02	95.975	8500	4.14E-02	114.65
860	6.3727	69.464	12040	9.16E-03	101.91	12040	2.25E-02	93.76	8600	4.22E-02	113.62
870	6.4032	66.915	12180	9.46E-03	101.55	12180	2.25E-02	91.502	8700	4.30E-02	112.46
880	6.4071	64.34	12320	9.75E-03	101.02	12320	2.23E-02	89.226	8800	4.38E-02	111.18
890	6.3849	61.759	12460	1.00E-02	100.32	12460	2.21E-02	86.96	8900	4.44E-02	109.79
900	6.3382	59.214	12600	1.03E-02	99.463	12600	2.17E-02	84.73	9000	4.50E-02	108.29
910	6.2692	56.72	12740	1.06E-02	98.45	12740	2.13E-02	82.562	9100	4.54E-02	106.69
920	6.1852	52.539	12880	1.09E-02	97.286	12880	2.09E-02	80.478	9200	4.58E-02	105
930	6.0874	50.197	13020	1.11E-02	95.979	13020	2.03E-02	78.483	9300	4.60E-02	103.24
940	5.9752	47.951	13160	1.14E-02	94.535	13160	1.97E-02	76.628	9400	4.61E-02	101.42
950	5.8514	45.809	13300	1.16E-02	92.963	13300	1.91E-02	74.91	9500	4.60E-02	99.553
960	5.7185	43.776	13440	1.18E-02	91.273	13440	1.85E-02	73.342	9600	4.58E-02	97.658
970	5.5809	41.328	13580	1.19E-02	89.476	13580	1.78E-02	64.241	9700	4.54E-02	95.756
980	5.4393	39.517	13720	1.21E-02	87.584	13720	1.72E-02	62.71	9800	4.49E-02	93.867
990	5.2952	37.817	13860	1.22E-02	85.613	13860	1.68E-02	42.885	9900	4.43E-02	92.009
1000	5.15	36.225	14000	1.22E-02	83.577	14000	1.64E-02	41.18	10000	4.35E-02	90.204