The Active Strain Energy Tuning On The Parametric Resonance Of Composite Plates Using Finite Element Method

*Zarina Yusof, Zainudin A.Rasid**
Malaysia-Japan International Institute of Technology,
Universiti Teknologi Malaysia, Kuala Lumpur, 54100
Malaysia

Jamaluddin Mahmud
Faculty of Mechanical Engineering
Universiti Teknologi MARA
40450 Shah Alam, Selangor

*, *arzainudin.kl@utm.my, jm@salam.uitm.edu.myz*
zarinayusof91@gmail.com

ABSTRACT

Studies on the effect of shape memory alloy (SMA) on structural behaviours of laminated composite that include mechanical and thermal buckling, vibration and deflection are numerous. However studies on such effect of SMA on parametric instability of composite plates are hardly to be found in literatures. The parametric instability is an important design consideration for structures that are loaded periodically as to avoid the possible occurrence of fatigue failure to the structures due to the parametric resonance. This paper is to report on a study conducted to investigate the improvement made by the SMA on the parametric instability behaviour of laminated composite plates subjected to periodic compressive load. SMA, well-known for having the shape memory effect property that is capable of inducing recovery stress in the SMA, in wire form is embedded within laminated composite plates. Brinson's model is used to predict the amount of recovery stress induced and the new property of the SMA after the phase transformation occurs in the SMA. Based on the third order shear deformation theories (TSDT), the governing equation for the parametric instability of the SMA composite plate is developed using finite element method (FEM). The Mathieu-Hill type of parametric instability

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equation is derived and solved using the Bolotin's method. The results due to the TSDT have been found to correlate well with the results due to the first order shear deformation theory (FSDT). Furthermore it is found that the SMA causes a significant improvement of delaying the parametric instability from occurring by shifting to the instability chart to the right. The effect of SMA on the dynamic instability of laminated composite plate depends greatly on the activation temperature and the initial stress of the SMA that determine the amount of recovery stress induced by the SMA.

Keywords: *Parametric resonance; shape memory alloy; Mathieu-Hill equation; Bolotin's method.*

Introduction

Fibre reinforced composite structures have attracted many applications that require structures with tailorable properties and weight saving capability. Specifically, laminated composite has been widely used in industries such as aerospace, marine and automotive where the composite can be subjected to static and periodic loadings. The latter loading may cause the occurrence of excessive vibration in the structures. This so called parametric resonance or parametric instability is a result of a type of dynamic instability of structure that is having time-varying (periodically) parameters which may be due to among others the asymmetric of the structure and the compressive periodic input load. The critical part about this parametric resonance as compared to the typical force resonance is that it may occur at sub or multiple of the frequency of the periodic loading. At the same time this means that parametric resonance may occur at loading that is even lower than the critical buckling load. The eventual consequence of the prolonged excessive vibration due to this parametric resonance is that the structures can fail due to fatigue failure [1]. Without any doubt the problem of parametric instability should be an important consideration in the design of structural components that are subjected to periodic loading.

The improvement of structural behaviours of composite structures has been made possible in recent years through combining composite structures with new advanced materials such as carbon nanotube [2], functionally graded material [3] and smart materials such as piezoelectric and shape memory alloy (SMA) [4]. SMA has been researched intensively because of its ability to induce stress and/or strain that can improve structural behaviours. The SMA's properties of shape memory effect (SME) and quasi-plasticity are exploited in this research. The SME is a property of SMA that allows the generation of stress and/or strain in SMA structures as temperature is increased above a certain value. The generated tensional stress improves strain energy and thus improves structural behaviours of the structure. As such this improvement method is termed as the active strain energy tuning (ASET). At the same time, the transformation of SMA from martensite to austenite will improve mechanical properties of the SMA and this type of improvement is called the active property tuning (APT). In this study, due to its simplicity, the Brinson's model [5] is used to predict the property change of the SMA and the amount of recovery stress provided by the SMA as a function of temperature.

Studies on parametric resonance of composite structures have been conducted for decades. Studies on the effect of SMA on structural behaviours including buckling and vibration are numerous. However specifically, the literature is lacking on researches made on improving parametric instability behaviour of SMA based laminated composites. Fazilati and Ovesy [6] used two versions of finite strip method and semi-analytical method to investigate the parametric instability of flat and curved thin-walled composite laminated structures subjected to harmonic in-plane loading. The classical plate theory and the Koiter-Sanders theory of shallow shells were applied. After conducting several analyses with the developed model, it can be said that the finite strip method is a reliable tool for calculating the parametric instabilities properties of the structures. Recently, Ramachandra and Panda [7] conducted a study on the dynamic instability of composite plates subjected to non-uniform in-plane loads. The static and dynamic components of the applied periodic in-plane loading were assumed to vary according to either parabolic or linear distributions within plates. The Ritz method was used to generate the stress distribution within the prebuckling stage. The Mathieu type of equation was developed using the Hamilton's variational principle and the Galerkin's method. Later the Bolotin's method [1] was used to solve the Mathieu's equation applying the first order and second order approximation. One important finding here was that the first order approximation predicts accurately the instability region while the shear deformation narrowed down the width of the instability region.

A. Rasid and co-workers [8-9] conducted numerous studies on the effect of SMA on buckling behaviour of laminated composite plates subjected to mechanical, thermal and combined loading. Ebrahimi et al. [10] developed a nonlinear equation of motion for the simply supported SMA hybrid composite moving beams based on the Euler-Bernoulli beam theory while including the von Karman type of nonlinearity. The Brinson's model was used to predict the recovery stress of the SMA. An analytical approach was used to solve the nonlinear equation where parametric studies were later conducted. Tsai and Chen [11] improved the dynamic instability behaviour of laminated composite beams by embedding within the beam the SMA wires. The Nitinol SMA transformational behaviour was modelled using the Liang and Roger's model. It was found that the activation of the SMA wires will shift the unstable region to the right of the instability chart.

In this paper, the effect of the SMA on the parametric instability of laminated composite plates is reported. The governing equation is developed based on both the first order shear deformation theory (FSDT) and the third order shear deformation theory (TSDT) where the formulations have been made general to fit both theories. Using the developed source codes, the effects of the SMA on the parametric instability of composite plates are studied through the improvement methods of the APT and the ASET. The instability charts are determined for several changes in parameters that include the activation temperature and the initial strain of the SMA.

Material and Method

The constitutive model of the SMA

This study uses the Brinson's model [5] to predict the SME behaviour of the SMA. The material parameters used in the constitutive and evolutionary equations of the Brinson's model [5] are shown in Table 1 [12]. The quassi-plasticity and SME behaviours of SMA are simulated to determine the recovery stress induced by the SMA as a function of activating temperature, T_a and initial strain of the SMA, ε_0.

Table 1: Parameters for the SMA Brinson's Model [12]

Parameters	Values
Critical Stress Start, σ_S (Pa)	80E6
Critical Stress Finish, σ_F (Pa)	155.0E6
Martensite Young's Modulus (Pa)	33.0E9
Austenite Young's Modulus (Pa)	69.6E9
Maximum Residual Strain, ε_L	0.058
Martensite Finish Temperature (^{0}C)	20.7
Martensite Start Temperature (^{0}C)	26.8
Austenite Start Temperature (^{0}C)	37.2
Austenite Finish Temperature (^{0}C)	47.0
Stress Influence Coefficient (Pa ^{0}C^{-1})	10.6E6
Stress Influence Coefficient (Pa ^{0}C^{-1})	9.7E6

The SMA composite plate

In this study, referring to Figure 1, the configuration of the composite is $[0/(\theta/-\theta)_n/0]$ where n is an integer to be specified. The 0° layers or the outer layers correspond to nitinol-epoxy (NE) layer while other layers are glass-epoxy (GE) layers. The plate has length of a = b = 500 mm. The volume fraction of Nitinol in a NE layer is 0.5 just like the volume fraction of the glass in the GE layer. The thickness of each layer is the same based on the a/t ratio used for a particular analysis. Simply supported boundary condition is applied throughout the study. **P(t)** is the periodic axial load. For comparison purpose, four cases of composite plates are used: 1. Plate without SMA (WO SMA) where the outer layers of the plate are the GE layers 2. Plate with non-activated SMA (NO ACT) 3. Plate with activated SMA but considers property improvement only (APT) 4. Plate with activated SMA that considers recovery stress and property improvement (ASET).

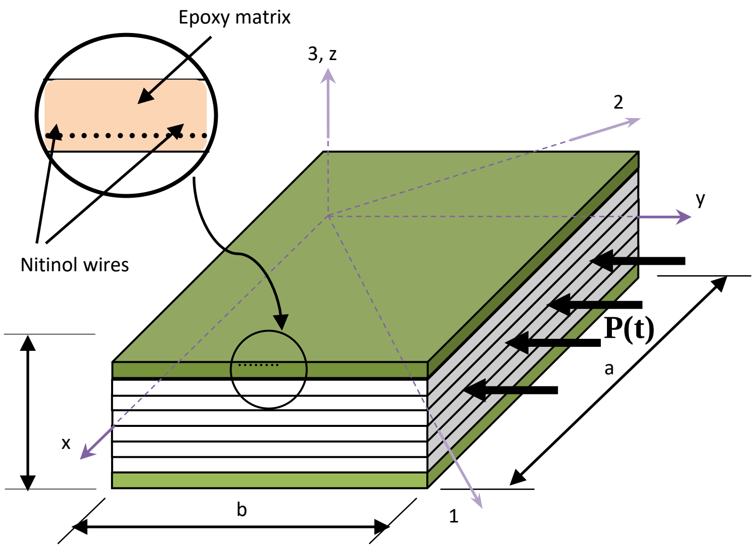

Figure 1: The SMA composite plate

The dynamic instability formulation

Assuming perfect bonding occurs between SMA wires and epoxy, the effective properties for NE layers can be calculated using the rule of mixture as it is typically done for the fibre-epoxy layer. As an example, referring to the material coordinate system (1-2-3) of the SMA composite plate in Figure 1, we have the effective Young's modulus for the SMA layer such as

$$E_1 = V_m E_m + V_a E_a \quad (1)$$

where E_1 is the Young's modulus in 1 direction, E_m and E_a are the Young's modulus for epoxy matrix and SMA respectively and V_m and V_a are the volume fractions for epoxy matrix and SMA respectively.

The kinematic of the SMA laminated composite plate is assumed to be as the following [13]:

$$\begin{aligned} u(x,y,z,t) &= u_0(x,y,t) + z\theta_x(x,y,t) + z^3\beta\xi_x \\ v(x,y,z,t) &= v_0(x,y,t) + z\theta_y(x,y,t) + z^3\beta\xi_y \\ w(x,y,z,t) &= w_0(x,y,t) \end{aligned} \tag{2}$$

where u, v and w are the generalized displacements at any points on the plates in the x, y and z directions respectively while u_0, v_0 and w_0 are the displacements at any points on the mid-plane of the plates in the x, y and z directions respectively. The rotations in the x-z and the y-z planes respectively are represented by θ_x and θ_y while ξ_x and ξ_y correspond to the warping functions in the x-z and the y-z planes respectively. β is a constant used to differentiate between the FSDT and the TSDT where $\beta = 0$ is for the FSDT theory and $\beta = 1$ is for the TSDT theory. The in-plane constitutive relationship for a SMA laminated composite plate in material coordinate system is

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix}_{12} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{33} \end{bmatrix}_k \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{Bmatrix} + V_a \begin{Bmatrix} \sigma_1^r \\ 0 \\ 0 \end{Bmatrix} \tag{3}$$

or in a short form,

$$\{\sigma\}_{12} = [Q]_k\{\varepsilon\}_{12} + V_a\{\sigma^r\}_{12} \tag{4}$$

where $[Q]_k$ is the reduced stiffness matrix of the kth layer of the composite and $\{\sigma^r\}$ is the recovery stress vector of the SMA.

Finite element implementation

Eight noded iso-parametric quadrilateral elements are used in this study. Each node carries 5 or 7 degrees of freedom for FSDT or TSDT respectively. Upon applying the Hamilton's principle, the governing equation for the dynamic instability of laminated composite with embedded SMA is

$$[M]\{\ddot{q}\} + ([K_L] + [K_s] + [K_r])\{q\} + P(t)[K_G]\{q\} = 0 \tag{5}$$

Assuming $P(t)$ is periodic and harmonic compressive load in the form of

$$P(t) = P_s + P_t cos\omega t \tag{6}$$

where P_s is the static portion of the load $P(t)$ and P_t is the amplitude of the dynamic portion of the $P(t)$. ω is the frequency of the periodic loading. The static and dynamic components of load can be expressed in terms of critical load of the plate, i.e.

$$P_s = \alpha P_{cr} \, . \quad P_t = \beta P_{cr} \tag{7}$$

where α and β are the static and dynamic load factors. Eqn. (5) then becomes

$$[M]\{\ddot{q}\} + ([K_L] + [K_s] + [K_r])\{q\} - (\alpha P_{cr}[K_G] - \beta P_{cr}[K_G]cos\omega t)\{q\} = 0 \tag{8}$$

Or in a simplified form,

$$[M]\{\ddot{q}\} + [K]\{q\} - (\alpha P_{cr}[K_G] - \beta P_{cr}[K_G]cos\omega t)\{q\} = 0 \tag{9}$$

Where

$$[K] = [K_L] + [K_s] + [K_r] \tag{10}$$

Eqn. (9) is the Mathieu-Hill type of equation that represents the dynamic instability problem of the SMA composite plate. Applying the Bolotin's method, we obtain

$$\left[[K] - \alpha P_{cr}[K_G] \pm \tfrac{1}{2}\beta P_{cr}[K_G] - \tfrac{\omega^2}{4}[M]\right]\{q\} = 0 \tag{11}$$

Eqn. (11) is an eigen value problem where the term $\pm$ gives the upper (Ω^U) and lower (Ω^L) stability boundaries of the dynamic instability region for known values of α, β and P_{cr}. FEM source codes have been developed in FORTRAN environment to solve Eqn. (11) and validations to the developed formulation and codes plus the results are given in the following.

Results and Discussion

The results of the present study on the dynamic instability of SMA composite plates are given next. The section starts on the validation of the developed formulation on the buckling, vibration and dynamic instability analysis of composite plates. Following this, parametric studies on the subject of dynamic instability of SMA composite plates with regard to several factors including the properties of the SMA are given.

Validation on the formulation and source codes

Since the results on the dynamic instability of SMA composite plates are not available in literature, the s on the developed formulation and source codes have been conducted rather on the composite plates without SMA or without activated SMA. In addition, a comparison analysis between the results of the dynamic instability of SMA composite plate due to the TSDT and FSDT based formulations are conducted.

Buckling analysis has been conducted on the composite plates embedded with non-activated SMA wires. The results are compared to the analytical results that are based on the classical lamination theory (CLT) and the FSDT of plates [14]. The results in Table 2 show quick convergence of critical loads that occurs in the finite element analysis for all SMA composite plates under consideration.

Table 2: Convergence tests on the non-dimensionalised first buckling mode of three simply supported anti-symmetric angle-ply SMA composite plates.

	$[0/(45/-45)_2/0]$	$[0/(45/-45)_4/0]$	$[0/(45/-45)_6/0]$
CLT[a]	235.75	269.88	264.43
FSDT[a]	235.75	267.33	261.98
3x3	236.49	264.70	270.06
4x4	234.07	267.45	262.29
5x5	233.78	267.34	261.99
6x6	233.72	267.27	261.92
7x7	233.70	267.25	261.88
8x8	233.69	267.24	261.88

[a] J.N. Reddy [14]

A study on the validation of the developed formulation of the dynamic instability of composite plate has been conducted for the WO SMA case. The following specifications of composite plates are used:

Dimension of the plate: length, a = b = 500 mm, thickness, a/t = 25
Material properties: $E_1/E_2 = 40$, $G_{12} = G_{13} = 0.6E_{22}$, $G_{23} = 0.5E_{22}$, $v_{12} = 0.25$
Fiber orientations: [0/90/0/90/0]

In this study, α and β are taken as 0 and 0.3 respectively. Table 3 shows that the results of lower non-dimensionalised frequency, Ω^L and upper non-dimensionalised frequency, Ω^U correspond to the FSDT and TSDT in this study agree excellently with results from past literature [15] that used the higher order shear deformation plate theory (HSDT). The non-dimensionalised frequency, upper or lower is $\Omega = \Omega_e a^2(\rho t/E_2)$ where Ω_e is the actual excitation frequency corresponds to the dynamic instability, ρ is density of the composite, t and E_2 are the thickness and the Young's modulus of the laminated composite in 2-direction.

Table 3: Dynamic instability of cross-ply symmetric plate

Ω	Present FSDT	Present TSDT	HSDT[a]
Ω^U	155.037	154.943	155.03
Ω^L	133.290	133.209	133.29

[a] Wang and Dave [15]

<u>Comparing the TSDT and the FSDT formulations</u>

A study has been conducted to compare the results of the dynamic instability of SMA composite plates analysis using the TSDT and the FSDT formulations. The configuration of the SMA composite plates in this study is [0/45/-45/45/-45/45/-45/0] where a/t = 100. SMA wires are activated at T_a = 55 °C and initial strain is ε_0= 0.01. From the simulation conducted on the Brinson's model, the recovery stress is σ_r=139.8 MPa while the Young's modulus of the SMA is E_s = 43.2 GPa . Simply supported boundary condition is used in this study. α is taken as 0 while β is varied from 0 to 2. Studies are conducted on the four cases of WO SMA, WO ACT, APT and ASET. Table 4 shows the results of lower non-dimensionalised frequency, Ω^L and upper non-dimensionalised frequency, Ω^U correspond to the FSDT and TSDT respectively for the cases of WO SMA and ASET. Figure 2 and 3 shows the instability charts of composite plates in the four cases of WO SMA, WO ACT, APT and ASET based on the TSDT and FSDT formulations respectively.

Table 4 shows that the results correspond to the TSDT are in a very close agreement with the results based on the FSDT formulation. The agreement between the two theories can also be seen in Figure 2 and 3. This shows that the TSDT formulation that does not require the use of the shear correction factor can be applied in the dynamic instability analysis of laminated composite plates. Figure 2 and 3 are the instability chart that show the instability regions where parametric instability occurs for values of loading frequencies and dynamic load factor, β. The figures also show that the effect of SMA is at the greatest when the method of ASET that considers both the property improvement and the recovery stress of the SMA is applied. The effect of SMA in ASET method comes in two ways: shifting the instability chart to the right and enlarging the unstable region.

Table 4: The non-dimensionalised loading frequencies correspond to dynamic instability boundaries for SMA composite plates based on TSDT and FSDT formulations.

		WO SMA				ASET			
		TSDT		FSDT		TSDT		FSDT	
α=0.0	β	Ω^U	Ω^L	Ω^U	Ω^L	Ω^U	Ω^L	Ω^U	Ω^L
	0	18.127	18.127	18.127	18.127	37.145	37.145	37.146	37.146
	0.2	19.011	17.196	19.012	17.197	38.959	35.239	38.959	35.240
	0.4	19.857	16.213	19.857	16.213	40.691	33.224	40.691	33.224
	0.6	20.668	15.166	20.668	15.166	42.352	31.078	42.353	31.078
	0.8	21.448	14.041	21.448	14.041	43.951	28.773	43.952	28.773
	1.0	22.201	12.817	22.201	12.818	45.494	26.266	45.494	26.266
	1.2	22.929	11.464	22.929	11.465	46.986	23.493	46.986	23.493
	1.4	23.634	9.928	23.635	9.929	48.432	20.345	48.432	20.345
	1.6	24.319	8.106	24.320	8.107	49.836	16.612	49.836	16.612
	1.8	24.986	5.732	24.987	5.732	51.202	11.746	51.202	11.746
α=0.2	0	16.213	16.213	16.213	16.213	33.224	33.224	33.224	33.224
	0.2	17.196	15.166	17.197	15.166	35.239	31.078	35.240	31.078
	0.4	18.127	14.041	18.127	14.041	37.145	28.773	37.146	28.773
	0.6	19.011	12.817	19.012	12.818	38.959	26.266	38.959	26.266
	0.8	19.857	11.464	19.857	11.465	40.691	23.493	40.691	23.493
	1.0	20.668	9.928	20.668	9.929	42.352	20.345	42.353	20.345
	1.2	21.448	8.106	21.448	8.107	43.951	16.612	43.952	16.612
	1.4	22.201	5.732	22.201	5.732	45.494	11.746	45.494	11.746
	1.6	22.929		22.929		46.986		46.986	
α=0.4	0	14.041	14.041	14.041	14.041	28.773	28.773	28.773	28.773
	0.2	15.166	12.817	15.166	12.818	31.078	26.266	31.078	26.266
	0.4	16.213	11.464	16.213	11.465	33.224	23.493	33.224	23.493
	0.6	17.196	9.928	17.197	9.929	35.239	20.345	35.240	20.345
	0.8	18.127	8.106	18.127	8.107	37.145	16.612	37.146	16.612
	1.0	19.011	5.732	19.012	5.732	38.959	11.746	38.959	11.746
	1.2	19.857		19.857		40.691		40.691	
α=0.6	0	11.464	11.464	11.465	11.465	23.493	23.493	23.493	23.493
	0.2	12.817	9.928	12.818	9.929	26.266	20.345	26.266	20.345
	0.4	14.041	8.106	14.041	8.107	28.773	16.612	28.773	16.612
	0.6	15.166	5.732	15.166	5.732	31.078	11.746	31.078	11.746
	0.8	16.213		16.213		33.224		33.224	

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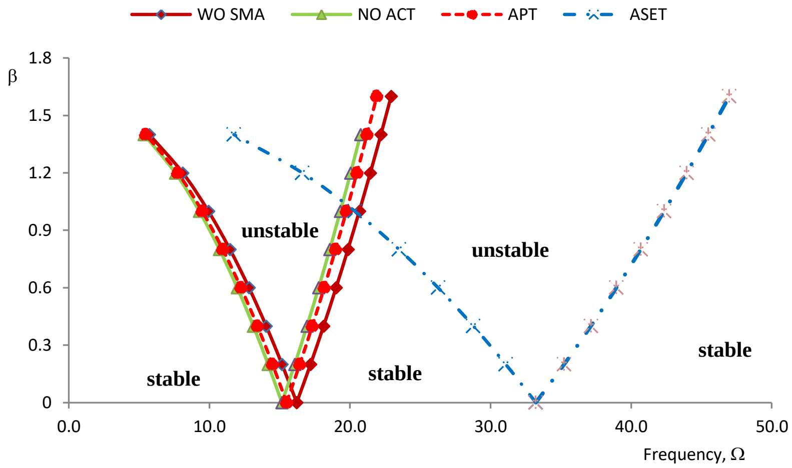

Figure 2: The effect of SMA on the dynamic instability of composite plates based on the TSDT formulation.

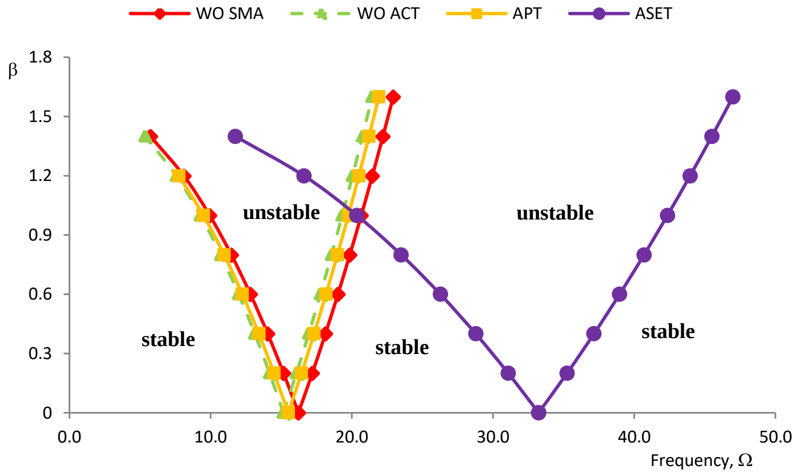

Figure 3: The effect of SMA on the dynamic instability of composite plates based on the FSDT formulation.

Looking at the frequency centre, the effect of SMA has increased the frequency centre from 16.213 to 33.224, i.e. the increase of more than 100%. It can also be seen that as the fiber of the outer layer of the composite is changed from glass (WO SMA case) to nitinol (WO ACT case), the instability chart is shifted to the left. This is obviously due to the better property of the glass fiber as compared to that of the nitinol fiber. The effect of applying the APT method of improvement after that can only give slight improvement to the instability chart as can be seen in a small right shifting of the chart. This effect of the ASET that is greater than the effect of the APT correlates with the finding in the study on the effect of the SMA on the buckling [8] and thermal buckling [9] of laminated composite plates.

<u>The effect of the static load factor</u>

The effect of static load factor, α on dynamic instability of SMA composite plates under the ASET method of improvement is given in this section. The 10-layer configuration of [0/45/-45/45/-45/45/-45/45/-45/0] is used in this study where the ratio of length to thickness of the plate is a/t = 25. The simply supported boundary condition is applied. The activation temperature of the SMA is T_a = 60°C while the initial strain is ε_0= 0.001. This gives the recovery stress of σ_r = 91.6 MPa. Figure 4 and 5 shows the effect of the static load factor, α on the instability charts of the laminated composite plates corresponds to the cases of WO SMA and ASET respectively. Figure 8 and 9 show that as the static load factor is increased, the easier the instability can occur at lower frequency value as the instability chart is shifted to the left. This trend is true for both cases of WO SMA and ASET and has been shown by other researcher [16] in the case of laminated composite plates without SMA. However the width of the instability charts seems to almost remain the same even with the increase of the static load factor. It can also be seen that the effect of the static load factor is not influenced by the presence of the SMA. The percentage change of the frequency center in the case of WO SMA moving from the case of α = 0 to α = 0.8 is approximately the same for the case of ASET i.e the change of about 55%.

<u>The effect of the activation temperature of the SMA</u>

A study on the effect of the activation temperature of the SMA on the dynamic instability of the composite plates is conducted where the initial strain of the SMA under consideration is ε_0= 0.001. The 12 layer SMA composite plate with configuration of [0/45/-45/45/-45/45/-45/45/-45/45/-45/0] is used here.

The static load factor was taken as α = 0.2 while the ratio of length to thickness of composite plate is a/t = 100. Simply supported boundary condition is applied. Figure 6 and 7 show the instability charts corresponds to the change of activation temperature, T_a for the cases of the APT and the ASET method of improvement. In the case of APT, the effect of the increase of the T_a is not significant.

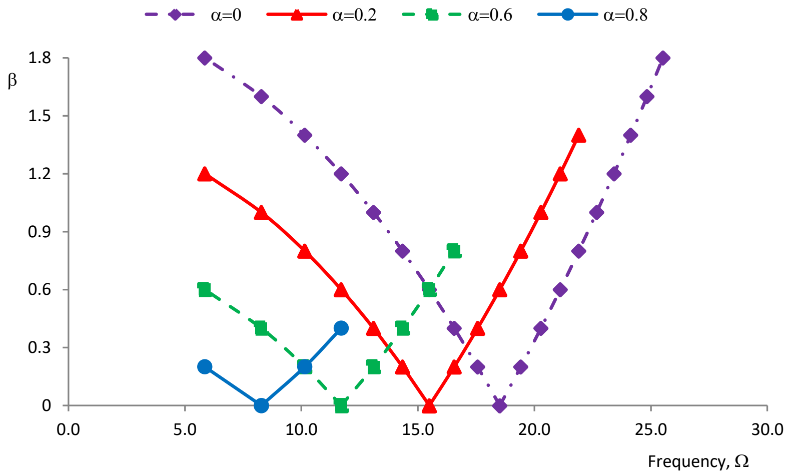

Figure 4: The effect of static load factor on the dynamic instability of composite plates for the case of WO SMA.

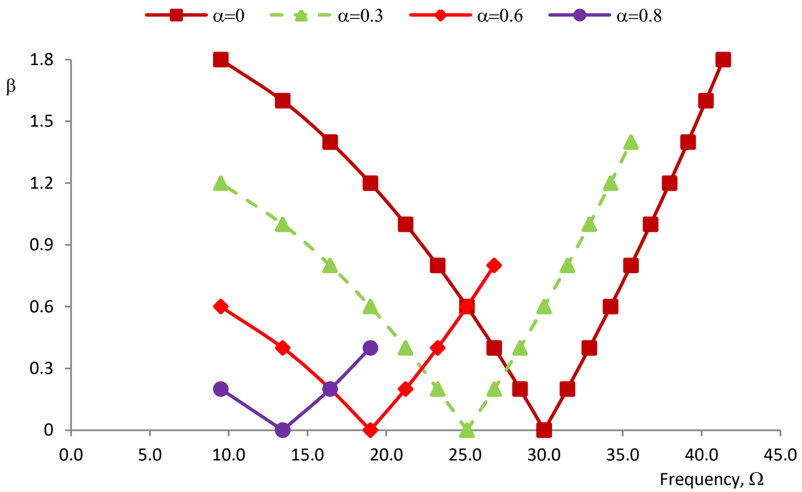

Figure 5: The effect of static load factor on the dynamic instability of composite plates for the case of ASET

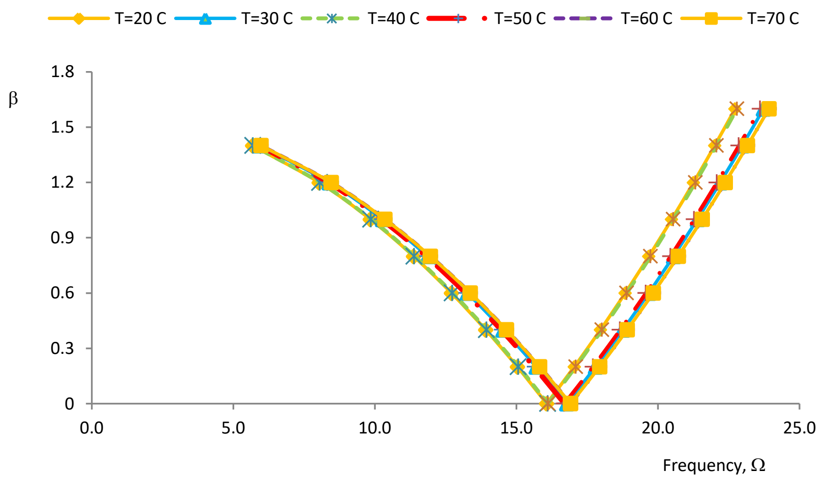

Figure 6: The effect of the activation temperature on the dynamic instability of composite plates for the case of APT.

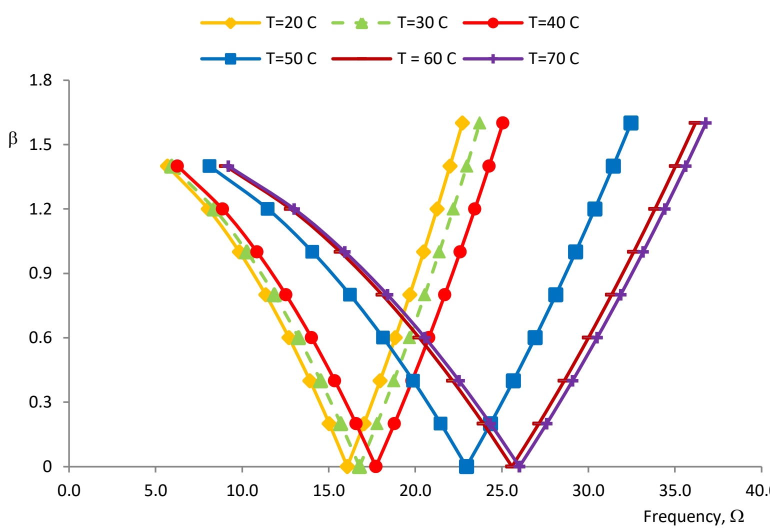

Figure 7: The effect of the activation temperature on the dynamic instability of composite plates for the case of ASET.

The effect of the T_a can be seen clearly in the case of ASET where the increase of the temperature has steadily shifted the instability chart to the right. The initial improvement here is however due to the effect of the thermal stress. The substantial shifting to the right of the instability chart occurs when the temperature changes from 40 °C to 60 °C. This is due to the phase transformation of the SMA from Martensite to Austenite that occurs within those temperatures that gives the property improvement and the recovery stress. The shifting slows down again after temperature, T_a = 70 °C when the phase transformation of the SMA is completed.

Conclusion

The study on the effect of SMA on the dynamic instability of laminated composite plate has been conducted. The FEM formulation has been developed based on the TSDT. The formulation and source codes have firstly been validated before parametric studies are conducted. The study finds that the SMA has significant effect in postponing the occurrence of the dynamic instability by shifting the dynamic instability chart to the right. The effect of SMA is significant when the ASET method of SMA improvement that considers property improvement and stress recovery is considered. The amount of improvement depends largely on the initial strain and the activation temperature given to the SMA.

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