Airbag Leakage Modeling in LSDYNA®

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Introduction

In the area of numerical simulations involving the use of airbags to absorb impact energy, passively or actively, accurate definitions of airbag leakage parameters play a crucial role in predicting the response of impacting objects (ex. occupants). LSDYNA provides various options for airbag leakage modeling that may appear overwhelming at first but are actually quite simple to use. This article discusses these various methods and options that are applicable to leakage modeling in airbags for control-volume and ALE inflation schemes.

Types of Leakage

There are two broad classifications of leakages that occur during and after airbag deployment as shown in Figure 1. In the first type, called *Venting,* the gas is discharged by means of "openings/vents/orifices" which are located on the airbag surface. The amount of gas that is discharged is a function of the vent area and its dependence on the airbag internal pressure. The second type, called *Porosity*, the leakage is attributed to porous nature of the airbag fabric. The amount of porosity leakage is a function of the airbag internal pressure and the characteristics of the bag material. Other types of leakages that could be potentially seen are through seams and inflator attachments which are usually grouped into *Venting*. For any given airbag, the total leakage is thus the summation of the leakages due to both venting and porosity. Both types of leakage are usually part of the design variables to "cushion" the impacting occupant.

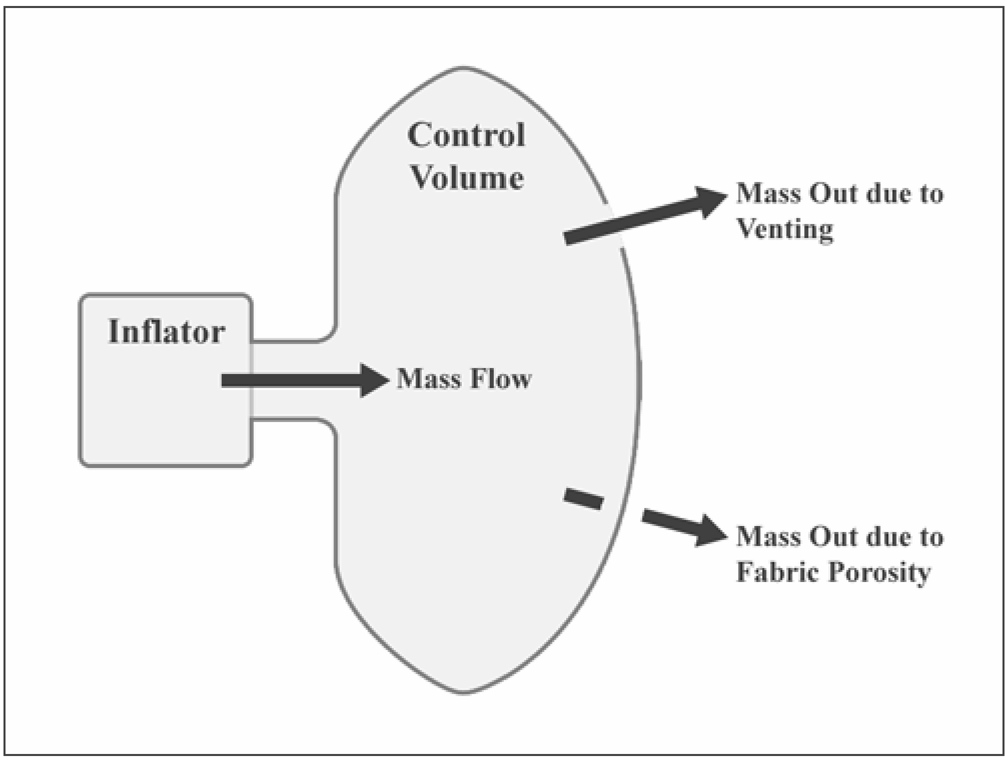

Figure 1: Airbag Setup

Leakage Formulations in LS-DYNA for Control Volume Airbags

Numerical treatment of leakage for control volume based airbag (EOS, WANG-NEFSKE, HYBRID, etc) involves computing the mass that needs to be removed from the incoming gas mass prior to computing the energy and the resulting uniform pressure. Besides formulation dependent parameters, the calculation of the outgoing mass, for both forms of leakage, primarily depends on three criteria: the area of the leakage, its dependence on some form of pressure (relative, absolute, gauge) and simulation time. Additional considerations include potential blockage of the leakage area due to contact-impact interactions. Since WANF-NEFSKE, HYBRID and ALE methods are most widely used inflation models, leakage options that apply to them are discussed in this article.

LSDYNA offers 1 type of venting formulation and 5 different types of porosity-based leakage formulation types. The choice of the porosity-based leakage formulations can be invoked using the parameter ***OPT*** in ***AIRBAG** keyword. Another variable that controls the porosity leakage formulation type is the parameter ***FVOPT*** option in ***MAT_FABRIC** which inherits its definition from *OPT* in *AIRBAG keyword. In other words, if *OPT*=0 then *FVOPT* is completely ignored. If *OPT* & *FVOPT* is greater than 0, then *FVOPT* determines the type of porosity leakage formulation. For more information, please refer to Remark #8 under *MAT_FABRIC keyword. Each of the porosity based leakage formulations optionally allow the user to consider blockage that may occur during or after deployment due to the interaction of the airbag surface with external entities. Wang-Nefske formulation (*OPT*=0) using leakage parameters defined in the *AIRBAG keyword is the default formulation.

Modeling Leakage due to Venting

The default method of modeling venting follows the original Wang-Nefske implementation. This approach uses two constants, ***C23*** and ***A23*.** The descriptor "23" is number inherited from the original paper as described by the formulation authors. *C23* is the venting-coefficient while *A23* is the venting-area. To enable more flexibility, the venting coefficient can be defined as a function of simulation time using ***LCC23*** (Load Curve Coefficient 23). Similarly, the venting-area can be defined as a function of absolute pressure using ***LCA23***(Load Curve Area 23). It must be noted that the load-curve based definitions of coefficient and area (*LCC23* and *LCA23*) will be ignored if its constant counterparts (*C23* and *A23*) are non-zero. When defining area as a function of absolute pressure, it is important that the definition covers the working range of the bag pressure.

In practice, it is not recommended to remove a portion of the airbag segments to physically model the vents using the control-volume approach. This is due to the fact that the airbag volume calculation in LS-DYNA, based on Green's theorem, requires a closed surface. If there are any open sections on the airbag surface, LS-DYNA detects them using its internal edge-location algorithm and closes them by projecting the n-sized polygon onto a two dimensional surface which is included as a separate airbag surface so a closed surface condition is met prior to the volume calculations. Consequently, the presence of any intentional physical holes on the airbag will not contribute to any leakage area and thus results in no gas discharge.

To model any open sections present in the airbag material, it is either recommended to fill the hole using null elements (this helps in preventing LS-DYNA spend any time in trying to close the open-sections) and refer its **PID** using *A23* variable (more in the next paragraph) OR use any one of porosity based leakage formulations using *MAT_FABRIC described later in this paper. For the non-control-volume airbag inflation schemes such as Euler/ALE, it is perfectly valid to include physical vent holes to allow the incoming gas to flow out of the airbag chamber skipping the fluid-structure-interaction. In the case of **ALE**, LS-DYNA performs an internal PID switch for the outgoing gas to enable easy measurement of the time-dependent mass and other related properties.

In LS-DYNA 970 revision 58xx and higher, negative inputs are permitted for *LCC23* and *A23* which invokes different definitions. When *LCC23* is less than zero, then abs(*LCC23*) is interpreted as the definition of the venting leakage coefficient as a function of relative pressure (P_{air}/P_{bag}) instead of simulation time. When *A23* is less than zero, then abs(*A23*) refers to a *PID* rather than to constant area. This allows LS-DYNA to dynamically compute the leakage area from summing up its individual element area of *PID* on every compute cycle. Using this approach allows the original Wang-Nefske venting implementation to use actual geometry for area calculations which was not available in earlier versions of LS-DYNA. This approach also provides an alternative way of defining the vent-holes in the airbag where the hole can be first filled using null elements (*MAT_NULL with shell elform type 9) and refer its *PID* using a negative value for *A23*. Since the actual airbag surface will not have any material in the vent-hole, it is recommended to define the part representing the vent-hole using negligible density and stiffness values so realistic stress can be computed around the vent hole.

Wang-Nefske Venting = [C23 (if >0) or LCC23] * [A23(if>0 or <0) or LCA23] * [OPT dependent properties]

Modeling Leakage Due to Porosity

There are five different formulations that are available in LS-DYNA to define porosity based leakage as shown in Table 1. These five different formulations can be further categorized as fabric-independent (default *OPT*=0) and fabric-dependent (*OPT* = 1 thru 8). Fabric independent formulation is the Wang-Nefske (Original) implementation for porous leakage using two constants ***CP23*** (Coefficient Porosity 23) and ***AP23*** (Area Porosity 23). *CP23* can be optionally defined as a function of time using ***LCCP23*** (LoadCurveCoefficientPorosity23) and *AP23* can be defined as a function of absolute pressure using ***LCAP23*** (LoadCurveAreaPorosity23). As in venting, load-curve based definitions for porosity coefficient and area (*LCCP23* and *LCAP23*) will be ignored if their constant counterparts are non-zero.

Fabric independent implementations of porous leakage formulations use the actual area of the fabric and use the *MAT_FABRIC constitutive model along with non-zero *OPT/FVOPT* values. Material constants ***FLC*** and ***FAC*** in *MAT_FABRIC also allow additional flexibility to define the porous leakage. The actual fabric area for a given part is computed by summing each element's area and is performed every cycle. *FLC* (Fabric Leakage Coefficient) allows the user to specify a leakage coefficient. If *FLC*>0, then it is assumed to be a constant value whereas if *FLC*<0, the abs (*FLC*) refers to a load curve (*DEFINE_CURVE) which defines the fabric leakage coefficient as a function of simulation time. *FAC* (Fabric Area Coefficient) allows the user to specify an area coefficient. Similar to *FLC*, when *FAC*>0, it is assumed to be a constant value while *FAC*<0, abs *(FAC*) refers to a load curve which defines the fabric area coefficient as a function of absolute pressure. It must be noted that the default value for both FLC and FAC is zero which will result in no discharge irrespective OPT/FVOPT parameters. To invoke the leakage, both must be non-zero and could be defined as unity which then removes the dependence of the leakage area on any form of pressure.

Porosity Based Leakage Formulations	**FVOPT / OPT Values**	**Equation**
Wang-Nefske (Original)	0	$\dot{m}'_{23} = C'_{23} A'_{23} \frac{p}{R\sqrt{T_2}} Q^{1/\gamma} \sqrt{2 g_c \left(\frac{\gamma R}{\gamma -1}\right)\left(1-Q^{\gamma-1/\gamma}\right)}$
Wang-Nefske (Fabric)	1 or 2	$\dot{m}_{out} = \sqrt{g_c}\cdot\left[\sum_{n=1}^{nairmats}\left(FLC(t)_n \cdot FAC(p)_n \cdot Area_n\right)\right]\cdot\sqrt{2p\rho}\sqrt{\frac{\gamma(Q^{\frac{2}{k}}-Q^{\frac{\gamma-1}{\gamma}})}{\gamma-1}}$
Graefe, et al	3 or 4	$\dot{m}_{out} = \left[\sum_{n=1}^{nairmats}\left(FLC(t)_n \cdot FAC(p)_n \cdot Area_n\right)\right]\cdot\sqrt{2(p-p_{ext})\rho}$
Porous Media	5 or 6	$\dot{m}_{out} = \left[\sum_{n=1}^{nairmats}\left(FLC(t)_n \cdot FAC(p)_n \cdot Area_n\right)\right]\cdot(p-p_{ext})$
Gas Volume Outflow vs. Pressure	7 or 8	*Not available at the time of publication*

Table 1: Porosity Based Leakage Formulations

In LS-DYNA version 970 and higher, a new option is available to compute the effective leakage area. This method, invoked by setting ***X0***=1 in *AIRBAG keyword, scales the original airbag surface area using *FLC* and *FAC* which have a different meaning. When *X0*=1 and *FLC* <0, abs (*FLC*) refers to a load curve definition defining leakage coefficient as function of the area stretch ratio ($A_{current}/A_{original}$) instead of simulation time. Similarly, when *FAC*<0, abs (*FAC*) is refers to a load curve that defines the area coefficient as a function of pressure ratio (P_{air}/P_{bag}) instead of absolute pressure.

Choice of the leakage formulations depends entirely on the available test data. Irrespective of the formulation type, it is however important to choose its variables such that they are not problem-dependent. For example, choosing a leakage coefficient that is a function of simulation time may be heavily dependent on the problem. Pressure-dependent leakage parameters are recommended since they have greater flexibility. *Note:* For *OPT/FVOPT* = 7/8, *FAC* always expect the dependent variable to be leakage volume rate instead of area coefficient The combined contributions of the porosity-based parameters are shown below:

Fabric-Independent Porosity Area (Default) = [CP23 or LCCP23 (if defined)] * [AP23 or LCAP23 (if defined)]

Fabric-Dependent Porosity Area (for X0=0) = [FLC or FLC (time)] * [FAC or FAC(pressure) (if defined)] * Fabric Area(time)

Blockage Considerations

When any part of airbag surface interacts with other entities through contact, it is possible that they prevent the local outflow of gas as shown in Figure 2. To model this in LS-DYNA the parameters *OPT/FVOPT* must be set to any non-zero even number (2, 4, 6, or 8). Invoking blockage treatment allows LS-DYNA to check if the airbag segments are involved in contact and remove its area contribution from the total effective leakage area prior to the actual leakage calculations. The amount of blocked area from each segment is dependent on the number of nodes that are in contact at the time of checking. If only one node of a 4-noded segment is in contact then 25% of its area is treated as blocked, while 2-node in contact would result in 50% of blocked area and so on. When blocking is considered in leakage formulations, the mass-flow rate is usually noisy since the bag could be in and out of contact between a small number of compute cycles due to airbag oscillations. This can be generally reduced by using a mass-weighted-damping, ***MWD*** in ***AIRBAG**. When a non-zero MWD is defined, LS-DYNA computes the damping force that is proportional to the relative velocity between the bag and the surface-point (node). The bag-velocity is determined by taking the average mass-weighted velocity of all the nodes used to define the bag. *It must be noted that airbag's interaction with Rigidwalls* ***(*RIGIDWALL)*** *does not account for any blockage in the leakage area. The blockage calculations in LS-DYNA are limited to only contact-impact interfaces defined using any of *CONTACT keywords.*

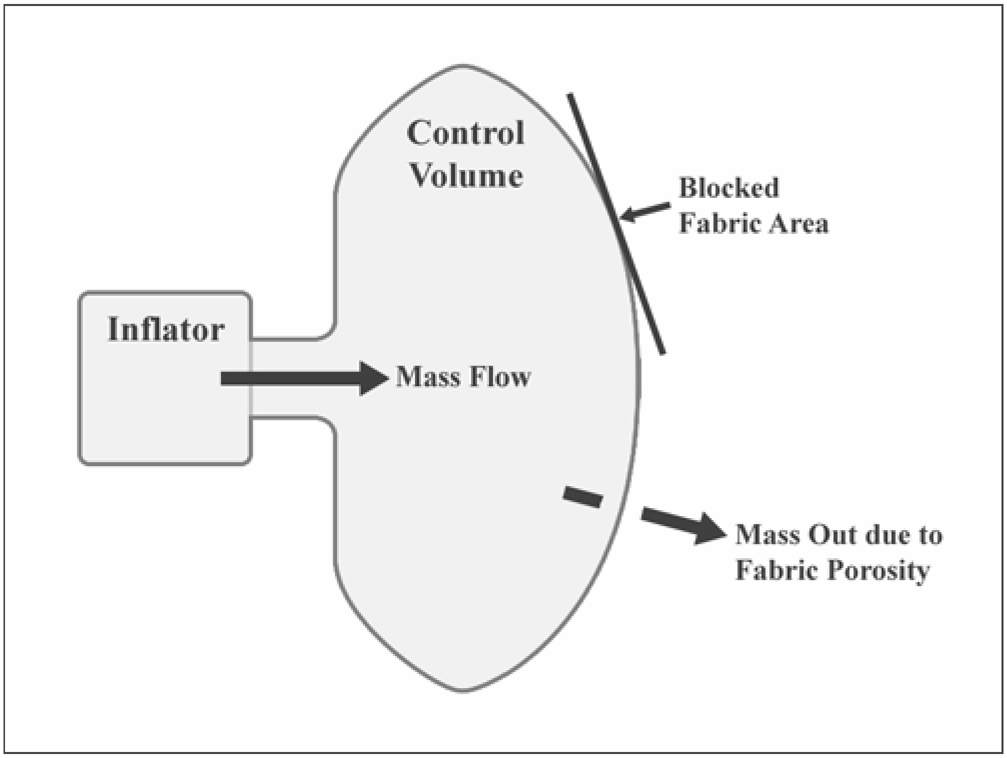

Figure 2: Fabric Blockage Due To Contact

Determining Leakage Coefficients

Measuring leakage coefficients, for both venting and porosity, can be a difficult task. Several tests, namely, Textest and Tube-flow, can be performed to determine the fabric's leakage properties for use in simulation. However, in some instances, such as non-porous venting, measuring the venting time-history could be extremely difficult. In such instances, the coefficients are best determined using an optimizer such as **LS-OPT®.** Assuming we have confidence in all other data, we can set up a simple problem, such as a free-falling object onto the airbag (after deployment for Control-Volume approach and during deployment for ALE/Euler approach) and monitor the objects behavior under no-venting and venting+porosity conditions for independent tuning of leakage parameters. Within LS-OPT®, one can define the leakage coefficients as design variables and relevant time-history information of the free-falling body as the response(s). Using either constants or load-curve based parameters, LS-OPT® can drive the simulations until we find the optimum leakage parameters such that the response of the object matches measured test values.

Special Considerations for Leakage in ALE/Euler Simulations

When modeling the airbag inflation process using ALE/Euler method, the process of venting is a relatively simple approach where the physical hole is incorporated in the airbag geometry. For modeling the porosity leakage, only two formulations, types 7/8, in *FVOPT/OPT* are supported. This requires the definition of volume rate as a function of absolute pressure using the parameter *FLC* in *MAT_FABRIC keyword. Alternatively, if experiment data is available one can use the parameter ***LCIDPOR*** in ***CONSTRAINED_LAGRANGE_IN_SOLID** to define a non-linear relationship between relative pressure and relative velocity between the Lagrangian structure and the gas. LS-DYNA allows the switching of inflation schemes between a control-volume and ALE using the SWITCH parameter in *AIRBAG_ALE. When the inflation scheme switch is used, the leakage formulations and parameters are also switched so as to achieve identical leakages irrespective of the scheme choice. This is limited to fabric-based porosity formulations and excludes *CONSTRAINED based porosity formulation.

Measuring Leakage in Output Files

Total leakage from the airbag control volume can be measured using the component "Output dm/dt" from ***ABSTAT*** output file which gives the rate at which the mass is flowing out of the airbag. The component can be used for both control-volume and ALE/Euler based airbag inflation models. To monitor blocked areas, LS-DYNA reports the unblocked and blocked areas for each fabric PID as a function of time to the ABSTAT ascii output. LS-PREPOST, a generic pre-and-post processor for LS-DYNA, allows the plotting of all the various components output to ABSTAT.

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