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Fluid-structure interaction of the Jaguar XK8 convertible car roof

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Abstract: The designer of convertible vehicles needs to consider the acoustical properties, quality of the interior environment, fatigue life and the aesthetic integrity of the flexible roof. Each of these concerns is affected, to a greater or lesser extent, by the interaction of the flexible roof material and its supporting structure with the aerodynamic loading on the material. For many convertibles, the roof quickly settles into a deformed shape for which the roof's internal forces are in equilibrium with the aerodynamic loading.

The use of mathematical modelling can reduce the amount of time spent using experimental methods to assess a large number of design alternatives. A better understanding of the problem is obtained in the computational approach due to the increased amount of information which is gathered as part of the calculation. Also, the approach can be used at the concept stage of a product as the lengthy and costly build of a physical model is not required until later in the design cycle.

The current research investigates the flow-induced deformation of the Jaguar XK8 convertible roof using a numerical method. A computational methodology is developed that entails the coupling of a commercial Computational Fluid Dynamics (CFD) code with a third-party structural solver. The computed flow-structure interaction yields stable solutions, the aerodynamically loaded flexible roof settling into static equilibrium. The flow-structure interaction is found to yield a static deformation to within 1% difference in the displacement variable after three iterations between the fluid and structural codes. The methodology is also shown to be robust even under conditions beyond those likely to be encountered. The full methodology could be used as a design tool. However, the present work demonstrates that reasonably accurate predictions, to within 20%, are possible using only a single iteration between the fluid and the structural codes.

Keywords: *Fluid-structure interaction, Computational methodology, Coupling of codes, Membrane deformation.*

1. INTRODUCTION

A mathematical model of the fluid–structure interaction of a convertible roof under aerodynamic loading was sought by Jaguar. A methodology has been developed and validated using a model approach by Knight (2003). This paper details the use of this computational tool with the complex shape of a real car. The Jaguar XK8 is used in the current work with the overarching aim of enabling a better understanding of the convertible roof's behaviour. This will assist in the future design and analysis of flexible vehicle hoods subject to aerodynamic loading.

A background to the modelling of flexible surfaces/materials is presented, followed by a representative formulation of the current problem. Thereafter, the computational approach is described beginning with the construction of the surface and volume meshes, which include geometric simplifications. The computed flow about the vehicle is then detailed. A third-party structural solver that is capable of handling the complex geometry of the convertible hood is used in our approach (Choong, 2002). The coupling of this to the commercial CFD code is presented including the software interfacing strategy. The results of the computational methodology are presented for various configurations. Finally, some conclusions are offered along with possibilities for future work.

2. PROBLEM FORMULATION

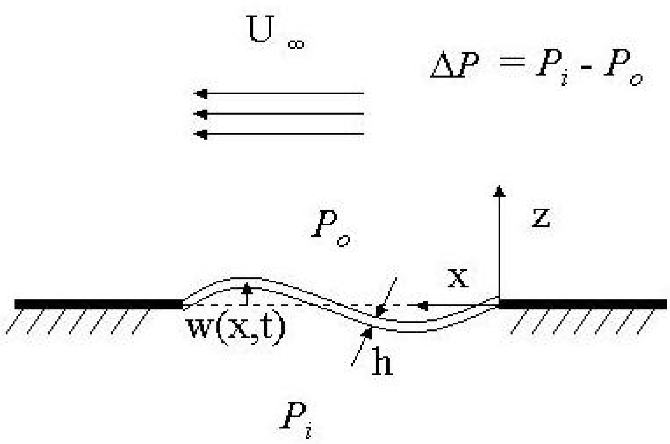


Figure 1. Schematic of the underlying principle used in the formulation of the problem.

Consider the deformation of a two-dimensional flexible surface subjected to a forcing pressure as shown in Figure 1. According to Lucey *et al* (1997), the governing equation for a this flat thin flexible surface is

$$\rho_m h \frac{\partial^2 w}{\partial t^2} + D\frac{\partial w}{\partial t} + B\frac{\partial^4 w}{\partial x^4} - (T_0 + T_I)\frac{\partial^2 w}{\partial x^2} = \Delta P \qquad (1)$$

where $w(x,t)$ is the wall displacement perpendicular to the x direction, t is the elapsed time, ρ_m and h are the material density and thickness. D is the damping constant, B is the flexural rigidity, T_0 and T_I are the pretension and induced tension terms respectively, whilst ΔP is the fluid pressure difference between the upper and lower surfaces of the flexible wall. Equation 1 assumes one-dimensional motions of the flexible surface, which is a line in two-dimensional space. The full form of the governing equation includes the fluid shear-stress loading acting parallel to the x direction. This is omitted in the current work as it is at least an order of magnitude smaller that the normal stress in the present problem, wherein a pressure distribution across the membrane is present.

In the present investigation we are interested in deformations with large (non-linear) amplitudes and the effects of pressure gradients including boundary-layer separation. To make the problem tractable, we follow the approach typical of sail design, for example see Cyr & Newman (1996), and omit the time-dependence in Equation 1. We also omit the flexural rigidity term from Equation 1 so that the objective is then to solve

$$-\left(T_0 + T_I\right)\frac{\partial^2 w}{\partial x^2} = \Delta P \qquad (2)$$

using a procedure which iterates towards a deformed static equilibrium. The induced tension, T_I is a function of displacement, w, so that Equation 2 is non-linear. By using a membrane, the motion of the flexible wall can be characterised solely by the consideration of surface points and thus *w(x)* defines the boundary of the fluid flow relative to the undeformed membrane surface. In the current approach, *w(x)* is a displacement in the vertical axis and the solution is assumed to be steady-state settling to static equilibrium after a certain period of time, so that the structural restorative forces balance the transmural pressure force applied. Equation 2 demonstrates the principle of the formulation in this paper. The actual implementation of the principle embodied in Equation 2 for the geometrically complex case of flow over a car roof is performed using a dynamic relaxation finite element method to calculate the left hand side of Equation 2.

3. MESH GENERATION

A surface file that described the geometry of the Jaguar XK8 convertible was created using the Rhinoceros surface modelling software (McNeel & Associates, 2000), which uses Non-Uniform Rational B-Splines (NURBS) to describe the vehicle's external or wetted surface. This was achieved by joining two files, one for the body and one for the hood. The surface file of the body was mirrored and a smooth underbody created according to the outer rim of the shell beneath the car.

The surface of a full-scale clay model of a Jaguar XK8 hood was digitally scanned by Jaguar using a CMM machine and translated into an IGES file. The IGES file contained a series of splines representing the traverse of the laser measuring equipment. This detail was mirrored and interpolated onto a grid by the structural program to create a list of co-ordinates describing the surface of the hood. The data points were imported into Rhinoceros and a surface generated as shown in Figure 2. This approach for generating the surface eased the coupling methodology. The co-ordinates at the edges of the roof remained fixed, so that the roof surface could be replaced easily by a revised shape. The surface description of the hood was joined to the surface file of the body and the wheel arches and side windows were then filled in to create a closed volume or solid body file.

The flow domain about the vehicle was created by a Boolean difference between the solid body of the vehicle and a box according to the dimensions of the test section at the MIRA wind tunnel. The outlet section of the fluid domain was extended and symmetry applied in the longitudinal streamwise plane. The surfaces of the hood, body and tunnel were exported as a separate stereolithography (STL) files with an tolerance of 0.1mm for the roof surface and 1mm for the car body and wind tunnel. The STL files of the hood and Jaguar body with wind tunnel boundaries were imported into the ICEM volume mesh generation software. Using these tolerances without a minimum edge length and a reference cell size of 1m in the far field for the fluid domain gave a coarse tetrahedral mesh, which could be solved at relatively low computational expense. This served to aid development of the methodology as a proof of concept wherein a large number of iterations between the fluid and structural codes could be needed. An example of the volume mesh near the body is shown in Figure 3.

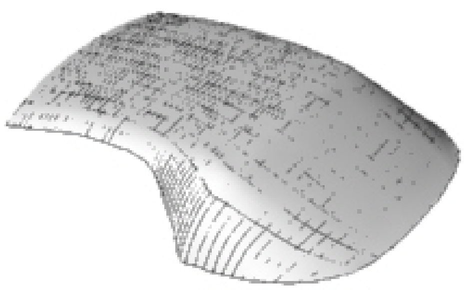


Figure 2. Surface description of XK8 hood.

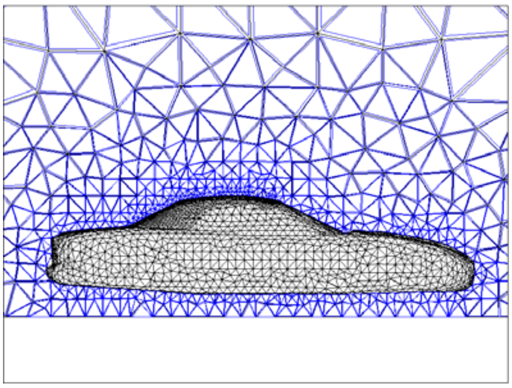


Figure 3. Volume mesh around XK8 centreline.

4. FLOW FIELD CALCULATION

The mesh was imported into StarCD and boundary conditions applied at the inlet, outlet and symmetry plane. A flow velocity of 36 m/s (130km/hr) was set at the inlet boundary. MARS discretisation, SIMPLE algorithm and the high Reynolds number RNG k-ε turbulence model with wall functions were used (Computational Dynamics, 1997). This turbulence model with Reynolds Averaged Navier-Stokes equations are noted to be inadequate in accurately capturing separation in these type of applications but are used as a compromise between accuracy and computational expense in this proof of concept study. The resulting pressure field in the longitudinal centreline plane is presented in Figure 4.

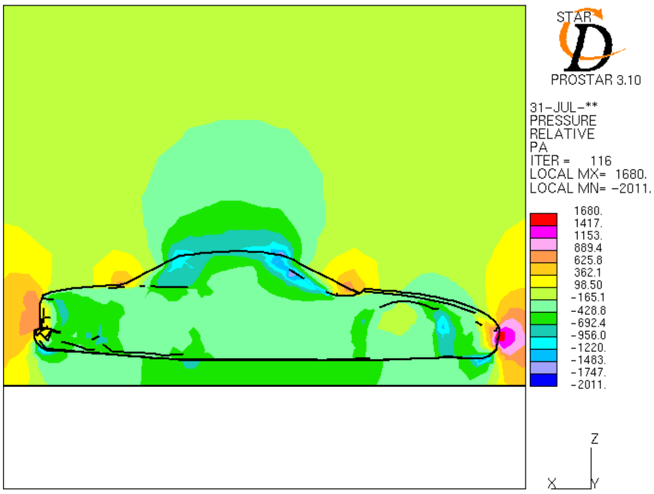


Figure 4. Pressure field in the longitudinal centreline plane of the XK8.

The pressure field can be seen to show most of the typical flow characteristics around vehicle. However, the mesh used in Figure 4 did not capture separation from the rear bar of the roof. Separation is known to occur from the surface of the XK8 hood (Knight, 2003) and is difficult to predict computationally unless there is a steep geometric gradient such as a sharp corner. Separation has been accurately captured from a curved surface using a model approach (Knight, 2003), but the same mesh resolution for the real car application would require an estimated 10 million cells. Also, the IGES file containing the surface of the hood did not appear to capture the geometric severity of the ridge at the rear bar, which was evident on the real car.

5. STRUCTURAL DATA ACQUISITION

The roof of a convertible vehicle is a composite structure consisting of three layers; inner layer, padding and outer layer. Only the deformation of the outer layer is required in the fluid-structure methodology. The structural behaviour of the padding and inner layer will be affected by the motion of the outer layer. This may have an effect on the outer layer but is considered to be negligible. The structural solver therefore only incorporates the outer layer, which is assumed to behave like a membrane.

A structural solver written by Choong (2002) is used in this work. The code uses a one-dimensional finite element approach and dynamic relaxation method to solve the displacement variable (Lewis, 2001). A fuller description of the code and its internal operations is given by Choong (2002). The code also incorporates pre-tension. Measurements of strain were taken along various sections of the hood by marking the unstrained fabric in the hood open position and then closing the hood so that the fabric is strained. The procedure was repeated a number of times to obtain an average and then converted to stresses using the methods of Choong (2002). Approximate values of 2000 N/m in the streamwise and 500 N/m in the spanwise direction were found using this approach. The Jaguar roof material is made up of two series of fibres, which are aligned perpendicular to each other. The fibres are nearly straight in one direction, which is referred to as the warp direction (Hepple, 1984). The material is manufactured by weaving fibres perpendicular to these, which is referred to as the weft direction. The fibres are then bonded to each other in a resin, which does not allow rotation or movement of the fibres relative to each other. The process of weaving requires a longer length of fibres in the weft direction over that in the warp direction for a given distance. Thus, the fibres in the weft direction tend to yield more readily under tensile loading. Therefore, the material has different mechanical properties in the warp and weft directions and at angles to these directions (Hepple, 1984). In the current work, we only measure the deformation of the membrane with the warp direction aligned to the flow. Material properties of 234,000 and 74,000 N/m in the warp and weft directions, respectively, were used as obtained from uni-axial experimental measurements by Choong (2002). These were assumed to be similar to anisotropic measurements and used as such in the structural solver. The resulting computed deformation of the roof, using the pressure field obtained by the CFD calculation, was found to have a maximum displacement of 13.9mm.

6. COUPLING OF CODES

Figure 5 shows the coupling strategy and software used in the approach. The deformation from the structural solver was fed back into the surface mesh generator using an interface according to Figure 5. This process was performed manually and continued to loop or iterate until there was a less than 1% difference in deformation at every data point on the roof. This small change in deformation between iterations was assumed to confirm a statically stable coupled equilibrium. The process of remeshing for each iteration is suitable for this low resolution proof of concept approach. However, a form of mesh deformation could be a more suitable approach where accuracy with large computational expense is required.

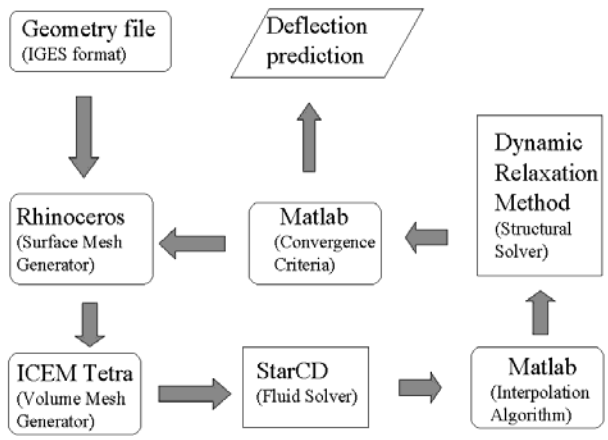


Figure 5. Coupling strategy and software used in the methodology.

7. RESULTS

7.1 Centreline

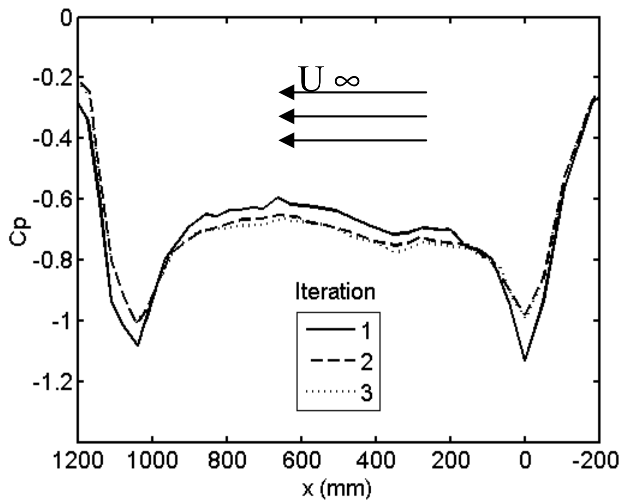


Figure 6. Pressure distributions along the longitudinal centreline of the Jaguar XK8 for each cycle of the codes.

The pressure distributions and resulting profiles along the longitudinal centreline of the Jaguar XK8 are shown in Figures 6 and 7 respectively. The pressure has been non-dimensionalised, using the freestream velocity, to give a co-efficient of pressure (Cp) in Figure 6. Also, it is useful to note in Figure 7 the datum is at the top of the windscreen where the convertible roof starts and flow is from right to left. The suction peaks in Figure 6 are seen to reduce after the first iteration owing to a reduction in the geometric severity, which is caused by the roof as it 'balloons' outwards. However, the overall negative pressure acting on the roof is larger as found in the model approach of Knight (2003).

The suction peak at the rear of the roof is deemed to be greater than reality due to the difficulty in accurately capturing separation in the computation. However the effect is assumed to be relatively small given the overall pressure acting on the roof. The second and third iterations are seen to show very similar pressure distributions, which is reflected in the resulting structural computation shown in Figure 7.

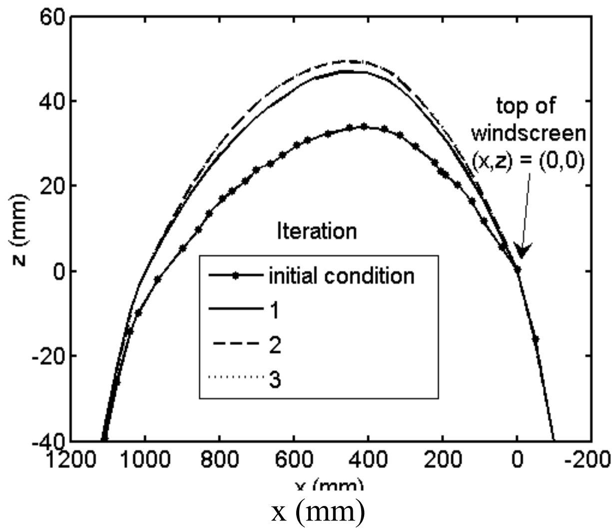


Figure 7. Profiles along the longitudinal centreline of the Jaguar XK8 for each cycle of the codes.

The initial profile also shown in Figure 7, is seen to have ripples, which is reflected in the pressure distribution shown in Figure 6. The maximum deflection point after three iterations lies 475 mm from the front edge of the hood and is 16.6 mm vertically displaced from that using no aerodynamic loading. This compares with 13.9 mm after a single iteration, an increase of 19%.

7.2 Surface

The final deformed shape of the hood can be seen in Figure 8, which is coloured according to vertical displacement the scale of which is in mm.

The hood can be observed to have negative vertical deformation near the side edges. This is because the material is being stretched upwards denting the fabric inwards relative to the original profile, which is supported by padding.

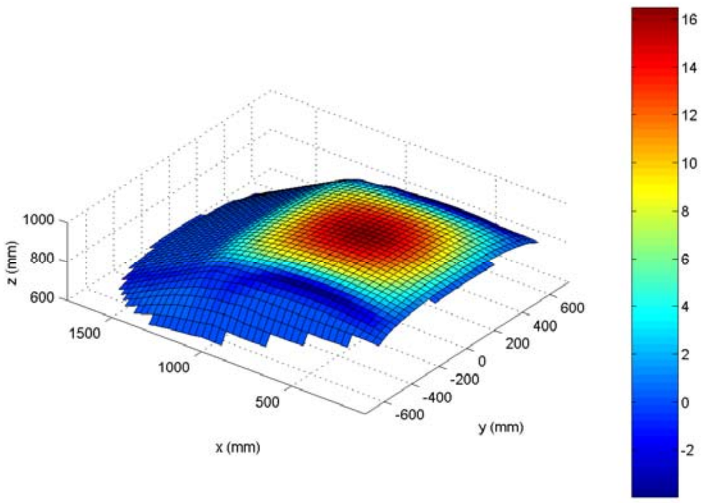
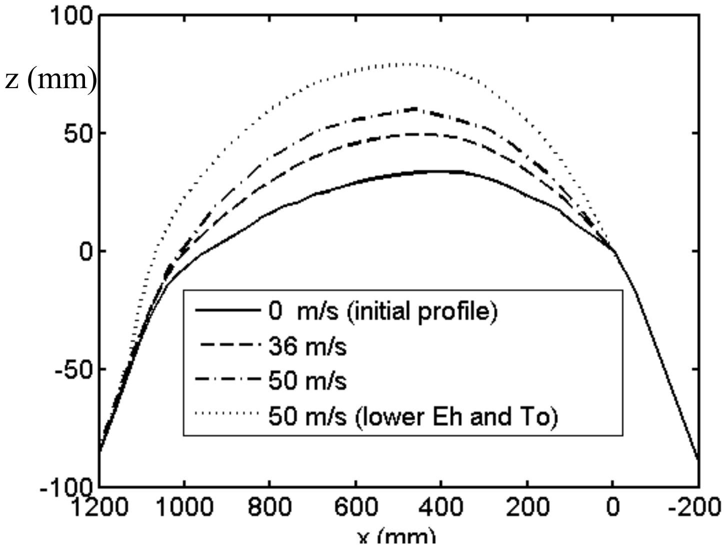


Figure 8. Deformed shape of the hood after 3 iterations.

7.3 Other configurations

In addition, two further coupled simulations were run using a wind speed of 50 m/s. The first used the same material properties and pre-tensions used in the simulation at 36 m/s. The second used material properties that were reduced by nearly 50% to 120,000 N/m in the warp and 40,000 N/m in the weft directions, which correspond to streamwise and spanwise directions respectively. In addition, the level of pre-stress in the warp direction was reduced by 50% from 2kN to 1kN and kept at 0.5 kN in the weft direction.



These changes in parameters were made so that a larger deformation was created. Both cases converged to statically stable equilibria after three iterations confirming the use of the methodology for this application. The final deformed shape along the longitudinal centreline of the Jaguar XK8 roof using the various parameters is shown in Figure 9 that has the same layout as that used in Fig. 7.

Figure 9. Converged profiles using various configurations.

The maximum displacement after 3 iterations was found to be 29.7 mm using 50 m/s and 42.4 mm with the reduced material properties and pre-tensions. This compares with deformations of 26.1 and 36.5mm, respectively, after a single iteration of the fluid-structure methodology. This results in increases of 13.8% and 16.1%, respectively.

8. CONCLUSIONS

A fluid-structure interaction methodology has been developed and found to be robust for the real car application studied herein. Furthermore, the model continued to function even when material properties were relaxed and wind speed increased to give larger deformations of the roof structure beyond conditions expected to be encountered. All of the fluid-structure interactions proved robust, yielding a converged statically stable equilibrium after three cycles between the codes. The importance of parameters such as material properties, slackness or pretension and the use of accurate geometrical data is noted to be highly influential on the overall predicted deformation. These factors can have a more significant influence than the modelling assumptions made in the methodology itself.

The methodology could be applied to any vehicle shape to provide an accurate description of pressure on, and stresses in, the hood. However, for engineering purposes, whereby a number of design alternatives are to be assessed, a simple fluid-structure coupling is believed to be sufficient to provide qualitative results within 20% of that obtained using a fully coupled solution of 3 iterations. This approach would be better suited to applications of large amplitude displacements such as that encountered in sail design or deployment of a parachute.

The structural solver used in the real car application could be extended to include the use of models that better represent the structure of real convertible roofs. This would require the modelling of the padding and inner membrane. More challenging is the development of a fully coupled computational model for the fluid-structure interaction that would simulate the dynamic behaviour of the roof in non-equilibrium conditions.

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