Simulation of a folded airbag inflating underwater with IMM method

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Abstract. Folded airbags have a wide range of applications in underwater salvage. Considering the influence of water pressure and inflation parameters, whether the airbag can be rapidly and steadily inflated is the key problem. Numerical simulations of the airbag can be used as a powerful tool to reduce the development time. To enable the behavior of the flotation bag to be accurately modeled, a combined Euler-Lagrange analysis was carried out in the finite element software MSC.Dytran using a general coupling surface. Two finite element models of the same cylinder flotation bag were established using the Initial Metric Method (IMM). One model is called Initial state and the other is called Reference state. The IMM folding technique can avoid negative deform of membrane elements significantly especially the final shape of the deformed bag. Besides, the relationships between the aeration rate and airbag parameters (volume and pressure) were discussed.

1. Introduction
Folded airbags[^6-8] are widely used in various fields. It has been more and more popular to utilize floating airbags for buoyancy aid, underwater salvage, life rescue, etc., which is flexible and convenient for transportation. A balloon-style gasbag with high strength PVC layer cloth was mainly applied for the salvage of South Korean Sewol steamship (2014). Different sizes of pipeline sealing airbags is an idea tool for the plumber to quickly block water and prevent the sediment pollution of underground pipeline drainage. WANG Guang-hui[^5] developed a portable, safe, convenient lifebuoy for single soldier, which is in shape “C” around wrist with quick and automatic gas-filled function for a single soldier to float in the sea when meeting an emergency. Tom Agapiades (2015) and his team developed a wearable called Kingii[^9] to increase personal water safety. Kingii[^9] is the smallest floatation device and can provide additional 124 kg of buoyancy of gas filling the airbag in only one second, in order to quickly pull a man out of water. Appropriate design of underwater folded airbags is a serious technique to conquer when considering heavy water pressure. Also, numbers of experiments are always conducted to test the airbag expansion features. With the development of simulation technology, it is wise to utilize finite element model to reduce research time[^1-4]. This paper is devoted to create an accurate and efficiency FE model simulating the inflating process of airbag underwater. By means of several times of calculations of airbag unfolding process with various design parameters, it is easy to decide the best choice for a steadily inflating airbag.
2. IMM method for a cylinder airbag

The Initial Metric Method (IMM method) is typically useful for air bag modeling. When using out-of-plane folding technique, the membrane elements can deform quite significantly. The final shape of the deformed bag can be negatively influenced. In order to overcome this problem, a finite element software-MSC.Dytran, offers a way to initialize strains inside elements such that the final shape is preserved. In this paper, two finite element models of the same cylinder flotation bag were established using the Initial Metric Method. One model is called Initial state and the other is called Reference state.

2.1. Modeling process

The modeling process of an airbag with IMM method includes five steps as follows.
1) Build the airbag FE model of the cylinder flotation bag as the **Reference state**. Calculate all the folding lines so as that the shape could then be flattened without wrinkles. Triangular mesh elements are preferred to build the model.
2) Build a mapped mesh model of a cuboid shape. Maintain the node coordinates along the folding lines.
3) Flatten the mapped mesh model according to both the folding lines of end faces and the cuboid edges to obtain the folded mapped mesh model.
4) Mesh the **Initial state** FE model of the actual shape of the airbag. The numbers of all nodes and elements in the Initial state must be consistent with the Reference state.
5) Merge the Initial state model and the Reference state model to obtain the final airbag model.

2.2. IMM usage in programming code

The IMM needs two models of the same air bag. One model is called Initial state and the second is called Reference state.

- The Initial state model has to be part of the main input file. This state can be visualized in output requests.
- The Reference state model has to be supplied to Dytran in a different file. Dytran reads this file

The Initial Metric Method is activated when the **IMMFIL = (filename)** directive is present in the File Management section.

The bag model is folded using offsets between all layers. Due to the nature of offset folding, the original element shapes are distorted, and it is necessary to use the Initial Metric Method (IMM). The bag model in unfolded shape (reference shape) is used to initialize the IMM strains in the folded model (initial model). The IMM strains are re-initialized every 5 milliseconds, using the following parameter:
PARAM, IMM, ON, 5e-3, 5E-3
To activate the Initial Metric Method, the reference shape must be stored in a separate file, which is referenced using the IMMFILE option in the main input file. For example:
IMMFILE=flat_imm.dat
Three formulations are available in Dytran. Using the parameter IMM, they are:
FULL: While elements are under IMM condition, they carry stresses when under compression. This is the default.
REDUCED: While elements are under IMM condition, the carry a reduced stress when under compression. The relative area factor, SMDFER, is used to reduce Young’s modulus.
ZERO: While elements are under IMM condition, compressive stresses are not carried. They code relies on the material damping to avoid excessive nodal velocities.
It has been shown that IMM formulation ZERO is most suitable when a couple of membrane elements with zero area exist in the initial state of the air bag model.
It should be noted that when elements are not under the IMM condition anymore (IMM strain tensor components are all zero), the elements start to behave like a regular membrane elements according to the material model attached.
The IMM strains can be recalculated during the simulation. This is especially beneficial for models that have initially many elements with zero area. This recalculation results in more stable behavior of these elements and also results in an improved shape near the end of the calculation.

3. Fluid-structure coupling

3.1. General coupling
The process of an airbag unfolding under water contains coupling between structure elements (membrane airbag) and fluid elements (water and air). With general coupling method, airbag structure and fluid domain are modeled with Lagrangian and Eulerian meshes respectively. The key task in coupling the Eulerian and Lagrangian sections of a model is to create a completely closed coupling volume on the Lagrangian surface. This surface is used to transfer the forces between the two solver domains. The surface acts as a boundary to the flow of material in the Eulerian mesh. At the same time, the stresses in the Eulerian elements cause forces to act on the coupling surface, distorting the Lagrangian elements. The two meshes would not ineract with each other until coupling algorithm is activated.
The coupling algorithm is activated using the COUPLE entry. For problems where the Eulerian material is inside a Lagrangian structure, COVER should be set to OUTSIDE since the Eulerian elements outside the coupling surface must be covered. For problems where the Eulerian material is outside the Lagrangian structure, the inside of the coupling surface must covered, and COVER should be set to INSIDE. As for the airbag inflating underwater, we choose INSIDE COVER to activate Eulerian material (water and air) outside the bag.

![Figure 2. Schematic of the cylindrical folded airbag underwater](image)
The position of the cylindrical folded airbag underwater is shown in Figure 2. The external fluid atmosphere (water and air) of the airbag are defined by an Euler domain, whose boundary is the
surface of the airbag. The area of the Euler domain is ought to be large enough to allow the airbag to have enough space to expand, also will not interfere with reflected waves from water boundary. The pressure at the outer boundary is defined as hydrostatic pressure, which is equivalent to the open boundary condition. The minimum pressure of water domain is defined as zero to prevent water flowing out and form a hole if part of the pressure becomes negative. The initial pressure of the air is defined as 1.0e5Pa (one bar pressure), and the pressure increases with the water depth due to gravity.

3.2. Mesh size
The mesh of the water air is Eulerian (orange meshes in Figure 2) and thus their mesh remains fixed in space. The fluid materials can move and deform within the fixed mesh. As the simulation progresses, the materials cross element boundaries, i.e., with each time step some small amount of each material may flow or advect out of one element into an adjacent one. (Figure 3)

![Figure 3. material transfer](image)

Tough Lagrangian mesh and Eulerian mesh are drawn seperately, the problem of which size is the perfect and the most efficiency is urgent to solve. A simple symmetric projectile element structure made of aluminum (Figure 4) was utilized to test the fittest mesh size in a water entry process, where impact overloading is seen as a pivotal history variable. Control a constant Lagrangian mesh size, change Eulerian mesh size, and compare impact overloading under parameter $\alpha$, i.e., ratio of the smallest Lagrangian mesh size to Eulerian mesh size. It is seen from the histogram (Figure 5) that when the ratio is smaller, the simulation result of impact overloading tends to converge. In a certain range, the smaller the grid size, the more the number of grids, the better the effect of the calculation. However, with the increasing density of the grid, the memory of the computer will be larger and the computation time will be longer, resulting in lower computational efficiency. Therefore, in the simulation calculation, the appropriate grid size should be selected, which can not only satisfy the accuracy, but also ensure the efficiency of calculation. With this example, we tend to choose a similar Lagrangian and Eulerian mesh size when calculating airbag inflating underwater to save simulation time.

![Figure 4. Schematic of a water-entry projectile structure](image)

![Figure 5. The tendency of impact overloading changes with $\alpha$](image)

4. Expansion process

4.1. Control volume model
Schematic of the Control volume model is shown in Figure 6. The process of airbag inflation is regarded as continuous expansion of the control volume. Internal pressure and temperature in the control volume are regarded as uniform. Assume the mass flow rate as the ideal gas inflow/outflow, the inflating gas as an ideal gas whose heat capacity of $C$ is constant, and assume no external heat exchange between airbag and outerspace, we have the equations below.

\[
\begin{align*}
P_2V_2 &= m_2RT_2 \\
P_2 &= (k-1)\rho E \\
dE \over E &= (1-k)\frac{dV_2}{V_2} \\
k &= \frac{c_p}{c_v}
\end{align*}
\]

where $P_2$ and $V_2$ are the internal pressure and volume of the airbag seperately, $m_2$ and $T_2$ are mass and temperature of internal gas respectively. $R$, $\rho$, $E$ represent for gas constant, density, and internal energy of gas respectively.

4.2. Simulation results

Take mass flow rate $\dot{m}_{in} = 4$kg/s into the calculation program and stress nephograms of 6 point of time are drawn as follows (Figure 7). It turns out the simulation results are basically good and the whole inflation process is uniform and stable. Single-surface contact is used to model buckling of structures where material may fold onto itself, also to prevent false winding. From the view of the whole expansion process, the stress on the airbag gradually increases with the inflation. During the inflation process, the stress of the airbag body is larger than that of the airbag end face. Therefore, it is possible to consider increasing the thickness of the airbag body membrane so that it can bear the corresponding stress and prolong the life.
5. Discussions

5.1. Comparison of unfolded airbag in air and underwater

It is obvious that the unfolding process of a folded airbag in water and in the air is very different due to pressure applied on the Lagrangian surface. In a comparison simulating calculation, the curves of the volume and pressure of the two airbags varying with time were calculated by Dytran software (Figure 8 and Figure 9). To ensure accuracy of comparing simulations, the initial air condition inside the bag, the air mass flow rate (4kg/s), the gas generating property and the total inflation time (1.2s) of the airbag were defined as the same.

We can see that under the same inflating conditions, airbags underwater and in air are fully expanded at a close time. But the fully-unfolded bag volume underwater turned to be smaller owing to heavy water pressure assigned on the airbag surface. At the same time, the internal pressure of the airbag is larger in the water than in the air. What’s more, the curves underwater fluctuating largely and the fluctuation amplitude decreases gradually with the inflation. This is because water has the viscous force on the membrane surface, which contribute to the airbag deployment becoming unstable, especially in the initial stage. When the folded airbag start inflating, it is necessary for the fabric elements to overcome folding deformation, but also prevent the blocking effect of water. As a result, the compression stress of the airbag membrane elements is greater in the water, which indicates an urgent demand for a strong airbag fabric material.

5.2. Comparison between different air mass flow rates underwater

Controlling other initial conditions as the same, four groups of simulating calculation of airbag inflating underwater were conducted with different air mass flow rates (2.0kg/s, 3.0kg/s, 4.0kg/s, 6.0kg/s). The Volume-Time and Pressure-Time curves are shown in Figure 10 and Figure 11. The initial air condition inside the bag, the air mass flow rate (4kg/s), the gas generating property and the total inflation time (1.2s) of the airbag were defined as the same. Airbags are all placed in the depths of 1.0m underwater.
According to the curves changing at the initial stage (0-0.15s), the airbag volume expands rapidly. The bigger the inflation rate is, the faster the airbag expanded (the larger the slope of the curve is). With the inflating process carries on, the speed becomes smooth, airbag volume continues to become larger. Finally, when the air bag fully expanded, the airbag volume tends to be stable. And the inflation rate increases, the volume stability of airbag is bigger. It can also be seen that the bigger the airbag inflation rate, the longer the time required for stability.

The great fluctuation at the initial stage of airbag unfolding process is observed for reasons. This is because the gas in the internal air distribution is not uniform when the airbag has just started from the folded state, which leads to uniform internal pressure. In addition, airbag pressure would easily be influenced by heavy water pressure. With the inflation, the airbag gradually becomes larger and the fluctuation amplitude decreases. At the same time, it is found that the greater the inflation rate is, the greater the internal pressure is when the airbag is fully stably expanded.

Figure 8. Volume-Time diagram of airbag in water and air

Figure 9. Pressure-Time diagram of airbag in water and air

Figure 10. Volume-Time diagram of airbags with different air mass flow rates underwater
6. Conclusion

In this paper, a cylinder folded airbag model is established by Initial Metric Method (IMM), and the simulation is carried out using MSC.Dytran software. Firstly, the airbag model of folded state is established, and the reference model is established. Varies parameters were tested to make the airbag effectively deployed underwater in a simulating way. The interaction between airbag and fluid domain is coupled by general coupling method.

There are some innovations in this paper:
1. Combine the IMM method with the fluid-solid coupling method to overcome the water pressure and finish the simulation of airbag unfolding in water. And the simulation effect has achieved a stable expansion of visual effects. Meanwhile, the time convergence of curves (pressure-time curves and volume-time curves) is guaranteed. In addition, the airbag structure is intact without being damaged, and the finite element has no false winding.
2. The influence of the mesh size in Lagrangian and Eulerian domain on the simulation results is studied by a group of comparing simulating calculations of a simple finite element model. To save simulation time, it is necessary to choose an appropriate mesh size not only to satisfy the accuracy, but also to ensure the efficiency of calculation.
3. The model of the same airbag unfolding in air and water is compared and analyzed. The differences between airbag volume and internal pressure were investigated.

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