Gearbox explosion effects modelling

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This paper is a summary of an investigation into the structural response of a marine gearbox when subjected to an oil mist explosion, using the DYNA3D structural modelling tool. The computer model of the complex gearbox structure was simplified to allow scoping studies aimed at evaluating whether the structure can withstand the loading pressure. The joint strengths in the model were calculated using simple bolt rules converted to critical failure stresses. The simulations demonstrated that a relatively simple approach gives good guidance to the likely structural response. They also give an insight into ‘what if’ studies whereby trade-offs in the structure can be explored to improve the survivability of the gearbox and hence increase the safety factor. Areas for further development are described.

INTRODUCTION

There has been a concern within the UK Ministry of Defence (MoD) for some time that a bearing failure within marine gearboxes may lead to a critical mixture of oil and air in the form of a mist, which is susceptible to combustion. The loading from this combustion process could then cause the gearbox structure to fail, leading to potential injury and loss of life. An incident of this nature happened in HMS Illustrious in 1986, causing a structural failure of the gearbox and a fire in the machinery space.

This incident raised an issue concerning the nature of the combustion loading and an understanding of the subsequent structural response. In particular, there was no capability to simulate this type of event and to determine whether the existing design rating is sufficient to withstand the combustion loading.

The aim of this study was to obtain a loading function from the combustion of the oil mist mixture, to evaluate the subsequent structural response and to indicate whether the structure could withstand the load. The loading function was determined using a simple combustion model for the oil mist (OEP_80 lubricating oil), determined by Fluid Gravity Engineering Ltd (FGE) in a separate study. This loading function consisted of a pressure/time history, which was used as input into the structural model.

The investigation was intended to be a scoping study to identify the influence of major structural features on its subsequent response, rather than attempting a full description of the extremely complex gearbox structure and components. The paper describes the techniques used, the main assumptions and a series of sensitivity runs to gauge the effect of various assumptions on the results. These results are discussed and potential future areas of work are outlined.

MARINE GEARBOX STRUCTURE

Structural information

The design drawings showed that the gearbox is an extremely complex structure as illustrated in Fig 1, particularly in its internal component structure. These drawings were converted into simplified IGES files, which were suitable for transfer into TRUEGRID, the mesh generator for the structural hydrocode DYNA3D.

For this process to occur, various assumptions were made to simplify the problem without, hopefully, neglecting key aspects, which could significantly influence the structural response. Therefore the following assumptions were made which were justified considering the nature of the scoping study:
The internal components were neglected, as they would not greatly affect the structural integrity of the gearbox when loaded by the pressure due to the combustion.

The fore and aft plates were considered to be much stronger than the top and side plates and all the plates were bolted together. They were therefore defined as single plates of a given thickness, defined by the webbing across them. The effect of this thickness on the structural response was investigated. This greatly simplified the structural model with consequent benefits in computer run-time.

The drain tank was neglected for this study since the drawings indicated that the drain tank structure was relatively solid compared to the rest of the gearbox. It would also complicate the simulations, as they were full of oil, thereby complicating the structural loading process. In addition a narrow fairly-long pipe connected the drain tank to the main gearbox. It is recognised that this may need a more detailed analysis in future studies. For this study there was also little dimensional information for the drain tank.

The boundary of the drain tank was assumed to be a rigid surface, since this was considered the worst case scenario in loading the rest of the structure.

The dimensions of the gearbox were assumed to be the worst-case condition (i.e., minimum machined thickness for the frame and minimum tolerances for the plates were used).

The joints (i.e., bolted plates) were simplified to failure under a critical stress condition defined by standard static bolt strengths and number of bolts. Therefore the finite element mesh was concentrated on resolving this aspect of the structural response.

- The gearbox structure was assumed approximately symmetrical from the drawings supplied so that only half the structure was simulated.

SIMULATION STRATEGY AND SET-UP OF GEARBOX STRUCTURE

Methodology
The basic methodology used in the simulations was to split the problem into two parts whereby the loading is calculated and applied to a structure. This has been demonstrated as a very robust and accurate technique, where there is little fluid/structure interaction. The first portion calculates the loading resulting from the oil mist explosion in the form of a pressure v time 'load curve'. This information was acquired from Fluid Gravity Engineering (FGE) under a related MoD programme, using a simplified analytical approach. The model predicted a peak absolute pressure of $9.4 \times 10^5$ N/m$^2$ (9.4 bar) which, taking into account the size of the gearbox, resulted in a typical flame speed in the 20 m/s region. This resulted in a pressure rise time of 0.076 s to a peak overpressure of $8.4 \times 10^5$ N/m$^2$ (8.4 bar), where overpressure is defined as the pressure above atmospheric pressure. Since the gearbox structure is relatively small, this load curve was applied throughout the internal structure.

The structural modelling tool used for these simulations was the public domain version of the explicit Lagrangian hydrocode DYNA3D, which originated from Lawrence Livermore Laboratories. DYNA3D is used world-wide for structural modelling application and features sophisticated contact and joint options as well as the ability to describe many types of materials, including metals, ceramics, glass etc.

DYNA3D has several different options for types of elements that may be used in a simulation, such as bricks or shells. Due to the complexity of the gearbox structure, using blocks would have dramatically increased the number of elements, since there should be a reasonable number through the plate thickness to resolve the material strength. This would dramatically increase the run time and, hence, the cost of the simulation, without enhancing the solution accuracy. Since many of the external plates were relatively thin, shell elements were used to reduce the complexity and the run-time of the problems. This would also allow more scoping runs to explore the effects of parameter excursions on the solution.

Shell elements are thin plates with no real thickness when first defined, but a thickness can be applied to them during the mesh generation stage. This allows a plate of any thickness to be created and does not have the problem of creating a large number of elements. One of the most important aspects of the simulations was the ability to accurately resolve the plate strengths when under the pressure loading. This was achieved by having several integration points through the shell thickness. These points act similarly to having elements through the thickness, and enable accurate resolution of the plate strength. However, it should be recognised that shell elements do not have an in-plane stress component and are therefore an approximation. The
The general mesh set-up for the gearbox structure is illustrated in Fig 2. It should be noted that in the graphical representation of the structure there are gaps before any loading. This is due to the intersection of two thin shells, which graphically (using GRIZ) have zero thickness at all interfaces between parts, giving the appearance of a gap. However, in the model calculation the thickness of the plates is correctly represented.

The simulations were run to a relatively long time-scale (ie 0.1s) which, in an explicit hydrocode, can result in extremely long run-times, since the time step control is dependent on wave propagation. However, in the loading regime considered in the gearbox, structural wave propagation effects have little bearing on the structural response. DYNA3D contains a feature called dynamic relaxation, whereby the loading can be applied in a quasi-static manner, resulting in a much larger time step size. This reduces the run-times of the calculations without unduly affecting the accuracy of the results. A typical run-time for the DYNA3D calculations in this study was about three-to-four hours on a 32 processor Silicon Graphics Origin System at Fort Halstead.

Calculation of joint strengths
Once the basic gearbox structure was complete, the separate sections that had been generated had to be joined together. In DYNA3D this is achieved using contact surfaces called slidelines. A slideline is a line of nodes along an interface that have been selected and given certain instructions about how to behave in certain impact scenarios. For the gearbox simulations a ‘tied-break’ slideline was used, which allowed values to be set for the force under which the nodes on it would fail in tension and shear. Since the sections were all joined together using bolts, the failure values that were entered for the slideline were calculated from the known quasi-static strength values for the bolts that are used in the construction of the real gearbox. The procedure for calculating these failure stresses is illustrated below in an example on one of the joints in the gearbox:

Using an M12 bolt with a core diameter of 9.853mm and a yield strength of $784 \times 10^6$N/m$^2$

Cross-sectional area of bolt $= \pi (9.853/2)^2 = 76.25 \text{mm}^2$

Force to fail for a single bolt $= 76.25 \times 784.0 \approx 60 \text{kN}$ (consistent with BS4395-1)

On a joint with 14 bolts $= 60 \times 14 = 840 \text{kN}$

The area applied over $= 0.06 \times 1.046 = 0.06276 \text{m}^2$

Failure stress $= 840 \text{kN} / 0.06276 = 134.0 \times 10^3 \text{N/m}^2$

This process was used to calculate the values to apply to all of the relevant slidelines, that were joining sections together in the gearbox. In the basic set-up there were five ‘tied-break’ slidelines and all but two of them had different failure values. This was due to the varying number of bolts on each joint in the technical drawings. The same failure stress was used for the tensile and shear values in the slidelines. Thus the simulations attempted to use all the available information from the technical drawings to minimise the number of assumptions.

SIMULATION RESULTS

Scoping runs
The procedure adopted in the simulations was to perform a selected number of scoping runs which were designed to explore some of the extremes in the model to ensure it was functioning correctly. For example, the joint strengths were set to a very high value so that under the combustion loading the structure would be stressed but would never fail. This served as a useful check that all the slidelines and joints were functioning correctly in the model. The results illustrated that the structure did deform, but did not fail, as shown in Fig 3. While this is not conclusive evidence, it does give additional confidence in the methodology. In addition, very simple joint problems were run where the applied loading rose up to the critical failure value. The joints failed when the loading stress was the same as the defined failure stress.

Effective Stress

Fig 2: Initial mesh set-up on DYNA3D

Fig 3: Structural stress distribution with high joint strengths
Effect of end plates

One of the assumptions made in the gearbox structure was the thickness of the end plates. In reality these plates had thick diagonal webbing of steel bars which would significantly strengthen them. In the simulations it was decided to run the structure with the minimum end-plate thickness and a maximum end-plate thickness corresponding to the webbing thickness. This was considered consistent with an initial scoping study. This resulted in the end plates being 12mm and 66mm respectively. In addition an intermediate value of web thickness of 25mm was run.

For the total applied pressure of $9.4 \times 10^5$ N/m$^2$ (9.4 bar), the minimum end-plate thickness (ie 12mm) and the calculated joint strengths, the structure failed along the joints as shown in Fig 4. Whilst this is a prediction, it is instructive to compare qualitatively with the known incident on the Illustrious, as shown in the photograph. It can be observed that the failure appears to have taken place along the joints, which appear to be the weak part of the structure. One should be a little cautious, however, since the gearbox in HMS Illustrious is significantly larger than a typical marine gearbox and thus there are issues of scale with the combustion loading as well as differences in the structure.

When the simulation was repeated with the 66mm-thick end plates, the structure still failed along the joints, but the deformation of the end plate was significantly larger, due to bulging effects (Fig 5). The same pattern was observed when the end plates were 25mm thick.

Effect of pressure loading

Whilst the above simulations predicted that the gearbox structure would fail under the predicted combustion loading, it was vital to ascertain that the gearbox would survive up to its design rated pressure of $7 \times 10^5$ N/m$^2$ (7 bar). The simulation was repeated using the same gradient of pressure rise but reducing the peak total pressure to 7 bar. The result shows that the structure with the calculated joint strengths used previously does deform, but does not fail (Fig 6).

Fig 4: Structural failure using calculated joint strengths and 12mm-thick end plates compared to the Illustrious gearbox incident

Fig 5: Failure of structure using calculated joint strengths and end plate thicknesses of 66mm

Fig 6: Structural deformation loaded to 7 bar design rated pressure
It is worth noting that finding the actual threshold for failure of the gearbox is not necessarily straightforward, since it depends on a critical relative displacement of the nodes along the interface. These will move anyway when the structure deforms due to the representation of the plates by shell elements. Therefore, it can become a subjective judgement by looking at stresses, positions of interfaces etc, unless the simulation is run to much longer time-scales.

Sensitivity of structural response
The simulations described above gave insight into the general behaviour of the gearbox structure and the relative behaviour of different plates and interfaces within the structure. This revealed that the behaviour of the end plates was quite an influence in controlling the behaviour of the rest of the structure. To explore this further, a simulation was performed whereby the end-plate joints to the fore and aft plates were made much stronger than the other joints, which were kept at the original joint strengths. The results show that the structure now fails along one of the central plates at a longer time (Fig 7). This demonstrates that, by changing certain aspects of the structural response, one can affect the behaviour of the overall response. This starts to raise the possibility of improving the gearbox design to withstand a greater pressure, for example.

A final feature investigated was an evaluation of whether the joints failed under tension or shear, or both. This was achieved by setting one of the critical stresses high and keeping the other at the calculated value. This demonstrated that although there were tensile forces present, the shear force dominated the failure of the structure.

DISCUSSION
The investigation has predicted that a typical marine gearbox structure cannot withstand the loading from the combustion of the OEP_80 lubricant, based on new information relating to peak pressures provided by recent combustion modelling studies. However, the structure can withstand pressures up to its design rating of 7bar total pressure. This has been achieved using a relatively simple analytical combustion loading model and a simplified structural description of the gearbox. This has proved sufficient for sensible scoping studies focused on addressing the real problem and has provided a good foundation for future, more-detailed studies concerning the structural response.

At present, the study does not include the effect of the drain tank or the pipes that connect it to the rest of the structure. The drain tank, in particular, is a feature that may influence the nature of the structural response and should therefore be considered in a future study. In addition there has been no account taken of any vents at any time in the system. Current developments on the combustion model may soon allow this to be considered in terms of the total vent area.

Although there is no validation of a real event for a marine gearbox, the features predicted in the modelling are exhibited in a related real event observed in the Illustrious. This gives some confidence in the approach and vindicates some of the necessary assumptions made in the simplification of the structural model.

An issue requiring further investigation is the methodology used to simulate the behaviour of the joints in the failure process. When the mesh resolution along the interfaces was changed, the time for the structure to fail tended to increase, since the stress field around the interfaces was resolved better. Although this did not affect the basic results, it would affect the threshold of the critical combustion load required to cause the structure to fail.

The combustion model used for the analysis was simplified in the sense that there was very little data for the higher level alkanes (ie, above C22), in terms of boiling points, specific heat capacity, specific enthalpy etc. Obtaining these would alter the loading conditions and hence the structural response. Whilst it is difficult to perform the experiments on the higher level alkanes, it is possible to calculate these properties using state of the art molecular dynamics modelling techniques. This would give added confidence in the loading on the structure and start to tie down some of the assumptions made.

An exciting possibility that could emanate from this investigation is to look at ‘what if’ studies by analysing trade-offs in certain parts of the structure on its overall response. This could be expanded to explore different design options for the structure in terms of increasing its resistance to the combustion load. While it may not be practical to redesign the gearbox, it may be that relatively-simple modifications greatly increase the safety margins and therefore minimise the possibility of injury to the marine engineers in the event of an explosion.

This investigation has illustrated the power of integrating the combustion model and structural modelling in terms of providing a much improved understanding of the effects of an explosion within a marine gearbox. It also demonstrates that to achieve a reasonable fidelity within
the models does not require attention to every possible detail in the processes operating. Thus the approach is extremely powerful in giving meaningful guidance in terms of pragmatically addressing the problem at hand.

CONCLUSIONS
The simulations predict that this marine gearbox loaded by a pressure from the combustion of the OEP_80 lubricant would fail structurally. They also predict that the structure of the gearbox can withstand a pressure of $7 \times 10^5 \text{N/m}^2$ (7bar), consistent with its design rating. The study has demonstrated that DYNA3D has a capability for the simulation of complex structures loaded by oil combustion products. The models developed for this gearbox can be used to evaluate different options in increasing its resistance to the combustion loading. More data for the higher-level alkanes should be obtained as input for the combustion model through established molecular dynamics modelling. The models developed for the marine gearbox should be used to explore options for increasing its resistance to the combustion loading.

REFERENCES

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