DESIGN AND FINITE ELEMENT ANALYSIS OF HYBRID CARBON/GLASS FIBER-REINFORCED EPOXY COMPOSITE AUTOMOTIVE DRIVE SHAFT

By

MOHAMED A. BADIE M. SOLIMAN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirement for the Degree of Master of Science

February 2007

This work is dedicated to my family.
Parents, brothers, sisters and to my wife, son and daughter

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

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Chairman: **Elsadig Mahdi Ahmed, PhD**

Faculty: **Engineering**

Weight reduction, fatigue resistance, vibration damping and design flexibility to meet critical vibration characteristics are offered by substituting fibrous composites for conventional metals in power transmission shafts, which utilized in many applications including automotive. Strongly related to stiffness, the optimal design constrained by rotational frequency, torsional frequency and applied torque, which are to be traversed by increasing the critical speed, torsional stiffness and critical torque, respectively. However, composite drive shaft (DS) design is a problem of prescribed stiffness with the variables of layers material, thickness and stacking. Least cost can be achieved by using a hybrid of carbon/epoxy and E-glass/epoxy as carbon fibers with their higher specific stiffness, have comparatively high price. The main objectives are to study the effect of fiber orientation angles and stacking sequence on the natural frequency, buckling strength and fatigue life. Besides, the study of the torsional stiffness and failure modes of composite tubes, are included in

the objectives.

Finite element analysis (FEA) software has been used to predict the fatigue life of composite (DS) after linear dynamic analysis for different stacking sequence. Eigenvalue analysis used to investigate the effect of two design variables, namely the fiber orientation angle and layers stacking sequence on the bending natural frequency and buckling torque. Results from the numerically developed models are validated by solutions obtained from a close-form analysis of the DS. Experimental study on scaled woven fabric composite models was carried out to investigate the torsional stiffness.

Based on FEA results, it was found that the natural frequency increases with decreasing fibers angles. The DS has a reduction equal to 54.3% of its frequency when the orientation angle of carbon fibers at one layer, among other three glass ones, transformed from 0° to 90°. On the other hand, the critical buckling torque has a peak value at 90° and lowest at a range of 20° to 40° when the angle of one or two layers in a hybrid or all layers in non-hybrid changed in sameness. The layers stacking sequence has no effect on the critical speed (natural frequency) of DS but significantly affect buckling torque and fatigue resistance. In the investigated design, the best stacking sequence gave a buckling torque of 2303.1 Nm, while the worst gave 1242 Nm with a loss of 46.07%. Concerning the buckling, the measuring factor for the goodness of stacking sequence is a component in the bending stiffness matrix [D]. This component D_{22} is the normal bending stiffness along the hoop direction. Therefore, D_{22} specify the ability of DS material to deflect in radial direction or to (buckle). In addition, the coupling between twist moment and normal curvature appears as D_{16} and D_{26} components, has a substantial effect on both the buckling torque and natural frequency. Concerning fatigue, longer life of DS realized by locating ±45° layers together and inner mostly while locating 0°/90° layers together with 90° layer exposed to outside. Indeed, the stacking sequence of [±45,0,90] is the best for both fatigue and buckling resistance.

From the experimental work, composite tubes of fiber orientation angles of ±45° experience higher load carrying capacity and higher torsional stiffness. Specimens of carbon/epoxy or glass/epoxy composites with fiber orientation angles of ±45° show catastrophic failure mode. In a hybrid of both materials, carbon layers dominate the failure mode.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

REKABENTUK DAN ANALISIS UNSUR TERHINGGA TERHADAP GENTIAN HIBRID KARBON/KACA ACI PACU AUTOMASI BERTETULANG KOMPOSIT EPOKSI

Oleh

MOHAMED A. BADIE

Februari 2007

Pengerusi: **Elsadig Mahdi Ahmed, PhD**

Fakulti: **Kejuruteraan**

Pengurangan berat, rintangan lesu, peredaman getaran dan kebolehlenturan rekabentuk untuk memenuhi ciri-ciri getaran genting ditawarkan dengan mengganti kan komposit bergentian bagi logam lazim dalam penghantaran kuasa aci-aci, yang digunakan dalam pelbagai kegunaan termasuk automotif. Berkait rapat dengan kekukuhan, rekabentuk optimum dikekang oleh frekuensi pemutaran, frekuensi kilasan dan tork kenaan, yang akan direntasi dengan meninggikan kelajuan genting. Walau bagaimanapun, rekabentuk komposit aci pacu (DS) adalah suatu masalah kekukuhan tetap dengan variasi lapisan bahan, ketebalan dan tindanan. Kos terendah boleh dicapai dengan menggunakan karbon/epoksi hibrid dan E-kaca/epoksi kerana gentian karbon dengan spesifikasi kekukuhan lebih tinggi, mempunyai harga tinggi secara perbandingan. Objektif utama adalah untuk mengkaji kesan sudut orientasi gentian dan turutan timbunan atas frekuensi semulajadi, kekuatan melengkok dan hayat lesu. Selain itu, kajian ke atas kekukuhan torsion dan mod kegagalan tiub-tiub komposit termasuk dalam objektif.

Perisian analisis unsur terhingga (FEA) telah digunakan untuk meramal hayat lesu komposit (DS) selepas analisis dinamik lelurus bagi turutan tindanan berbeza. Analisis nilai eigen digunakan untuk menyiasat kesan dua pembolehubah rekabentuk iaitu sudut penghalaan gentian dan turutan tindanan lapisan atas frekuensi semulajadi lenturan dan tork lengkokan. Keputusan dari model yang terorak berangka disahkan dengan penyelesaian yang didapati daripada suatu analisis bentuk tertutup ke atas DS. Kajian ujikaji atas model komposit fabrik tenunan berskala dijalankan untuk menyiasat kekukuhan kilasan.

Berdasarkan keputusan FEA, didapati frekuensi semulajadi bertambah dengan pengurangan sudut gentian. DS mempunyai pengurangan sama rata sehingga 54.3% daripada frekuensinya apabila sudut orentasi gentian karbon pada satu lapisan, antara tiga gentian kaca, terjelma dari 0^o ke 90^o. Manakala, lengkok genting tork mempunyai nilai puncak pada 90^o dan terendah pada julat 20^o ke 40^o apabila sudut salah satu lapisan di dalam hibrid atau semua lapisan dalam bukan hibrid berubah dalam kesamaan. Turutan lapisan tindanan tidak mempunyai kesan ke atas kelajuan genting (frekuensi semulajadi) DS tetapi mempunyai kesan bererti ke atas tork lengkokan dan rintangan lesu. Dalam rekabentuk yang disiasat, turutan tindanan terbaik memberikan tork lengkokan 2303.1 Nm, sementara yang paling lemah memberikan 1242 Nm dengan kehilangan 46.07%. Berkait dengan lengkokan, faktor utama bagi kebaikan turutan tindanan ialah satu komponen dalam matriks kekukuhan lenturan [D]. Komponen D_{22} ini ialah kekukuhan lenturan normal sepanjang arah gegelang. Oleh itu, D_{22} menentukan kebolehan bahan DS untuk memesong dalam arah jejarian atau untuk (lengkok). Tambanan pula, penggandingan antara momen piuhan dan lengkungan normal yang muncul sebagai komponen-komponen D_{16} dan

$D_{26,}$ ada kesan nyata ke atas kedua-dua lengkok tork dan frekuensi semulajadi. Berkait dengan kelesuan, jangka hayat lebih panjang DS didapati dengan menempatkan lapisan ±45^o bersama dan pada kedudukan paling dalam manakala lapisan 0^o/90^o ditempatkan bersama lapisan 90^o terdedah ke luar. Dengan pasti, turutan tindanan [±45.0,90] ialah yang terbaik bagi kedua-dua rintangan lesu dan lengkokan. Dari kerja eksperiman, tiub-tiub komposit dari tindanan 45^o yang mengalami kapasiti menanggung beban yang lebih tinggi menunjukkan kekukuhan tork yang lebih tinggi. Spesimen-spesimen karbon/epoksi atau kaca/epoksi dengan tindanan ±45° menunjukkan mod kegagalan bencana. Dalam hibrid kedua-dua bahan, lapisan karbon menguasai mod kegagalan.

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I certify that an Examination Committee met on February 16 2007 to conduct the final examination of Mohamed Abdel Badie Mohamed Soliman on his Master of Science thesis entitled "Design and Finite Element Analysis of Hybrid Carbon/glass Fiber-Reinforced Epoxy Composite Automotive Drive Shaft" in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

Mohd Ramly Mohd. Ajir, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Mohd. Sapuan Salit, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Rizal Zahari, PhD
Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Mohd. Nasir Tamin, PhD
Professor
Faculty of Mechanical Engineering
Universiti Teknologi Malaysia
(External Examiner)

____

HASANAH MOHD. GHAZALI, PhD
Professor/Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 27 APRIL 2007

This thesis submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee are as follows:

Elsadig Mahdi Ahmed Saad, PhD
Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Abd. Rahim Abu Talib, PhD
Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Ermira Junita Abdullah, MS
Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

____
AINI IDERIS, PhD
Professor / Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 10 May 2007

DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Putra Malaysia or other institutions.

MOHAMED ABDEL BADIE MOHAMED SOLIMAN

Date: 20 April 2007

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