Description of TEAM Workshop Problem 24: Nonlinear Time-Transient Rotational Test Rig

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Abstract—A test rig for validating 3D nonlinear time-transient codes is presented. The rig, of configuration similar to that of a switched reluctance machine, is made of solid medium-carbon steel and mounted in a nonmagnetic cage which can rotate about a stainless steel shaft. The steel magnetization curve and conductivity have been measured. Various measured output quantities are presented for comparison with computer simulations.

GENERAL DESCRIPTION OF THE TEST RIG

The test rig consists of a rotor mounted on a nonmagnetic stainless steel shaft and a stator fixed inside a swinging nonmagnetic cage which can move relative to the shaft. The dimensions of the solid steel rotor and stator are shown in Fig. 1. The axial length is chosen to be 25.4mm, which should be small enough compared with radial dimensions to produce non-negligible 3D end effects. The stator poles are fitted with 350-turn coils, of dimensions as detailed in Fig. 2. The rotor is locked at 22° with respect to the stator, providing only a small overlap between the poles. A step voltage of 23.1V is applied to the coils which are connected in series and have a combined resistance of 3.09Ω . The resulting torque rise which would tend to align the stator and rotor poles is measured using a piezoelectric force transducer restraining the movement of the stator cage. The magnetic fields are high enough to significantly saturate the iron in the overlapping pole corners. Preliminary results under conditions similar to those described here are presented in [1].

The test rig is not design-specific for only this experiment but can potentially be of use for other types of experiments. The rotor can be set to any angle and different levels of saturation can be easily studied.

MATERIAL PARAMETERS

The conductivity of the EN9 steel used for the rotor and stator is measured on a sample of regular cross-section and found to be approximately 4.54×10^6 S/m. The *B*-*H* initial magnetization curve of the material is also measured. A Magnet-Physik Remagraph RE3 BH tester is used for measurements up to approximately 2T. Lucas A.V.S.D. provided measured values for the range 2T ~ 2.5T. The



Fig. 1. Dimensions of stator and rotor

combined B-H curve is shown in Fig. 3. A set of points taken from the curve is presented in Table I. It is worth noting that prior to these material measurements, the samples, rotor, and stator pieces are annealed after machining in order to homogenize the magnetic characteristics.

MEASUREMENT SYSTEM AND RESULTS

The test rig design offers a range of measurement quantities which can be compared with those obtained through computer simulations. A Kistler piezoelectric force link





Fig. 3. Measured initial magnetization curve

TABLE I			
Sampled points from $B-H$ curve			
Point	Н	В	
number	$(imes 10^4 \ { m A-t}/{ m m})$	(T)	
1	0	0	
2	00.400	1.413	
3	00.801	1.594	
4	01.601	1.751	
5	02.402	1.839	
6	03.203	1.896	
7	04.003	1.936	
8	04.804	1.967	
9	06.405	2.008	
10	08.007	2.042	
11	09.608	2.073	
12	11.210	2.101	
13	12.811	2.127	
14	14.412	2.151	
15	17.615	2.197	
16	20.818	2.240	
17	24.020	2.281	
18	27.223	2.321	
19	30.426	2.361	
20	33.629	2.400	
21	39.634	2.472	

restraining the swinging stator cage measures the force rise when the step voltage is applied, and is easily converted to a torque curve. The force link is calibrated in situ using a range of weights. A current shunt connected in series with the set of coils measures the rise in current. The coil current is considered as an unknown variable in the computer modelling. Only the coil voltage and resistance are known initial parameters. A search coil wrapped around a rotor pole at 8.7mm from the corner, as shown in Fig. 1, enables the measurement of the total magnetic flux. Lastly, a Hall probe is secured at a known position, shown in Fig. 4, in the air gap between the overlap of the stator and rotor poles. The reference point shown is the stator pole corner. The Hall probe measures a single component of the magnetic flux density (B_y in Figs. 1) and 4). It also serves as a check when a variable amplitude A.C. signal is used to demagnetize the rig before applying the step voltage. Figs. 5 through 9 show the measured step voltage, coil current, torque, search coil flux, and Hall probe flux density, respectively. As may be observed from Fig. 5, the experimental step voltage is not perfect. There is an initial overshoot of approximately 0.5V, which is disregarded in the authors' computer model. However, others may wish to use the actual measured voltage versus time. Sampled points of the voltage curve are shown in Table II.



Fig. 4. Hall probe location in air gap



Fig. 5. Measured step voltage waveform

SUGGESTED COMPUTATIONS AND DISCUSSION

Current, torque, rotor pole flux, and air gap point flux density measurements should all be compared with computer predictions. Since the size of the experimental curves included in this problem description may not be sufficiently detailed for accurate reading, Tables III to VI contain sampled points. These points are obtained from smoothed versions of the raw data. The actual raw data is readily available on request.







Fig. 7. Measured torque

Although the proposed problem has a relatively short axial length and would be better suited to 3D eddy current modelling, a 2D representation could be used to initially explore a few aspects of the problem. The choice of the time step and option to have a variable time-stepping



Fig. 8. Measured total flux in rotor pole



Fig. 9. Measured point flux density

scheme for computational efficiency is an obvious point of discussion. The size and order of the element in the skin of the iron may be of interest. The detail of the air gap mesh required for accurate force computaions can also be discussed. The periodicity property of the problem can be exploited to reduce the size of the model. Finally, for codes which do not incorporate external circuit connection, the current curve can be directly used as the input.

A complete set of all actual measured quantities can be supplied on request by email (eepna@ee.bath.ac.uk, D.Rodger@bath.ac.uk).

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References

 D.Rodger, N.Allen, H.C.Lai, and P.J.Leonard. "Calculation of Transient 3D Eddy Currents in Nonlinear Media - Verification Using a Rotational Test Rig". *IEEE Transactions on Magnetics*, vol.30(no.5):pp.2988-2991, September 1994.

TABLE II Sampled points from voltage curve		
Point	${ m Time}$	Voltage
number	(s)	(V)
1	0	0
2	0.0002	23.60
3	0.002	23.48
4	0.005	23.38
5	0.010	23.32
6	0.030	23.18
7	0.050	23.13
8	0.070	23.12
9	0.090	23.10
10	0.120	23.10
11	0.140	23.10

TABLE III		
Sampled poi	nts from o	current curve
Point	Time	Current
number	(s)	(A)
1	0	0
2	0.002	0.91
3	0.005	1.80
4	0.010	2.95
5	0.015	3.82
6	0.020	4.49
7	0.030	5.45
8	0.040	6.05
9	0.050	6.45
10	0.060	6.71
11	0.070	6.91
12	0.080	7.04
13	0.090	7.15
14	0.100	7.22
15	0.120	7.31
16	0.140	7.36
17	0.160	7.38
18	0.180	7.40
19	0.200	7.40
20	0.240	7.41
21	0.300	7.41

TABLE V Sampled points from rotor pole flux curve

Point	Time	Flux
number	(s)	$(\times 10^{-4} \text{ Wb})$
1	0	0
2	0.002	0.29
3	0.005	0.77
4	0.010	1.44
5	0.015	1.99
6	0.020	2.44
7	0.030	3.11
8	0.040	3.58
9	0.050	3.91
10	0.060	4.14
11	0.070	4.31
12	0.080	4.43
13	0.090	4.52
14	0.100	4.58
15	0.120	4.65
16	0.140	4.69
17	0.160	4.71
18	0.180	4.72
19	0.200	4.72
20	0.240	4.72
21	0.300	4.72

TABLE IV

Sampled points from torque curve		
Point	Time	Torque
number	(s)	(N.m)
1	0	0
2	0.002	0.02
3	0.005	0.17
4	0.010	0.39
5	0.015	0.68
6	0.020	0.96
7	0.030	1.48
8	0.040	1.90
9	0.050	2.24
10	0.060	2.48
11	0.070	2.68
12	0.080	2.82
13	0.090	2.93
14	0.100	3.02
15	0.120	3.11
16	0.140	3.17
17	0.160	3.19
18	0.180	3.21
19	0.200	3.22
20	0.240	3.22
21	0.300	3.22

TABLE VI Sampled points from magnetic flux density curve

Point	Time	Flux density
$\operatorname{numb}\operatorname{er}$	(s)	(T)
1	0	0
2	0.002	0.07
3	0.005	0.21
4	0.010	0.38
5	0.015	0.53
6	0.020	0.64
7	0.030	0.82
8	0.040	0.94
9	0.050	1.03
10	0.060	1.09
11	0.070	1.14
12	0.080	1.17
13	0.090	1.19
14	0.100	1.21
15	0.120	1.23
16	0.140	1.24
17	0.160	1.25
18	0.180	1.25
19	0.200	1.25
20	0.240	1.26
21	0.300	1.26