

Design and Experimental Investigation of an Automotive Hybrid Aluminium Composite Drive Shaft

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ABSTRACT: This work represents the replacement of two piece conventional metallic drive shaft with the single piece hybrid drive shaft. First we will study design of shaft concentrating on natural frequency, buckling torque, and fibre orientation etc. By using classical laminate theory design of hybrid drive shaft is done. Manufacturing of the hybrid drive shaft is done by using composite of carbon fibre and epoxy resin and aluminium. For the shaft consist of four layers stalked as $[90^0/+45^0/-45^0/20^0]_s$ and then aluminium is used on it. Finite element analysis is carried out to find static and modal analysis results. Modal analysis has been carried out for finding the natural frequency. Experimental set up will carried out to find static results, torsion behaviour and the natural frequency of hybrid drive shaft. The percentage of mass saving is 73.38 % by using hybrid drive shaft as compared to steel drive shaft.

KEYWORDS: Hybrid Shaft, Torque transmission, Natural frequency, Mode shape, FFT.

I. INTRODUCTION

The drive shaft is used in an automobile to transmit power from the engine to the differential gear of a wheel drive vehicle. The advanced composite material such as Graphite, Kevlar and Glass with suitable resins is widely used because of their high specific strength and modulus. The drive shafts are used in an aircraft, aerospace and the automobile application. The weight reduction of the drive shaft is an important role in the weight saving of the vehicle and is a highly desired goal, if it can be achieved without increase in price and decrease in quality and reliability. The torque competence of the drive shaft for passenger cars should be higher than 3500 N-m and the fundamental bending natural frequency should be greater than 9200 rpm to avoid spinning vibration. The bending natural frequency of a one piece drive shafts made of aluminum or steel is normally reduced than 5700 rpm when the length of the drive shaft is around 1.5 m, then the steel drive shaft is generally manufactured in two pieces to maximize the necessary bending natural frequency.

Lien-Wen Chen et al.[4] studied the stability behaviour of a rotating composite shaft subjected to an axial compressive loads using finite element technique. The laminated composite shaft is modelled as a Timoshenko shaft by applying the equivalent modulus beam theory. Mathematical results correlate with the reported beam models. The dangerous speed of the thin-walled composite shaft is in need of the stacking sequence, the length-radius ratio and the boundary conditions. In adding, the effects of the rotational speeds and the disk location on the rotating shafts' stability are studied as well.

R. R. Chang et al.[5] studied the failure strengths of laminated composite drive shafts subjected to static bending load and or torque are calculated using both experimental and theoretical approaches. We investigate optimal angle-ply orientations of laminated composite drive shafts with the design of symmetric main fiber layups and anti-symmetric reinforcing fiber lay-ups for maximum stiffness. Different analytical techniques, together with various failure criteria, are used to forecast the first-ply failure strengths of the composite drive shafts. A hand lay-up and pressure bag technique was used to fabrication the composite drive shafts, which includes the stacking of pieces of pre-preg in the desired orientations and the curing procedure.

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Dai Gil Lee et al. [6] studied by substituting composite structures for conventional metallic structures has many benefits because of higher stiffness and higher specific strength of the composite materials. In this work single piece automotive hybrid aluminium/composite drive shaft was developed with a new manufacturing technique, in which the carbon fibre epoxy composite layer was co-cured on the inside surface of an aluminium tube rather than covering on the outer surface to avoid the composite layer from being damaged by external impact and absorption of moisture. The optimal stacking sequence of the composite layer was found by considering the thermal residual stresses of interface between the aluminium tube and the composite layer designed by finite element analysis.

S. A. Mutasher [10] a hybrid aluminum/composite is an advanced composite material that consists of aluminum tube wound against outside by layers of composite material. The result from this combination is a hybrid drive shaft that has a higher fundamental natural bending frequency, a higher torque transmission capability and less noise and vibration. This paper examines the higher torsion capacity of the hybrid aluminum/composite drive shaft for different stacking sequences, number of layers and winding angle. The hybrid drive shaft consists of aluminum tube wound outside by carbon fibres/epoxy and E-glass composite.

M. A. Badie et al. [12] studied that the effect of stacking sequence and fibre orientation angles on the torsional stiffness, buckling strength, natural frequency, fatigue life and failure types of composite tubes. Finite element analysis has been used to predict the fatigue life of drive shaft using linear dynamic analysis for the different stacking sequence. Experimental program on climbed woven fabric composite models was done to investigate the torsional stiffness.

M. R. Khoshrovan et al. [15] studied design method and vibrational analysis of composite propeller shafts. A propeller shaft is not limited to vehicles, but in several transmission applications can be used, but the aim is to exchange a metallic shaft by a two-piece composite shaft. Designing of a composite drive shaft is divided in two main sections such as design of the composite drive shaft and design of couplings. In composite shaft design some parameters such as static torque, adhesive joints and critical speed are studied the behaviour of materials is considered linear isotropic for metal, nonlinear isotropic for adhesive and orthotropic for composite shaft.

Secil Eksi et al. [17] studied that the buckling is characterized by a quick failure of a structural member subjected to maximum compressive load. In this study, the buckling performance of the aluminium tubular beam was analysed using finite element method, and the reinforcing arrangements as well as its combinations were decided for the composite beams based on the FE results. Buckling and bending behaviours of thin-walled aluminium tubular beams with internal cast polyamide and external glass and carbon fibre reinforcement polymers were investigated systematically. The use of plastics and metal composed as a reinforced structure yields better mechanical performance properties such as peak resistance to bending loads and buckling, dimensional stability and high energy absorption capacity, including weight decline.

Ercan Sevkati et al. [18] studied experimental and numerical investigation regarding residual torsional properties of composite shafts subjected to impact loadings. Carbon/epoxy and E-glass-carbon/epoxy hybrid composite shafts were produced by filament winding technique. Composite drive shafts were impacted at 5, 10, 20 and 40 J energy levels. Force-time and energy-time histories of impact tests were noted. One composite drive shaft with no impact, and four composite shafts with impact damage, five in total, was tested under torsion. Torque-twisting angle relations for each test were obtained.

R. Srinivasa Moorthy et al. [20] studied the use of advanced composites has resulted in remarkable accomplishments in many fields containing aeronautics, marine and automobile engineering, sports and medicine, in terms of enhanced fatigue and erosion resistances, high specific modulus and specific strength and reduction in energy requirements owing to reduction in weight. The purpose of this work is to exchange the conventional steel drive shaft of automobiles with an appropriate composite drive shaft.

II. DESIGN SPECIFICATION

The following specifications are considered which are based on the literature and available standards for the automobile drive shaft is

1. Torque transmission capacity of the steel drive shaft = 3676 N-m
2. Speed of drive shaft = 2400 rpm
3. Outside diameter of drive shaft = 0.068 m

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4. Length of drive shaft = 1.3 m

III. DESIGN OF STEEL DRIVE SHAFT

The mechanical material properties of the steel (SM45C) are given in Table-1

Table 1 Mechanical Properties of the Steel

Mechanical Properties	Symbol	Steel	Unit
Young's Modulus	E	207	GPa
Shear Modulus	G	80	GPa
Poisson's Ratio	μ	0.3	-
Density	ρ	7800	Kg/m ³
Yield Strength	S _y	370	MPa

A. Design of Steel Drive Shaft Based on Torsional Strength

The primary load in the steel drive shaft is torsion. The maximum shear stress (τ_{max}), in the drive shaft is at the outer radius and is given as,

$$\tau_{max} = \frac{T_{max} r_o}{J}$$

We know, polar moment of inertia of the hollow circular shaft in cross section is given by,

$$J = \frac{\pi}{32} (d_o^4 - d_i^4)$$

Therefore,

$$d_i = 0.05254 \text{ m}$$

B. Mass of Steel Drive Shaft

$$m = \rho A L$$

Where,

m = mass of steel drive shaft (kg)

ρ = material density (kg/m³)

L = length of the shaft (m)

Therefore,

$$m = \rho \times \frac{\pi}{4} (d_o^2 - d_i^2) \times L$$

$$m = 14.84 \text{ kg}$$

C. Torsional Buckling Capacity of the Steel Drive Shaft

The torsional buckling capacity of the steel drive shaft given by

$$T_b = (2 \pi r_m^2 t) (0.272) (E) \left(\frac{t}{r_m} \right)^{\frac{3}{2}}$$

Where,

T_b = buckling torque (N-m)

r_m = mean radius of shaft (m)

E = young's modulus (GPa)

t = thickness of steel drive shaft (m)

$$T_b = 322.60 \times 10^3 \text{ N-m}$$

The value of critical torsional buckling moment is larger than the applied torque of $3676 \times 10^3 \text{ N-m}$. Thus the shaft need to withstand torsional buckling (T_b) capacity such that T_b > T. Hence the condition is satisfied.

D. Natural Frequency of Steel Drive shaft

Natural frequencies can be found by using two theories

- i. Timoshenko Beam Theory.

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ii. Bernoulli-Euler Beam Theory.

Out of these two theories, as per assumptions Bernoulli-Euler Beam Theory is more suitable in this case. The first natural frequency is given by

$$f_{nt_1} = \frac{\pi P^2}{2L^2} \sqrt{\frac{E I_x}{m_1}}$$

Where,

f_{nt_1} = first natural frequency (Hz)
 m_1 = mass per unit length (kg/m³)

$$f_{nt_1} = 102.81 \text{ Hz}$$

This value is greater than the minimum desired natural frequency of 40 Hz. Thus, the steel design of hollow drive shaft of outer diameter 0.068 m and thickness 0.00773 m is an acceptable design.

E. Critical speed

The first critical speed is given by

$$N_{crt_1} = 60 f_{nt_1}$$

Where,

N_{crt_1} = first critical speed (rpm)

$$N_{crt_1} = 6168.62 \text{ rpm}$$

IV. DESIGN OF COMPOSITE DRIVE SHAFT

Classical lamination theory is used for design of composite drive shaft.

A. Selection of Material

1. Carbon Fiber
2. Epoxy Resin
3. Aluminum Material

In this project work the design of drive shaft by a combination of aluminum and composite materials carbon fibers/epoxy resin. The major role of the aluminum tube is to sustain a applied torque while the role of the carbon fiber epoxy composite is to increase natural bending frequency.

B. Macro mechanical Analysis of Laminate

Macro mechanical analysis will be developed for a laminate. A real structure however will not consist of a one lamina but a laminate consisting of more than one lamina bonded together through their thickness. Based on in-plane loads of extension, shear, bending and torsion, stresses and strains will be found in the local and global axes of each ply. Stiffness's of whole laminates will also be calculated. Intuitively, one can see that the strength, stiffness properties of laminate will depend on

1. Elastic moduli.
2. Stacking sequence.
3. Thickness.
4. Angle of orientation of each lamina.

C. Composite Ply Orientation

Only 20°, ±45° and 90° were consider for the ply orientations, due to their greater advantages, such as ±45° plies increases the torsional strength/stiffness, and 90° plies increase the critical torsional buckling load, and the 20° plies increase the natural frequency of the drive shaft.

D. The Stiffness Matrices [A], [B] and [D] for Eight-ply [90°/45°/-45°/20°] Carbon/ Epoxy Laminate

The extensional stiffness matrix [A] is given by,

$$A_{ij} = \sum_{k=1}^8 [\bar{Q}_{ij}]_k (h_k - h_{k-1})$$

Where,

A_{ij} = extensional stiffness matrix

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h_{k-1} = top surface
 h_k = bottom surface

Longitudinal modulus

$$E_x = 47.16 \text{ GPa}$$

Transverse modulus

$$E_y = 57.10 \text{ GPa}$$

The Bending stiffness matrix [D] is given by,

$$D_{ij} = \frac{1}{3} \sum_{k=1}^8 [\bar{Q}_{ij}]_k (h_k^3 - h_{k-1}^3)$$

$$E_x = 21.58 \text{ GPa}$$

$$E_y = 106 \text{ GPa}$$

E. Torsional Strength of Shaft

Assuming that the drive shaft is a thin hollow cylinder, an element in the cylinder can be assumed to be flat laminate. The applied torque then is

$$T = (\tau_{xy})_{\text{average}} \pi (r_o^2 - r_i^2) r_m$$

The average shear stress is given by,

$$N_{xy} = (\tau_{xy})_{\text{average}} \times t$$

$$(\tau_{xy})_{\text{average}} = \frac{N_{xy}}{t}$$

$$(\tau_{xy})_{\text{average}} = 100.23 \text{ MPa}$$

Therefore,

$$T = 3895.06 \text{ N-m}$$

F. Torsional Buckling Capacity of Composite Shaft

When hollow shaft is subjected to torsion, at the certain amount of torsional load instability occurs. This is called torsional buckling load. An orthotropic thin hollow cylinder will buckle torsionally, if the applied torque is greater than the torsional load is given by,

$$T_c = (2 \pi r_m^2 t) (0.272) (E_x E_x^3)^{\frac{1}{4}} \left(\frac{t}{r_m} \right)^{\frac{3}{2}}$$

$$T_c = 69293.63 \text{ N-m}$$

The value is greater than the applied torque of 3676 N-m, thus the composite drive shaft is safe in buckling.

G. Torsional Buckling Capacity of Aluminum Tube

The torsional buckling capacity of aluminium tube is given by,

$$T_{(\text{Buckling})al} = \frac{\pi \sqrt{2} E_{al}}{3(1 - \mu_{avg}^2)^{0.75}} \sqrt{r_{avg} t_{al}^5}$$

Where,

E_{al} = young's modulus of aluminum tube (GPa)

t_{al} = thickness of aluminum tube (m)

r_{avg} = average radius of aluminum tube (m)

$$T_{(\text{Buckling})al} = 3857.31 \text{ N-m}$$

H. Torque Transmitted by the Hybrid Drive Shaft

The torque transmitted by the hybrid drive shaft is given by,

$$T = T_{al} + T_c$$

Where,

T_{al} = torque transmitted by aluminum tube (N-m)

T_c = torque transmitted by aluminum tube (N-m)

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Therefore,

$$T = 73150.94 \text{ N-m}$$

This values is greater than the applied torque of 3976 N-m, thus the composite drive shaft is safe in buckling.

I. Fundamental Natural Frequencies of the Hybrid Drive Shafts

The natural frequencies of the hybrid drive Shaft is given by,

$$f_n = \frac{9.869}{L^2} \sqrt{\frac{E_{al}I_{al} + E_cI_c}{m_{al} + m_c}}$$

Where,

E_{al} = young's modulus of aluminum tube (GPa)

E_c = young's modulus of composite tube (GPa)

I_{al} = moment of inertia of aluminum tube (m^4)

I_c = moment of inertia of composite tube (m^4)

m_{al} = mass per unit length of aluminum tube (kg/m)

m_c = mass per unit length of composite tube (kg/m)

$$f_{n1} = 691.79 \text{ Hz}$$

Similarly,

$$f_{n2} = 1050.10 \text{ Hz}$$

$$f_{n3} = 1860.3 \text{ Hz}$$

Thus the calculated frequency is more than the lowest natural frequency i.e. 80 Hz. Thus the requirement is also meet by the hybrid drive shaft.

J. Mass Saving

The mass saving of the carbon/epoxy drive shaft is

$$m = \frac{14.84 - 3.95}{14.84} \times 100$$

$$m = 73.38 \%$$

V. FINITE ELEMENT ANALYSIS

A. Modal Analysis

The Figure 1 shows the first natural frequency of hybrid drive shaft and the deformation value with the help of colour bar. Colour bar is used to determine the value ranges on object. First natural frequency of hybrid drive shaft drive shaft is 649.89 Hz which are within permissible limit. The Figure 2 shows the second natural frequency of hybrid drive shaft and the deformation value with the help of colour bar. Colour bar is used to determine the value ranges on object. Second natural frequency of hybrid drive shaft drive shaft is 735.75 Hz which are within permissible limit. The Figure 3 shows the third natural frequency of hybrid drive shaft and the deformation value with the help of colour bar. Colour bar is used to determine the value ranges on object. Third natural frequency of hybrid drive shaft drive shaft is 1124.67 Hz which are within permissible limit.

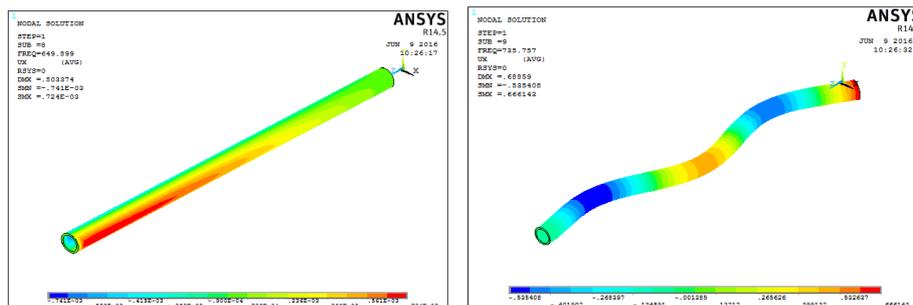


Figure 1 First Natural frequency of hybrid drive shaft Figure 2 Second Natural frequency of hybrid drive shaft

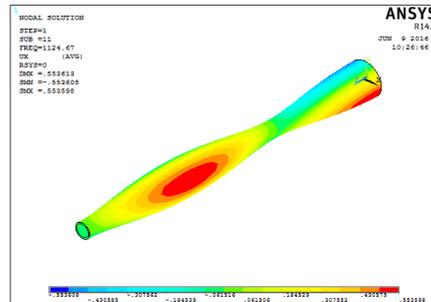


Figure 3 Third Natural frequency of hybrid drive shaft

Comparison results of hybrid and steel drive shaft by using FEA are shown in Table 3.

Table 3 FEA Results

Analysis Type	Hybrid drive shaft	Steel drive shaft
	Modal Analysis	
1 st Frequency	649.89 Hz	101.66 Hz
2 nd Frequency	735.75 Hz	441.16 Hz
3 rd Frequency	1124.67 Hz	1036.87 Hz

VI. EXPERIMENTATION

A. Torsion Test Setup

The torque is the product of the tangential force is multiplied by the radial distance from the twisting axis and the tangent, measured in a unit of N-m. The torsion testing, the relationship between degree of rotation and torque is presented by the graph and parameters such as ultimate torsional shearing strength, shear strength at proportional limit and shear modulus are generally investigated.

B. Results

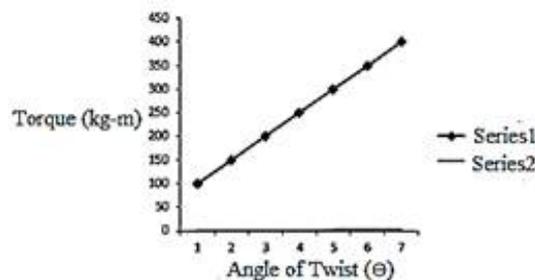


Figure 5 Graph of Torque vs. Angle of Twist

The above graph shows that linear increase in deflection with increasing torque. In this torsion testing we apply torque up to 4415 N-m (450 kg-m) on the hybrid drive shaft. Here we want to transmit the torque up to 3676 N-m and the shaft is slightly twisted at 3950 N-m. This is an expected output and it checks with the theoretical behavior of a shaft subjected to torsional loading.

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Analytical and Experimental FFT Results of Hybrid Drive Shaft is given in Table 4.

Table 4 Analytical and Experimental FFT Results of Hybrid Drive Shaft

Analysis Type	Hybrid Drive shaft	
Modal Analysis	Analytical	Experimental
1 st Frequency	691.79 Hz	698.1 Hz
2 nd Frequency	1050.10 Hz	1140.75 Hz
3 rd Frequency	1860.3 Hz	1840.3 Hz

VII. CONCLUSION

A one piece hybrid drive shaft for an automobile has been designed by using classical lamination theory with the objective of minimization of weight of the shaft which was subjected to the constraints such as torque buckling capacities and natural frequency. The weight of the hybrid drive shaft is reduced by 73.38 % as compared to steel drive shaft.

REFERENCES

- [1] James C. Leslie, Lee Truong and Bruce Blank., "Composite Drive shaft's", Technology and Experience, Advanced Composite Products and Technology, Inc. 962209 (1996).
- [2] Durk Hyun Cho, Jin Ho Choi., "Manufacture of One Piece Automotive Drive Shafts with Aluminum and Composite Materials", Composite Structure Vol. 38, No. 1-4, pp. 309-319, (1997).
- [3] Robert S. Salzar., "Design considerations for Rotating Laminated Metal Materix Composite Shafts", Composite Science and Technology 59 (1999) 883-896.
- [4] Lien-Wen Chen Wen-King Peng., "The Stability Behaviour of Rotating Composite Shafts under Axial Compressive Loads", Composite Structures 41 (1998), 253-263.
- [5] R. R. Chang and J. M. Chu., "Predictions of First Ply Failure of Laminated Composite Shafts", Experimental Mechanics, November 12 (2002).
- [6] Dai Gil Lee, Hak Sung Kim, Jong Woon Kim, Jin Kook Kim., "Design and Manufacture of an Automotive Hybrid Aluminum/Composite Drive Shaft", Composite Structures 63 (2004) 87-99.
- [7] Mahmood M. Shokrieh, Akbar Hasani, Larry B. Lessard., "Shear Buckling of a Composite Drive Shaft under Torsion", Composite Structures 64 (2004) 63-69.
- [8] Khalid Y.A, Mutasher S. A, Sahari B. B, Hamouda A. M. S., "Bending Fatigue Behaviour of Hybrid Aluminum/ Composite Drive Shafts", Material and Design 2007; 28(1):329-34.
- [9] Sino R, T. N. Baranger., "Dynamic Analysis of a Rotating Composite Shaft", Composite Science and Technology 68 (2008) 337-345.
- [10] S.A. Mutasher., "Prediction of the Torsional Strength of the Hybrid Aluminum/Composite Drive Shaft", Materials and Design 30 (2009) 215-220.
- [11] A. R. Abu Talib, Aidy Alib, Mohamed A. Badiya, Nur Azida Che Lahb, A.F. Golestaneh., "Developing a Hybrid Carbon/Glass Fiber-Reinforced Epoxy Composite Automotive Drive Shaft", Materials and Design 31 (2010) 514-521.
- [12] M.A. Badie, E. Made, A.M.S. Hamouda., "An investigation into Hybrid Carbon/Glass Fibre Reinforced Epoxy Composite Automotive Drive Shaft", Materials and Design 32 (March 2011) 1485-1500.
- [13] Chowdhuri A. K., Hossain R. A., "Design Analysis of an Automotive Composite Drive Shaft", International Journal of Engineering and Technology Vol.2(2), 2010, 45-48.
- [14] O. Montagnier, Ch. Hochard, "Optimisation of Hybrid High Modulus/ High Strength Carbon Fibre Reinforced Plastic Composite Drive Shafts", Materials and Design 46 (2013) 88-100.
- [15] M.R. Khoshravan, A. Paykani, "Design of a Composite Drive Shaft and its Coupling for Automotive Application", Journal of Applied Research and Technology, vol 10, Dec. (2013), 826-834.
- [16] Hamouda Almsan, "Investigation into Hybrid Carbon/Glass Fiber Reinforced Epoxy Composite Automotive Drive Shaft", Original Research Article materials and Design, Volume32, Issue 3, March (2012), Pages 1485-1500.
- [17] Secil Eksi, Akin O. Kapti, Kenan Genel, "Buckling Behaviour of Fibre Reinforced Plastic-Metal Hybrid-Composite Beam", Materials and Design 49 (2013) 130-138.
- [18] Ercan Sevkati, Hikmet Tumer, "Residual Torsional Properties of Composite Shafts Subject to Impact Loadings", Materials and Design 51 (2013) 956-967.
- [19] Jinguang Zhang, Rue Yang, Year Hu, Gulping Ding, Yan Xu, and Jiaying Niu, "Dynamic Characteristics Research of a Steel/CFRP Drive Shaft", Hindawi Publishing Corporation Advances in Mechanical Engineering Volume (2013).
- [20] R. Srinivasa Moorthy, Yonas Mistake and K. Sridhar, "Design of Automobile Driveshaft using Carbon/Epoxy and Kevlar/Epoxy Composites", American Journal of Engineering Research (AJER) e-ISSN : 2320-0847 p-ISSN : 2320-0936 Volume-02, Issue-10, pp-173-179, (2013).