

DESIGN OF THE LEVER AND REACTION BEAMS FOR THE UK TORQUE MACHINE

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Abstract: The IMEKO - XV, World Congress provided the opportunity to describe the design of the first UK national torque calibration machine. Torque is realised by a lever-deadweight system with the transducer under calibration mounted vertically. The vertical deadweight forces are converted to a horizontal torque using castored pulley bearings mounted on a reaction beam positioned underneath the lever beam. The two beams are of identical material construction, consisting of high modulus carbon fibre tubes with stainless steel end fittings and central boss.

To provide confidence in the design and modelling of the composite lay-up to optimise material properties, a detailed finite element (FE) analysis of the lever beam and reaction beam were undertaken. The FE analysis considered the beam structures both singly and as a sub-assembly. The results predicted the deflection of the beam under self-weight and at the full torque application. In addition, the frequency responses of the beams and sub-assembly were analysed.

During commissioning of the machine the lever beam and reaction beam deflections will be measured and the frequency response established to close the design loop with the FE analysis.

Keywords: 2 kN·m static torque machine, FE analysis, Carbon fibre beams

1 INTRODUCTION

In common with other national standard torque calibration machines, torque will be realised in the UK's first national standard torque machine by a lever mass system. However, in this torque machine the transducer under calibration is mounted vertically [1]. The target uncertainty budget of the machine is 1×10^{-5} over the majority of its operating torque. To convert the vertical deadweight forces to a horizontal torque vector, castored pulley bearings are mounted on a reaction beam positioned below the lever beam. The two are constructed from identical material combinations: a pair of parallel 2 m long high modulus carbon fibre tubes with stainless steel end fittings and central boss.

In consultation with NPL's Centre for Materials Measurement and Technology (CMMT) the lay of the carbon fibre to provide the required mechanical properties and thermal expansion was optimised. Reiterative design and evaluation of the carbon fibre lay was carried out by the supplier of the composite tubes, Hunting Engineering, and their data compared with NPL's CoDA software [2].

Once the material lay had been optimised the respective mechanical properties were used as input to the FE analysis. The beams were analysed both singly and as a sub-assembly to establish self-weight deflection and deflection resulting from a force of 1 000 N (the maximum deadweight load), applied to either one end of the lever beam or both. In addition, an analysis to establish the post-dynamic (forced dynamic) frequency response of the individual beams individually and beams/air bearing sub-assembly was carried out. For the target uncertainty budget of the machine it was calculated that the deflection contribution for lever beam and reaction beam should not exceed 1,0 mm and 1,1 mm respectively.

In addition, a forced vibration study was undertaken predicting the relative importance of the different modes of vibration. Both the modal frequency and the forced vibration study provided necessary input to the design of the central pivot air bearing damper.

The results of the FE analysis will be compared with practical experimentation during commissioning of the torque machine to close the loop with design.

2 THE ANALYSIS

2.1 Material Analysis

The lay of the carbon fibre was designed to minimise thermal expansion and optimise the performance of the beams. The principle longitudinal fibres provide both rigidity for bending moments and a near zero coefficient of thermal expansion. Hoop wound fibres of various orientations maintain the longitudinal fibres, provide additional torsional strength (required for the reaction beam) and provide strength in the areas of machining for the fixing pins for the stainless steel central boss and end fittings. Additionally, the hoop wound fibres provide a reduced thermal expansion in the radial direction. The carbon fibre was wound on to a 45,00 mm mandrel. The wound tube was then ground along its circumferential length to a final diameter of 77,30 mm with a epoxy resin sealant coat. The CoDA predicted mechanical properties of the individual tubes are shown in Table 1 and were in a good agreement with the properties predicted by Hunting Engineering. These properties were confirmed by proof tests performed by Hunting Engineering.

Table 1. Predicted properties of carbon fibre tubes

Longitudinal modulus	171 756 MN·m ⁻²
Transverse modulus	64 614 MN·m ⁻²
Shear modulus	22 057 MN·m ⁻²
Longitudinal Poisson's ratio	0,276
Transverse Poisson's ratio	0,104

2.2 Deflection of beams and loading

Cosmos/m is a general purpose finite element code. The effects of loading the beams were analysed for the individual beams, and for the complete air bearing/beam sub-assembly. The analysis was to establish self-weight deflection and deflection resulting from a force of 1 000 N (the maximum deadweight load), applied either to one end of the lever beam or at both ends. The weight of the lever beam was calculated to be 10 kg and the reaction beam including the castored bearing estimated to be a maximum of 60 kg. The dynamic frequency response of the beams was also evaluated.

Figure 1 presents the final full 3D model that was generated and shows little simplification in the modelling of the beams or stainless steel central boss and end fittings. The beams were meshed using 8 node brick elements and these were attributed orthotropic properties. An advantage of this approach is the ability to alter the model to account for changes in the composite properties and any design changes. The lever/reaction beam sub-assembly used a simplified central air bearing; however, this did not compromise the analysis as the compliance was high.

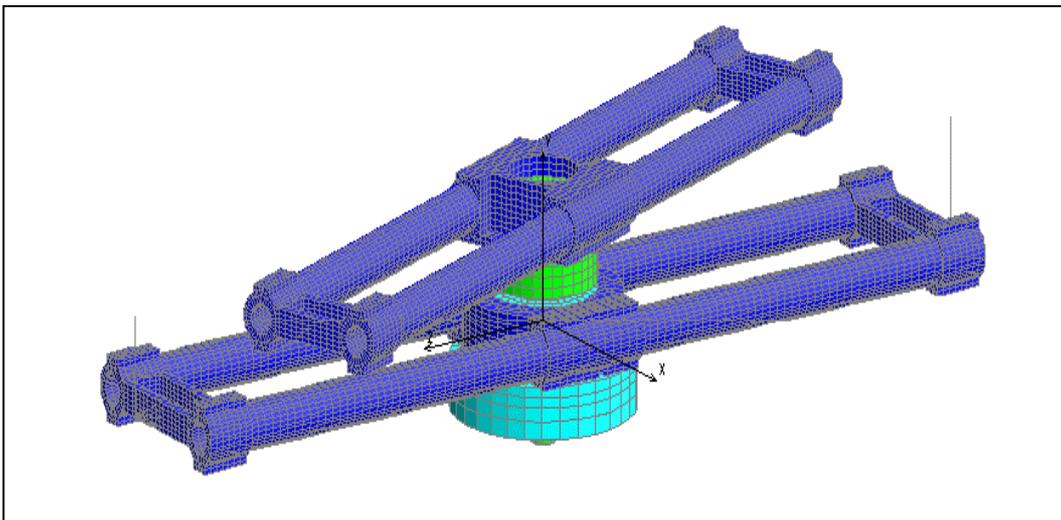


Figure 1. Lever and reaction beam sub-assembly model

Results from the original design of the lever/reaction beam sub-assembly indicated modal vibration frequencies that were considered to cause instability. Table 2 shows the beam deflections for the original design; the values were considered to be excessive. Further modelling indicated that by increasing the spacing between the tubes of the reaction beam by ~50 mm a reduction in the vertical spacing between the lever and reaction beams of ~40 mm could be achieved. This re-design offered improvements in both modal vibration frequencies and resultant deflections of the beam sub-assembly.

Table 2. Deflection of the original lever and reaction beams design, as shown in Figure 2.

Results Quantity	Lever Beam	Reaction Beam
Force Only		
x direction deflection	0,390 mm	0,51 mm
y direction deflection	0,012 mm	-1,08 mm
Resultant deflection	0,390 mm	1,196 mm
Mass Only		
x direction deflection	0,0017 mm	0,0065 mm
y direction deflection	-0,058 mm	-0,503 mm
Resultant deflection	0,058 mm	0,500 mm
Force and Mass		
x direction deflection	0,390 mm	0,513 mm
y direction deflection	-0,070 mm	-1,583 mm
Resultant deflection	0,396 mm	1,67 mm
Von-Mises Stress	29,23 N·mm ⁻²	26,23 N·mm ⁻²

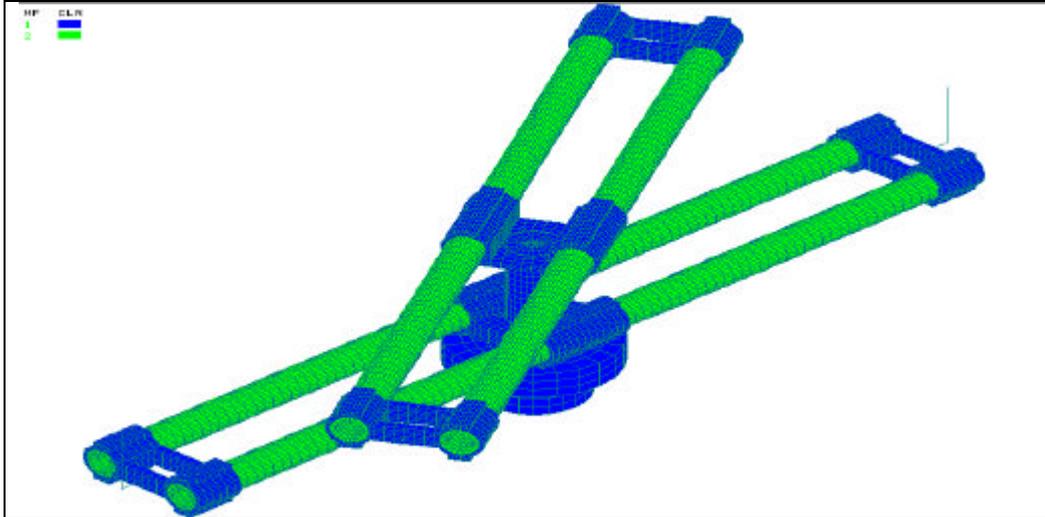


Figure 2. Original lever and reaction beam sub-assembly model

The stainless steel central boss and end fittings were modelled as a linear, isotropic material with a Young's modulus of 190 GN·m⁻² a Poisson's ratio of 0,29 and a density of 7,8 x 10³ kg·m⁻³. The composite sections were modelled as a linear orthotropic material with the modulus values and longitudinal Poisson's ratio as quoted in Table 1 and a density of 1,56 x 10³ kg·m⁻³.

In the individual beam analyses, the bearing bore of the central stainless steel boss was fully constrained whilst, for the sub-assembly, the lower face of the reaction beam was fully constrained.

2.3 Dynamic Excitation

A forced vibration study was carried out, where an acceleration was applied at the nominal level of $1 \text{ mm}\cdot\text{s}^{-2}$ and 1 % of critical damping between 0 Hz and 250 Hz. This was done in the three orthogonal directions.

3 RESULTS

3.1 Beam deflection

For the preferred beam sub-assembly design, the static analysis calculated both deflection and stresses, as shown in Table 3. The Von Mises stress level distribution is shown in Figure 3; the example shown considers the reaction beam at 1 000 N load plus gravity. Von Mises stresses analysis provides an overall impression of the stress level within the lever and reaction beams under the various loading conditions.

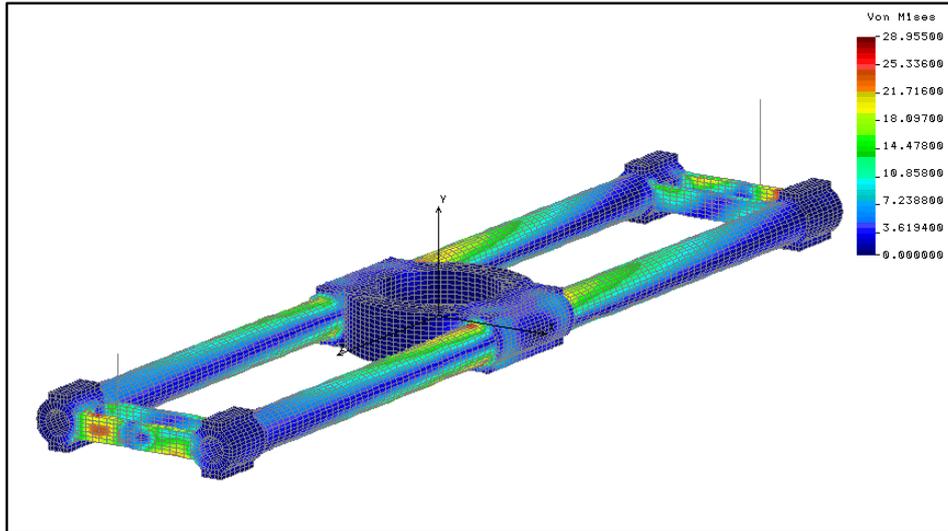


Figure 3. Von-Mises stress levels ($\text{N}\cdot\text{mm}^{-2}$) in reaction arm – load both ends with gravity considered

Results for the deflection of the lever beam and reaction beams under the various model conditions are presented in Table 3.

Table 3. Deflection of the lever and reaction beam.

Results Quantity	Lever Beam	Reaction Beam
Force Only		
x direction deflection	0,140 mm	0,34 mm
y direction deflection	0,007 mm	0,60 mm
Resultant deflection	0,140 mm	0,70 mm
Mass Only		
x direction deflection	Negligible	0,002 mm
y direction deflection	0,036 mm	0,037 mm
Resultant deflection	0,036 mm	0,039 mm
Force and Mass		
x direction deflection	0,140 mm	0,34 mm
y direction deflection	0,036 mm	0,90 mm
Resultant deflection	0,150 mm	1,01 mm
Von-Mises Stress	$10 \text{ N}\cdot\text{mm}^{-2}$	$29 \text{ N}\cdot\text{mm}^{-2}$

The beam deflection results show the benefit gained by the re-design. For the lever beam an improvement of 38 % in deflection was calculated (a factor of 6,6 times better than the target deflection specification of 1,0 mm) whilst, for the reaction beam an improvement of 60 % in deflection was calculated (approximately 8,5 % better than the target specification of 1,1 mm). The effect of applying load to only one end of the lever beam was reflected in half the overall deflection of the beam.

3.2 Modal Analysis

Modal analysis of the individual beams and the beams/air bearing sub-assembly showed fundamental resonance up to mode 14. Figure 5 provides typical examples of the modal analysis of the beam sub-assembly for the mode 1 and mode 12 models

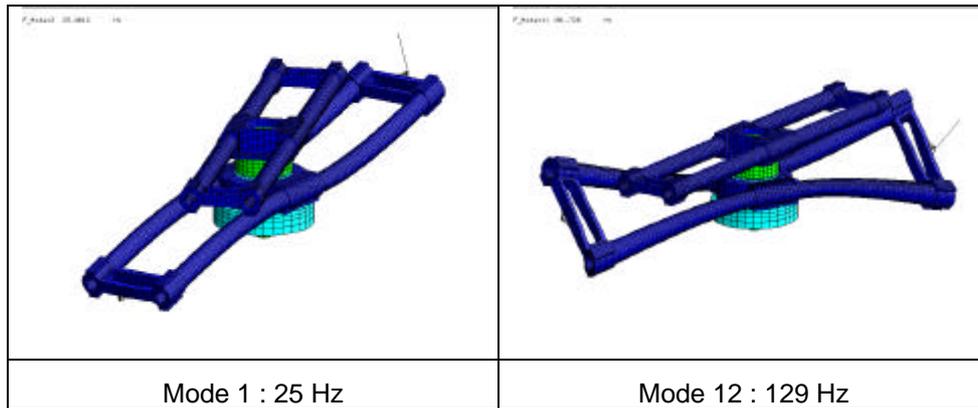


Figure 5. Examples of modal analysis results

The modal analysis showed that the dynamic response of the re-designed beam sub-assembly had increased the fundamental vibration frequency by 39 %. This increased vibration frequency provided enhanced stability of the beam sub-assembly and was considered to be above the natural frequency vibrations of the most common torque transducers that would be subject to calibration. In addition, this modal data provided useful information to the design of the air bearing assembly and, in particular the damper system required to eliminate the polar inertia of loading the beam sub-assembly.

3.3 Post-dynamic response (Forced Dynamic Response)

An example of the post dynamic response is shown in Figure 6.

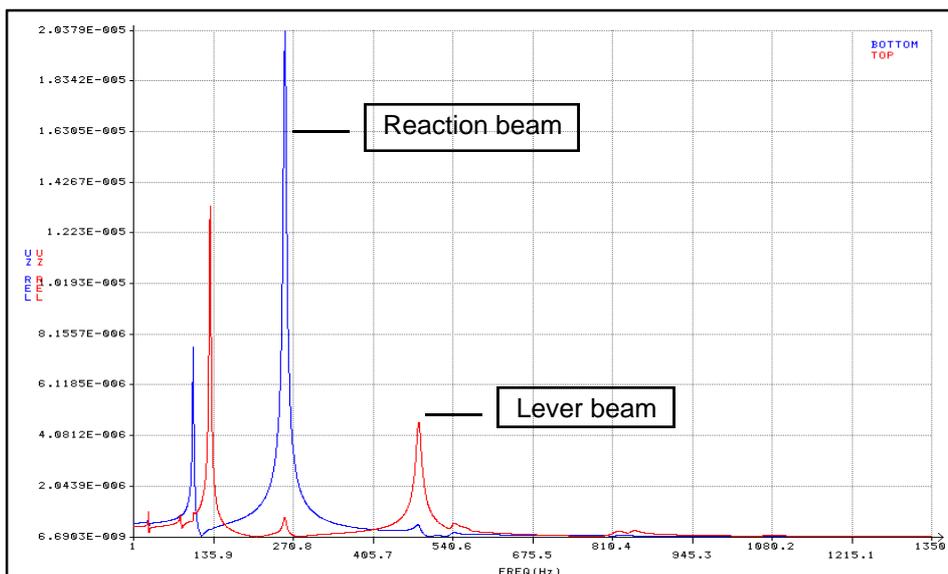


Figure 6. z direction forced response – 1 mm·s⁻² input in z direction

Figure 6 plots the relative displacement response in mm, i.e. the amplitude of vibration (y axis) against the frequency of excitation (x axis) for each beam within the sub-assembly. These results will

be used to validate the FE model against experimentation to demonstrate the importance of modelling during the design phase of the torque machine. This relationship between FE modelling and experimentation will provide additional confidence in design technique for future design improvements and development of this 2 kN·m torque standard calibration machine.

4 CONCLUSIONS

The FE analysis of the deflections of the final design of the beam sub-assembly showed the following:

- For the lever beam an improvement of 38 % in deflection was calculated compared to the initial design. This represents a factor of 6,6 times better than the target deflection specification of 1.0 mm.
- For the reaction beam an improvement of 60 % in deflection was calculated compared to the initial design, approximately 8,5 % better than the target specification of 1,1 mm.
- The effect of applying load to only one end of the lever beam was reflected in half the overall deflection of the beam. Practical experimentation will be carried out to confirm the analysis.
- These improvements were shown to be due to increasing the spacing between the tubes of the reaction beam by ~50 mm which enabled the vertical spacing between the lever and reaction beams to be reduced by ~40 mm.

The FE modal analysis showed that the dynamic response of the re-designed beam sub-assembly had increased the fundamental vibration frequency by 39 % and would provide additional stability to the beam sub-assembly.

Vibration experimentation will be carried out to compare with the post-dynamic response analysis.

Experimentation will provide a detailed relationship between practise and theory to close the design loop and demonstrate the usefulness of FE modelling, at the design stage, to predict performance of such critical sub-assemblies.

ACKNOWLEDGEMENT

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