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Mechanical Testing of High Performance Vehicle Composite Flywheel for Optimal Performance

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Abstract: Flywheel energy storage systems employing light weight-high speed composite flywheel can be evaluated to replace the traditional heavy wheels in vehicles. The composite flywheel can provide extended operating life and significant reduction in weight and volume comparatively. This study describes the testing of a composite vehicle composite flywheel with emphasis on materials allowable test methods, design criteria and analysis techniques. The flywheel is a composite of an aluminium alloy hub, cast iron friction surface and a steel alloy gear rim resulting in compact, lightweight, high energy density structure. The study also describes the heat treatment processes to upgrade metallurgical and mechanical properties; including hardness test, tensile test, vibration analysis and dynamic balancing. The aluminium hub was solution treated and artificially aged, cast iron friction surface was annealed and the steel rim quenched and tempered. The components were assembled using high strength fasteners. A description of the experimental setup and a discussion of spin testing of the wheel up to 455 rpm (7.58 Hz) and 2,995 rpm (49.25 Hz) are also presented. A CSI 2120 portable dual channel vibration analyzer was used to conduct vibration analysis on the wheel and also a CSI ultraspec 8117 balancing kit was used to carry out dynamic balancing of the wheel.

Key words: Mechanical testing, high performance, vehicle, flywheel, optimal performance

INTRODUCTION

The flywheel technology for energy storage systems is gaining wider application in recent time. A light-weight flywheel is most applicable in automobiles in race cars. The drive is not only to improve energy storage but also to concurrently reduce the gross weight depending on the specific application for a given race car (Hawkins *et al*., 2000). Some of the major challenges in flywheel technology for the race cars include high-speed and bearing support that can meet the safe life design requirements, reliability and durability to end-of-life (Georage *et al*., 2000). In this study, the research is limited to the NDE of composite flywheel for replacement on a test automobile.

MATERIALS AND METHODS

Heat treatment of aluminium component: A very high performance in service is required of the aluminium component of the composite flywheel (JICA, 1982; Ajuwa, 1998). The aluminium component as cast is soft. The hardness of Aluminium component as cast obtained was 72 HBN using a standard control sample AA. To achieve the desired properties of the alloy an appropriate heat-treatment for the component was carried out. The strength of the component was tremendously improved by heat treatment.

Heat treatment 1: The aluminium sample was heat-treated to temper designation T6, i.e., solution treated and artificially aged (Ajuwa, 1998).

Heat treatment II: To heat-treat to temper designation T4, i.e., solution treated and naturally aged.

Heat treatment III: To heat-treat to temper designation T7, i.e., solution treated and stabilized.

Heat treatment of cast iron component: The friction surface was annealed to soften the cast iron so that it may be easily machined.

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Heat treatment of steel component: Quenching operation was carried out on the machined gear and test specimens to increase the hardness so that it can resist wear. It was then tempered to reduce brittleness, remove the internal stresses and finally toughened to resist shock.

RESULTS AND DISCUSSION

Hardness test result after heat treatment I (T6): The samples were then subjected to hardness test so that their physical properties can be compared to the control sample AA (a cast). The result of the hardness test for the sample is presented in Table 1. The hardness test result was 108 HBN (Brinell Hardness Number). It was observed that the colour of the component changed from silver-bright to light gray after solution treatment. It became dull grayish after artificial ageing.

Hardness test result after heat treatment II (T4): The result of the hardness test for the Sample is also presented in Table 1. It was observed for the sample test that the colour was light-grey after solution treatment but changed to dull-grey after 6 days, the hardness was increasing daily but at a lower rate towards day 6, the hardness tends to stabilize after the 4th day and cutting through the material shows that the grayness is only a surface effect.

Hardness test result after heat treatment III (T7): The result of hardness test for the sample is also presented in Table 1. The following observations were made the sample had the colour of a shade light grey after stabilizing and the hardness was stable between 96 and 99 Brinell Hardness Number (BHN). The plot of hardness versus number of days for the 3 samples presented in Table 1 is depicted in Fig. 1.

General observation:

- As cast hardness was too low at 72 HBN.
- The mechanical properties of the aluminium component were improved by heat-treatment operations.
- Artificial ageing gave the highest property improvement while natural ageing the lowest.
- The hardness level achieved with heat treatments I, II and III, was within the limits of specification (i.e., 75-80 HBN) according to the Japanese International Standard (JIS) H5202.
- The hardness value of heat-treated samples (i.e., 89 HBN, 108 HBN and 99 HBN) were higher.

Table 1: Results of Brinell Hardness (HB) test

	Hardness (HB)		
Period	Sample I	Sample II	Sample III
Day 1	78	107	96
Day 2	85	107	99
Day 3	85	107	99
Day 4	87	107	98
Day 5	88	108	97
Day 6	89	108	99
Heat treatment type	T4	T6	T7

Table 2: Hardness value for the cast iron sample

	Samples						
Detail	1st	2nd	3rd	4th	5th	Final AV	Remark
						188	Conforms with literature value
Average reading (HBN)	208	214	211	209	208	210	

Table 3: Hardness value for the steel samples

	Samples						
Detail	1st	2nd	3rd	4th	5th	Final AV	Remark
Average reading (HBN)	172	175	175	173	175	174	Conforms with literature value

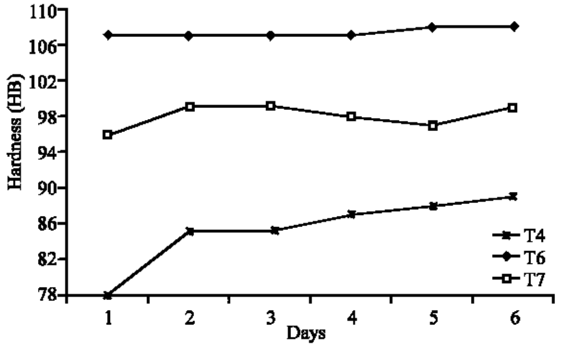


Fig. 1: Hardness Profile for Aluminium Samples after heat-treatment

Hardness test result after heat treatment of cast iron component: The hardness value was then determined as 211 HBN and the average reading taken as recorded in Table 2.

Hardness test result on gear rim: The hardness value was then calculated determined as 174 HBN and the average reading taken as recorded in Table 3.

Tensile strength: Tensile strength for aluminium component was determined as 273.75 N mm^{-2} and the elongation 1.6%. Also, the tensile strength for steel component was determined as 614.34 N mm^{-2} and elongation 14.8%.

Table 4: Tensile test result for aluminium and steel alloy test piece

Load (KN)	20	40	60	80	100	120	140	160	180	200
Extension (mm) (Steel alloy)	1.48	2.96	4.44	5.92	7.40	8.88	10.36	11.84	13.32	14.80
Extension (mm) (Aluminium alloy)	0.32	0.64	0.96	1.28	1.6					

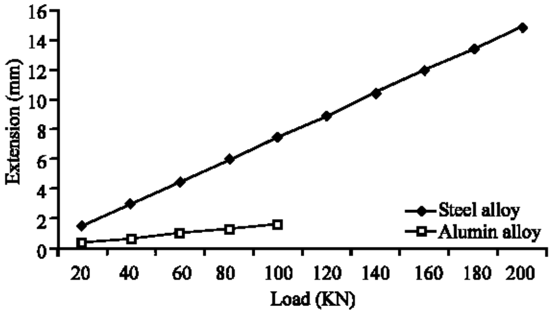


Fig. 2: The plot of load against extension for Aluminium and Steel Alloy

The proportional increase in load against extension was recorded during the pull to destruction, i.e., up to fracture and the graph of load against extension (or stress against strain) plotted for the material as in Table 4 and Fig. 2. The following results were obtained during the tensile test on the aluminium test piece. The result is also presented in Table 4 and Fig. 2.

The plot of load versus extension using data from Table 4 is shown in Fig. 2.

Vibration and balancing: Modern machines run at high speed. It is therefore, very essential that any rotating and reciprocating component part is completely balanced as far as possible. If a part is not properly balanced, dynamic forces are set up. These forces not only increase the loads on bearings and various members, but also produce unpleasant and even dangerous vibrations.

The tests also allow for material characterization testing for qualification of composite structures for automobile applications, including the race cars.

The flywheel was configured for spin testing in a vertical orientation, with the aluminium hub assembly providing the structural base for the cast iron friction surface and the steel alloy gear components mounted on a configured shaft. The shaft was designed for a two bearing support configuration. Experimental static and dynamic testing of the rim flywheel disclosed unbalance resulting in vibration. The vibration tests showed that it was possible to, to a certain degree, to balance the wheel and control the position of natural frequencies as regards the operating range of rotation velocities of flywheels (Hawkins, 2000; George, 2000; Kenny, 2001; Herbst *et al*., 2002).

Though the flywheel was designed to be inherently balanced by its geometry, however, due to the vagaries of production tolerances, there is no guarantee that there will not still be some small unbalance in the part. Thus, a vibration analysis and balancing procedure is applied after manufacture.

Vibration analysis of flywheel: During the weeks of July 3-21-2006, a composite flywheel was mounted and tested at the Nigerian National Petroleum Corporation (NNPC), Ekpan Test Device. The flywheel was mounted temporarily in the balance machine with the use of a precision mandrel clamped onto the outer diameter of the steel hub at the universal joint, which is supported in bearings (Inboard and Outboard) within the balancer. These two bearings are each mounted on a suspension, which has an inbuilt transducer that measures dynamic force. Plate 1 is a photograph of the flywheel mounted by the mandrel from the balance machine.

Vibration analysis was carried out on the flywheel using a CSI 2120 portable dual channel vibration analyzer, tachometer, speed laser sensor and CSI machinery management software (Vib View Platinum). The diagnostic facts for the test include:

- The measurement orientation is radial.
- There is excessive vibration at 1 × RPM.
- The 1 ×RPM is one of the biggest peels.

Dynamic balancing was carried out using CSI Ultraspec 8117 balancing kit. Plate 2 is a photograph of the arrangement.

Dynamic balancing of flywheel: The procedure used for the balancing operation was the single (1) phase balancing which involves one reference run, one trial run and one trim run.

Reference run was conducted to acquire data for the flywheel “As is RUN”. This measurement was necessary and taken before trial weight was placed on the weight plane. Multiple measurement points (IBH, IBV, IBA, OBH, OBV and OBA) were specified. The balance machine was then run at 455 RPM (7.58 Hz) and measurement taken at all points.

Analysis result at 455 RPM (7.58 HZ): The spectrum/ waveform and spectral peaks is presented in Fig. 3.

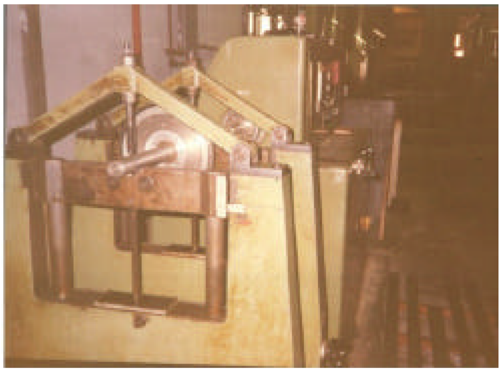


Plate 1: The flywheel mounted on balance machine

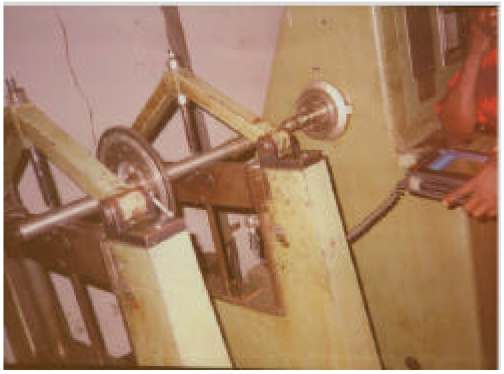


Plate 2: Taking vibration and balance data

However, the result at this frequency (7.58 Hz) did not indicate significant level of vibration and unbalance. The vibration spectral peaks are shown in Table 5.

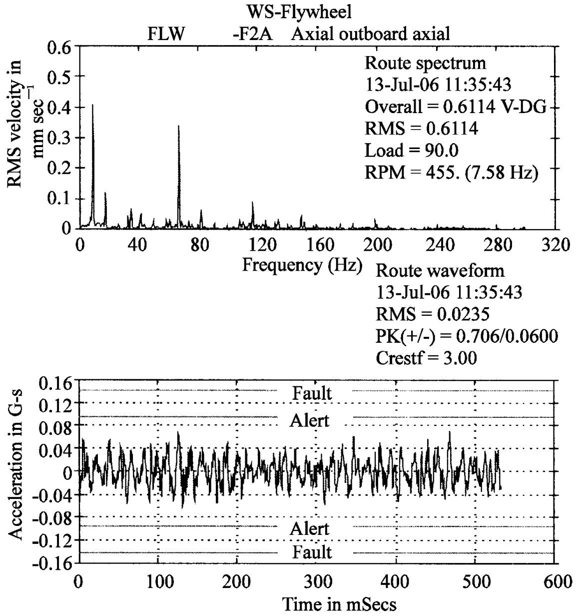
Analysis result at 2955 RPM (49.25Hz) before balancing: The same procedure was repeated at the speed of 2955 RPM (49.25 Hz) and measurement taken. The spectrum/waveform and spectral peaks are presented in Fig. 4.

At this frequency (49.25 Hz), the vibration spectrum showed evidence of spectral sidebands at intervals. The vibration spectral peaks are shown in Table 6.

The vibration spectrum indicated significant level of vibration and imbalance in the flywheel of the following orders:

Port F1V - Severity - 68%
Port F2V - Severity - 68%

These severities are evidence of the existence of imbalance in the flywheel as the CSI analyzer was set at 99%.



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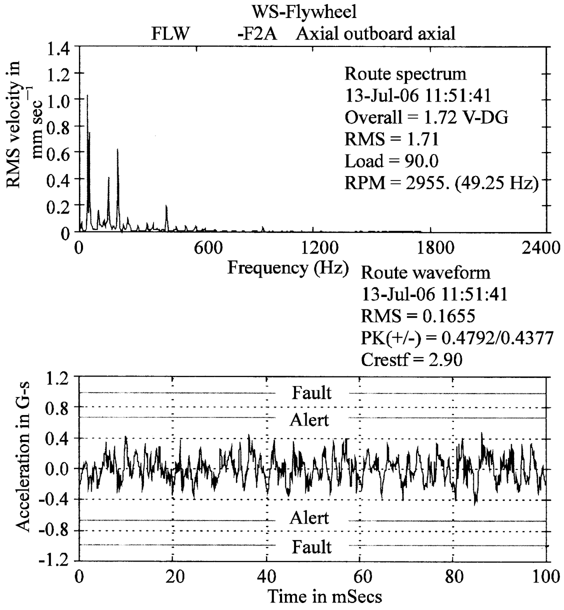
List of spectral peaks
**********************
Equipment: (WS ) FLYWHEEL
Meas. Point: FLW -F2A --> Axial Outboard Axial
Date/Time: 13-Jul-06 11:35:43 RPM= 455. Units = mm/Sec RMS
Peak Frequency  Peak    Order   Peak Frequency  Peak    Order
No.  (Hz)       Value   Value   No.  (Hz)       Value   Value
---- ---------  -----   -----   ---- ---------  -----   -----
1       7.23    0.0449  0.953   13     73.67    0.0273   9.714
2       8.67    0.4155  1.143   14     82.33    0.0759  10.856
3      12.95    0.0238  1.707   15    108.19    0.0300  14.266
4      17.33    0.1275  2.285   16    110.46    0.0288  14.566
5      32.50    0.0517  4.286   17    114.88    0.0249  15.149
6      34.65    0.0784  4.570   18    116.97    0.0938  15.425
7      41.16    0.0567  5.428   19    125.61    0.0289  16.564
8      49.83    0.0261  6.570   20    132.15    0.0233  17.427
9      58.48    0.0350  7.712   21    134.31    0.0360  17.712
10     60.62    0.0382  7.994   22    149.48    0.0452  19.711
11     67.15    0.3456  8.856   23    151.63    0.0301  19.995
12     69.18    0.0245  9.122   24    199.31    0.0321  26.283
Total mag subsynchronous synchronous nonsynchronous
0.5927     0.0449/1%        0.0486/1%        0.5890/99%
(Electrical = 0.00E+00/ 0% Floor = 0.0736 Spec Crest = 1.53)
Total mag subsynchronous synchronous nonsynchronous
1.6637     1.1666/49%       1.0775/42%       0.4959/9%
(Electrical = 0.00E+00/ 0% Floor = 0.3636 Spec Crest = 2.07)
```

Fig. 3: OBA Spectrum at 7.58 Hz

Table 5: Vibration Spectral peaks at 455 RPM (7.58 Hz)

Plane	Synchronous (mm s^{-1})
FIH (F1H)	0.0000
FIV (F1V)	0.0000
FIA (F1A)	0.0000
FOH (F2H)	0.1463
FOV (F2V)	0.0389
FOA (F2A)	0.0486

Analysis result at 2955 RPM (49.25Hz) after balancing: The same procedure was repeated at the speed of 2955 RPM (49.25Hz) and measurement taken. The spectrum/waveform and spectra peaks are presented in Fig. 5.



List of spectral peaks
****

Equipment: (WS) FLYWHEEL
Meas. Point: FLW -F2A --> Axial Outboard Axial
Date/Time: 13-Jul-06 11:51:41 RPM = 2955. Units = mm sec^{-1} RMS

Peak No.	Frequency (Hz)	Peak Value	Order Value	Peak No.	Frequency (Hz)	Peak Value	Order Value
----	---------	-----	-----	----	---------	-----	-----
1	8.93	0.0813	0.181	13	226.43	0.0607	4.598
2	41.00	1.1638	0.833	14	248.32	0.1323	5.042
3	49.45	0.7746	1.004	15	256.27	0.0735	5.204
4	75.62	0.0303	1.535	16	301.18	0.0518	6.115
5	81.86	0.0265	1.662	17	347.00	0.0700	7.046
6	98.68	0.1920	2.004	18	376.97	0.0634	7.654
7	108.56	0.0623	2.204	19	396.05	0.0327	8.042
8	123.94	0.1038	2.517	20	445.97	0.2294	9.055
9	136.51	0.0872	2.772	21	495.65	0.0356	10.064
10	148.69	0.4862	3.019	22	543.88	0.0521	11.043
11	175.00	0.0624	3.553	23	593.54	0.0452	12.052
12	197.63	0.6371	4.013	24	940.48	0.0455	19.096

Total mag subsynchronous synchronous nonsynchronous
1.6637 1.1666/49% 1.0775/42% 0.4959/9%
(Electrical = 0.00E+00/ 0% Floor = 0.3636 Spec Crest = 2.07)

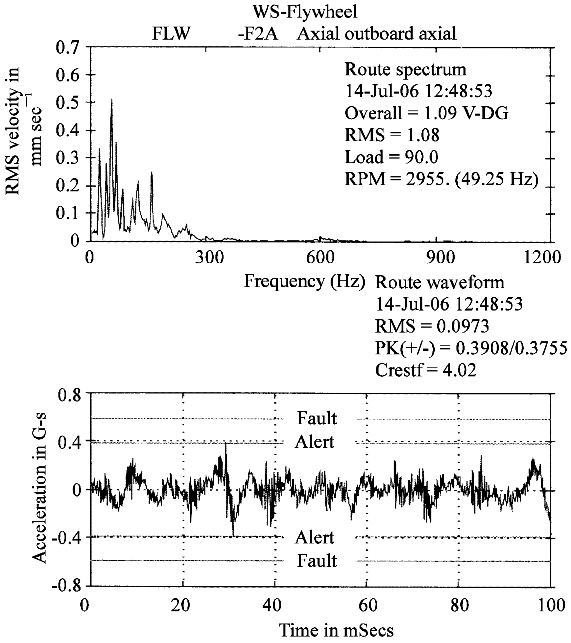
Fig. 4: OBA Spectrum at 49.25 Hz

Table 6: Vibration spectral peaks at 2955 RPM (49.25 Hz)

Plane	Synchronous (mm s^{-1})
FIH (F1H)	5.0337
FIV (F1V)	1.6373
FIA (F1A)	1.0078
FOH (F2H)	3.7200
FOV (F2V)	1.4598
FOA (F2A)	1.0775

Table 7: Vibration spectral peaks at 2955 RPM (49.25 Hz)

Plane	Synchronous (mm s^{-1})
FIH (F1)	0.2828
FIV (F1V)	0.2058
FIA (F1A)	0.0268
FOH (F2)	0.0000
FOV (F2V)	0.2937
FOA (F2A)	0.0000



List of spectral peaks
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Equipment: (WS) FLYWHEEL
Meas. Point: FLW -F2A --> Axial Outboard Axial
Date/Time: 14-Jul-06 12:48:53 RPM= 2955. Units=mm/Sec RMS

Peak No.	Frequency (Hz)	Peak Value	Order Value	Peak No.	Frequency (Hz)	Peak Value	Order Value
----	---------	-----	-----	----	---------	-----	-----
1	8.78	0.0497	0.178	13	136.31	0.0921	2.768
2	13.84	0.0398	0.281	14	145.80	0.0850	2.960
3	22.63	0.3356	0.459	15	158.36	0.2746	3.215
4	41.24	0.3334	0.837	16	171.29	0.0619	3.478
5	54.25	0.5457	1.101	17	180.95	0.0520	3.674
6	66.64	0.3902	1.353	18	188.58	0.1076	3.829
7	81.62	0.2082	1.657	19	191.27	0.1028	3.884
8	89.12	0.0460	1.809	20	201.09	0.0776	4.083
9	96.15	0.0606	1.952	21	228.94	0.0434	4.648
10	103.60	0.0826	2.103	22	238.88	0.0543	4.850
11	109.20	0.1559	2.217	23	248.80	0.0740	5.052
12	123.78	0.2503	2.513	24	255.94	0.0457	5.197

Total mag subsynchronous synchronous nonsynchronous
0.9793.4773/24% 0.0/0% 0.8551/76%
(Electrical = 0.00E+00/ 0% Floor = 0.4553 Spec Crest = 3.22)

Fig. 5: OBA Spectrum at 49.25 Hz

Table 8: Vibration result before and after balancing

Plane	V_{RMS} Before (mm s^{-1})	V_{RMS} After (mm s^{-1})
FIH	7.88	2.4000
FIV	2.86	0.5586
FIA	1.84	0.5879
FOH	6.00	2.16
FOV	6.41	1.91
FOA	1.71	1.08

Following balancing, vibration level decreased. Tooth mesh frequency harmonics became low. The vibration spectral peaks are shown in Table 7.

The vibration spectrum also showed decrease in velocity (V_{RMS}) after balancing as showing in Table 8.

Table 9: Detailed balance report for the flywheel

```
                                  Balance Report-Detailed
                                  14 JUL 06 12:03:09
                 JOB # : 001                User ID : Sheidi
                 Machine ID: FLW            Shaft #: 1
Machine Description: Flywheel
                 Station ID: Workshop
Results (all amplitudes in MM/SEC RMS )
                 Tolerance Specification = 2.5
Plane:                            1          1          2          2
MPT:                              IBH        IBV        OBH        OBV
SPD 1: 2955
Initial:                          7.88       2.66       6.00       8.41
Final:                            1.70       0.437      0.196      0.579
% Reduction:                      78.0       84.0       97.0       93.0
Number of trial runs = 1                                Number of trim runs = 1
Trial weights:
Trial run 1- Weight plane 1:                 13.00      (113)      0.00       (0)
Reference run data:
                                  IBH        IBV        OBH        OBV
SPD 1:
Magnitude:                        7.88       2.66       6.00       8.41
Phase:                            214        279        35         277
RPM:                              2869       2860       2876       2912
Trial run data:
                                  IBH        IBV        OBH        OBV
TR 1, SPD 1:
Magnitude:                        0.624      6.39       7.04       13.5
Phase:                            96         271        34         266
RPM:                              2871       2882       2891       2918
Balance Correction-Applied Weights
BAL. Corr. -Weight Plane 1:                  22.00      (106)      0.00       (0)
Trim run data (Correction Weights are Applied Weights):
TM 1, SPD 1:
Magnitude:                        1.70       0.437      0.196      0.579
Phase:                            78         194        267        168
RPM:                              2993       2999       3000       2999
```

Vibration data acquired after adding the correction weights revealed 88% drop in the overall vibration level. Analysis results for the reference run, trial run, correction weight and trim run are presented in Table 9.

CONCLUSION

The composite flywheel have been designed, fabricated and tested to validate the design and analysis tools and develop fabrication and assembly techniques for the full scale flywheel. Experimental study of properties, heat-treatment, vibration analysis and dynamic balancing was conducted. The composite wheel was made of AC1A Aluminium alloy hub machined from casting and heat treated to destination T6. The friction surface was of special heat-treated FG 220 cast iron alloy casting to withstand heat and pressure and it was attached to the hub using high-strength fasteners. The gear rim was made of heat-treated SC Mn 3 steel alloy of high-strength and hardness and attached to the wheel hub with 3 safety fasteners. Hardness test was carried out for the aluminium samples using the Light Deformation (LD) Tester with digital readout. The cast iron and steel alloy samples were tested for hardness using the steel ball indenter. Tensile test was conducted for Aluminium and steel alloy samples on a tensiometer and readings used to plot for load against extension. The test result conforms to standard. Vibration analysis and dynamic balancing was carried out on the composite flywheel using CSI 2120 portable dual channel vibration analyzer and CSI ultraspec 8117 balancing kit. The vibration analysis result at 7.58 Hz before balancing did not show significant level of vibration and imbalance. However, the vibration analysis result at 49.25 Hz produced a spectrum, which showed evidence of vibration at intervals. Vibration severity of 68% was shown on the vertical plane (Port F1V and F2V). Applying a trial weight, correction weight and a trim run weight effected balancing. After balancing, the overall vibration level decreased by 88%. The general approach to ensure quality of composite flywheel and to help in the certification of flywheels was briefly outlined. Dynamic test data from spin testing of the composite flywheel showed good performance from the system. Good agreement was found between the analysis and test data.

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