*ISPG

The *ISPG keywords enable creating a model for incompressible smooth particle Galerkin (ISPG) parts. This model can be used for simulating incompressible fluids and for coupling with structural parts. We created this family of keywords because these keywords cannot be in the normal LS-DYNA input deck. They can only be in a file included in the LS-DYNA input deck with *INCLUDE_ISPG. The keywords in this section are defined in alphabetical order:

*ISPG_ASCII_CPL

*ISPG_ASCII_SUMFORC

*ISPG_BOUNDARY_CONVECTION_SET

*ISPG_BOUNDARY_SYMMETRIC

*ISPG_CONTROL_ADAPTIVITY

*ISPG_CONTROL_D3ISPG

*ISPG_CONTROL_IMPLICIT

*ISPG_CONTROL_MPP

*ISPG_CONTROL_SOLUTION

*ISPG_DAMPING_SURF

*ISPG_DEFINE_MERGER_MPP

*ISPG_INITIAL_TEMPERATURE_SET

*ISPG_LOAD_GRAVITY

The following keywords are additional ISPG-related keywords:

*DEFINE_ISPG_TO_SURFACE_COUPLING

*INCLUDE_ISPG

*MAT_ISPG_CARREAU

*MAT_ISPG_CROSS_CASTRO_MACOSKO

*MAT_ISPG_CROSSMODEL

*MAT_ISPG_ISO_NEWTONIAN

*MAT_THERMAL_ISPG

*SECTION_ISPG

All of the above keywords, except *DEFINE_ISPG_TO_SURFACE_COUPLING and *INCLUDE_ISPG, can only be in the ISPG input file.

Note that *SECTION_FPD and *MAT_IFPD are for an older ISPG solver. They cannot be used with these *ISPG keywords and can only be in a normal LS-DYNA input deck.

*ISPG_ASCII_CPL

Purpose: Output the contact area and reaction forces to an ASCII file for the coupling between ISPG parts and structures.

> **NOTE:** This keyword may only be used in an ISPG input deck included with *INCLUDE_ISPG.

Card 1	1	2	3	4	5	6	7	8
Variable	ASCII_ID	CPL_ID	DT					
Type	I	I	F					
Default	none	none	none					

VARIABLE	DESCRIPTION
ASCII_ID	Used for ASCII file name. For example, if ASCII_ID = 1, then the file name will be ispg_ascii000001.
CPL_ID	ID of the defined ISPG to surface coupling (see *DEFINE_ISPG_-TO_SURFACE_COUPLING)
DT	Time interval for output of files

*ISPG_ASCII_SUMFORC

Purpose: Output the reaction forces to structures from all the ISPG parts to the ASCII files ispg_sumforc_above and ispg_sumforc_below. The total reaction forces to the structure above and below the cutting plane based on COORD and NDIR are output to the respective ASCII files.

> **NOTE:** This keyword may only be used in an ISPG input deck included with *INCLUDE_ISPG.

Card 1	1	2	3	4	5	6	7	8
Variable	DT	COORD	NDIR					
Type	F	F	I					
Default	none	none	3					

VARIABLE	DESCRIPTION
DT	Time interval for the data output
COORD	Position along the direction defined by NDIR of the cutting plane for the force summation
NDIR	Normal direction of the cutting plane: EQ.1: Along the global X-axis EQ.2: Along the global Y-axis EQ.3: Along the global Z-axis

*ISPG_BOUNDARY_CONVECTION_SET

Purpose: Apply a convection boundary condition to ISPG parts in a coupled thermal and flow analysis. See also *ISPG_CONTROL_SOLUTION.

> **NOTE:** This keyword may only be used in an ISPG input deck included with *INCLUDE_ISPG.

Card 1	1	2	3	4	5	6	7	8
Variable	FP	FPTYPE						
Type	I	I						
Default	none	none						

Card 1	1	2	3	4	5	6	7	8
Variable	HLCID	HMULT	TLCID	TMULT				
Type	I	F	I	F				
Default	0	none	0	none				

VARIABLE	DESCRIPTION
FP	Part ID for the fluid particles
FPTYPE	Type for FP: EQ.0: Part set ID EQ.1: Part ID
HLCID	Load curve ID for the curve giving the convection heat transfer coefficient, h, as a function of time. EQ.0: h is a constant defined by the value HMULT.
HMULT	Convection heat transfer coefficient, h. Ignored if HLCID > 0.
TLCID	Load curve ID for the curve giving the environment temperature,

VARIABLE	DESCRIPTION
	T_∞, as a function of time. EQ.0: T_∞ is a constant given by the value TMULT.
TMULT	Environment temperature, T_∞. Ignored if TLCID > 0.

*ISPG_BOUNDARY_SYMMETRY

Purpose: Define a symmetric boundary condition for pseudo 2D, planar 2D, and axisymmetric 2D simulations of adaptive ISPG.

> **NOTE:** This keyword may only be used in an ISPG input deck included with *INCLUDE_ISPG.

Card 1	1	2	3	4	5	6	7	8
Variable	NDIR	COORD1	COORD2	ILOC				
Type	I	F	F	I				
Default	none	none	none	0				

VARIABLE	DESCRIPTION
NDIR	Normal direction of the symmetric planes used to define the symmetric boundary condition: EQ.1: Global X-axis EQ.2: Global Y-axis EQ.3: Global Z-axis
COORD1	Minimum coordinate value along the direction set with NDIR (ignored if ILOC = 2)
COORD2	Maximum coordinate value along the direction set with NDIR (ignored if ILOC = 1)
ILOC	Location of symmetric planes: EQ.0: Symmetric planes at both coordinates COORD1 and COORD2 EQ.1: Symmetric plane at coordinate COORD1 EQ.2: Symmetric plane at coordinate COORD2

*ISPG_CONTROL_ADAPTIVITY

Purpose: Control adaptivity parameters for ISPG.

NOTE: This keyword may only be used in an ISPG input deck included with *INCLUDE_ISPG.

Card 1	1	2	3	4	5	6	7	8
Variable	IALIGN	IMOV	RA_SCL	RD_SCL	SSANGLE	ASANGLE	NDIV_MIN	IQCP
Type	I	I	F	F	F	F	I	I
Default	0	0	1.5	0.2	0.524	0.0873	0	0

Card 2	1	2						
Variable	HMIN	SCL_CE	IMERGE					
Type	F	F	I					
Default	0.001	1.0	0					

VARIABLE	DESCRIPTION
IALIGN	Flag to determine whether ISPG nodes automatically align with structural nodes and divisions in the structural segment determined using NDIV_MIN (see Remark 1): EQ.0.OR.EQ.1: Automatic alignment NE.0.AND.NE.1: No automatic alignment
IMOV	Enable staggering algorithm (see Remark 2): EQ.0.OR.EQ.1: Enable staggering. NE.0.AND.NE.1: Disable staggering.
RA_SCL	Scale factor for determining whether to add a new ISPG node. The adaptivity algorithm adds a node if the distance between two adjacent ISPG nodes is larger than RA_SCL $\times D_{\mathrm{avg}}$. D_{avg} is the

VARIABLE	DESCRIPTION
	original average element edge length of an ISPG part.
RD_SCL	Scale factor for determining whether to delete an ISPG node. The adaptivity algorithm deletes a node if the distance between two adjacent ISPG nodes is smaller than RD_SCL × D_{avg}. D_{avg} is the original average element edge length of an ISPG part.
SSANGLE	Critical angle (unit rad) between adjacent structural segments for ISPG edges to stagger (see IMOV defined above).
ASANGLE	Critical angle (unit rad) of adjacent structural segments for ISPG nodes to align to structural nodes (see IALIGN defined above).
NDIV_MIN	Minimum number of divisions of the structural segment for ISPG node alignment (see IALIGN above). The number of divisions in the local s- (nodes 1→2 and 4→3 for a 4-node segment) and t-directions (nodes 2→3 and 1→4 for a 4-node segment) for a 4-node structural segment is determined by $\mathrm{ndiv}_s = \max(\mathrm{ndiv}_{\mathrm{min}}, 2\,L_s/D_{\mathrm{avg}})$ and $\mathrm{ndiv}_t = \max(\mathrm{ndiv}_{\mathrm{min}}, 2\,L_t/D_{\mathrm{avg}})$, where $L_s = \max(L_{12}, L_{34})$, $L_t = \max(L_{23}, L_{14})$, and D_{avg} is the original average element edge length of an ISPG part. For three-node segments, the segment's maximum length is used to determine the division number.
IQCP	Control the number of quadrature points in the ISPG element used for the detection of ISPG element penetration into structural elements: EQ.0: Use one quadrature point (center of the ISPG element) for the detection. EQ.1: Use 5 points for the detection.
HMIN	Minimum relative element height compared to the average element edge length D_{avg}. If the element's height (for the tetrahedral elements, whose 4 nodes are at the surface of the ISPG part) after adaptivity is smaller than HMIN × D_{avg}, then this element is excluded from the ISPG part. The default value of HMIN is 0.001. We recommend values of HMIN between 0.001 and 0.05.
SCL_CE	Scale factor for the element size at the regions near the contact edges (see Figure 31-1). The element size near the contact edges is SCL_CE × D_{avg} for the refinement. Here, D_{avg} is the original average element edge length for the ISPG elements. The default value of SCL_CE is 1.0. If SCL_CE is smaller than 0.333, then it is reset to

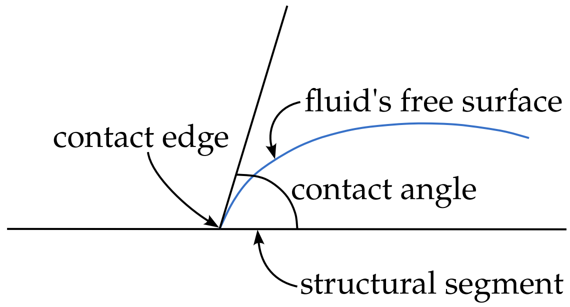

Figure 31-1. Example of contact between a structure and ISPG element. In the 3D the contact edge is the line going into the plane. In 2D, it is the point.

VARIABLE	DESCRIPTION
	0.333.
IMERGE	Flag to automatically merge parts that are sufficiently close together into one part: LE.0: Do not enable merging. GT.0: Enable merging. Note that for merging to work in MPP the parts for which merging is possible must be on the same processor. Use *ISPG_DEFINE_MERGER_MPP to distribute these parts to the same processor.

Remarks:

1. **Automatic alignment.** Automatic alignment of ISPG nodes to structural segments only occurs at structural segments under the following conditions:

   a) the angle between a structural segment and the structural segment adjacent to it is larger than ASANGLE (see the description of ASANGLE), and

   b) ISPG fluid contact surfaces cover all the nodes of the structural segment.

   The ISPG nodes align to both structural nodes and a number of locations along the structural segment (see NDIV_MIN).

2. **Staggering algorithm.** Usually, the ISPG contact edges (see Figure 31-1) move by internal forces (e.g., pressure and viscosity forces) and external forces (e.g., surface tension forces and wall adhesion forces). But at some sharp corners of the structure, it is difficult to determine the normal vector of the contact needed for calculating the wall adhesion and normal contact forces. The strong discontinuity in the structural segments causes this issue. We implemented a staggering algorithm to handle this scenario. In these regions, the ISPG edge staggers forward or backward depending on the contact angle (see *DEFINE_ISPG_TO_-

SURFACE_COUPLING). If the contact angle is larger than the advancing angle (ACA on *DEFINE_ISPG_TO_SURFACE_COUPLING), the ISPG contact edge moves forward along the structural segment. Otherwise, if the contact angle is smaller than the receding contact angle (RCA on *DEFINE_ISPG_TO_SURFACE_COUPLING), the ISPG contact edge staggers backward. The staggering occurs only at adjacent structural segments with an angle larger than SSANGLE.

*ISPG_CONTROL_D3ISPG

Purpose: Control the data output for the ISPG method into the d3ispg file for further post-processing. The d3ispg file is automatically output during ISPG simulations. *DATABASE_BINARY_D3PLOT controls the output frequency of this file. By default, d3ispg only contains pressure data. This keyword enables outputting additonal data to this file.

> **NOTE:** This keyword may only be used in an ISPG input deck included with *INCLUDE_ISPG.

Card 1	1	2	3	4	5	6	7	8
Variable	STRESS	STRAINR	VIS	TEMP	CURG			
Type	I	I	I	I	I			
Default	0	0	0	0	0			

VARIABLE	DESCRIPTION
STRESS	Flag to output stresses into d3ispg (see Remark 1): LE.0: No GT.0: Yes
STRAINR	Flag to output shear strain rates into d3ispg (see Remark 2): LE.0: No GT.0: Yes
VIS	Flag to output viscosity into d3ispg: LE.0: No GT.0: Yes
TEMP	Flag to output temperature into d3ispg: LE.0: No GT.0: Yes
CURG	Flag to output material curing into d3ispg: LE.0: No

VARIABLE	DESCRIPTION
	GT.0: Yes

Remarks:

1. **Stress output.** Setting STRESS greater than 0 causes the output of the normal, shear, and equivalent (σ_{eq}) stresses in the order: σ_{xx}, σ_{yy}, σ_{zz}, σ_{xy}, σ_{xz}, σ_{yz}, σ_{eq}. The equivalent stress is given by:

$$\sigma_{eq} = \sqrt{\frac{\sigma_{xx}^2}{2.0} + \frac{\sigma_{yy}^2}{2.0} + \frac{\sigma_{zz}^2}{2.0} + \sigma_{xy}^2 + \sigma_{xz}^2 + \sigma_{yz}^2}$$

2. **Strain-rate output.** Setting STRAINR greater than 0 causes the output of the normal, shear, and equivalent ($\dot{\varepsilon}_{eq}$) strain rates in the order: $\dot{\varepsilon}_{xx}$, $\dot{\varepsilon}_{yy}$, $\dot{\varepsilon}_{zz}$, $\dot{\varepsilon}_{xy}$, $\dot{\varepsilon}_{xz}$, $\dot{\varepsilon}_{yz}$, $\dot{\varepsilon}_{eq}$. The equivalent strain rate is given by:

$$\dot{\varepsilon}_{eq} = \sqrt{\frac{\dot{\varepsilon}_{xx}^2}{2.0} + \frac{\dot{\varepsilon}_{yy}^2}{2.0} + \frac{\dot{\varepsilon}_{zz}^2}{2.0} + \dot{\varepsilon}_{xy}^2 + \dot{\varepsilon}_{xz}^2 + \dot{\varepsilon}_{yz}^2}$$

*ISPG_CONTROL_IMPLICIT

Purpose: Control the implicit parameters for the ISPG method.

NOTE: This keyword may only be used in an ISPG input deck included with *INCLUDE_ISPG.

Card 1	1	2	3	4	5	6	7	8
Variable	BETA	GAMMA	CFL	MX_SUBS	MX_ITERS			
Type	F	F	F	I	I			
Default	0.38	0.60	1.0	512	20			

Card 2	1	2	3	4	5	6	7	8
Variable	BIRTH	DTIMP						
Type	F	F						
Default	0.0	0.0						

VARIABLE	DESCRIPTION
BETA	β used by the Newton-Raphson iteration algorithm
GAMMA	γ used by the Newton-Raphson iteration algorithm
CFL	Courant number
MX_SUBS	Maximum subcycles of the ISPG solver for each structural time step
MX_ITERS	Maximum number of iterations for the ISPG implicit method in each sub-step
BIRTH	Starting time for the fully implicit ISPG iteration. Before BIRTH, only one-way coupling occurs, meaning no forces from the solder return to the structure. The implicit time step for ISPG parts is DTIMP instead of the structural implicit step to guarantee that the

VARIABLE	DESCRIPTION
	fluid moves with the solid boundaries. After BIRTH, two-way coupling occurs, and the ISPG solver performs a full iteration with the structural implicit step. This option is very useful for cases where the structural simulation time is very long (e.g., in seconds or minutes) while the reflow process to steady state is very short.
DTIMP	Implicit time step for ISPG parts during the simulation time before BIRTH

*ISPG_CONTROL_MPP

Purpose: Control the MPP decomposition of the ISPG fluid. Currently, this keyword is valid for the decomposition of the ISPG fluid parts into different CPU cores. During the decomposition, the nodes and elements of one fluid part are decomposed into the same CPU core to minimize the MPI communication.

NOTE: This keyword may only be used in an ISPG input deck included with *INCLUDE_ISPG.

Card 1	1	2	3	4	5	6	7	8
Variable		DX	DY	DZ				
Type		F	F	F				
Default		0.0	0.0	0.0				

VARIABLE	DESCRIPTION
DX, DY, DZ	Size of the box in the global x, y, and z directions. The box is used to detect the adjacent structural segments used to define the coupling between the structure and ISPG fluids. If zero is given, $10.0 \times D_{avg,max}$ is used. $D_{avg,max}$ is the maximum value of the original averaged nodal distance for all ISPG parts.

*ISPG_CONTROL_SOLUTION

Purpose: Set the analysis solution procedure for ISPG if performing a combined thermal and flow analysis.

> **NOTE:** This keyword may only be used in an ISPG input deck included with *INCLUDE_ISPG.

Card 1	1	2	3	4	5	6	7	8
Variable	SOLN							
Type	I							
Default	0							

VARIABLE	DESCRIPTION
SOLN	Analysis solution procedure: EQ.0: Flow analysis only EQ.1: Combined flow and thermal analysis

*ISPG_DAMPING_SURF

Purpose: Define Rayleigh damping related to the fluid surface tension on all the ISPG parts. Currently, this feature supports only the 2D ISPG formulation.

NOTE: This keyword may only be used in an ISPG input deck included with *INCLUDE_ISPG.

Card 1	1	2	3	4	5	6	7	8
Variable	DAMP							
Type	F							
Default	none							

VARIABLE	DESCRIPTION
DAMP	Rayleigh damping value, related to the stiffness of the surface tension term

*ISPG_DEFINE_MERGER_MPP

Purpose: Associate ISPG parts with a merging group so that these parts will be distributed to the same processor to facilitate merging them into one part for solder reflow simulations in MPP. For merging to occur IMERGE must be greater than 0 on *ISPG_CONTROL_ADAPTIVITY. This keyword is needed because sufficiently close parts may be decomposed onto different processors. If that occurs, they will not be merged.

NOTE: This keyword may only be used in an ISPG input deck included with *INCLUDE_ISPG.

Include as many cards as desired. The next keyword ("*") card terminates this input.

Card 1	1	2	3	4	5	6	7	8
Variable	MRGID	PID1	PID2	PID3	PID4	PID5	PID6	PID7
Type	I	I	I	I	I	I	I	I
Default	none	none	none	none	none	none	none	none

VARIABLE	DESCRIPTION
MRGID	Merging ID. All parts on this card are put into a group with this merging ID. The parts in the merging group are distributed to the same processor to make merging possible.
PID*i*	ISPG fluid part ID

*ISPG_INITIAL_TEMPERATURE_SET

Purpose: Define initial nodal point temperatures of ISPG parts in a coupled thermal and flow analysis. See also *ISPG_CONTROL_SOLUTION.

NOTE: This keyword may only be used in an ISPG input deck included with *INCLUDE_ISPG.

Card 1	1	2	3	4	5	6	7	8
Variable	FP	FPTYPE	TEMP					
Type	I	I	F					
Default	none	none	none					

VARIABLE	DESCRIPTION
FP	Part or part set ID of the fluid particles
FPTYPE	Type for FP: EQ.0: Part set ID EQ.1: Part ID
TEMP	Temperature of the fluid particles

*ISPG_LOAD_GRAVITY

Purpose: Define the gravity load applied to all the ISPG parts.

> **NOTE:** This keyword may only be used in an ISPG input deck included with *INCLUDE_ISPG.

Card 1	1	2	3	4	5	6	7	8
Variable	IDIR	GRAV						
Type	I	F						
Default	none	none						

VARIABLE	DESCRIPTION
IDIR	Global axis direction of the gravity load: EQ.1: Global X-axis EQ.2: Global Y-axis EQ.3: Global Z-axis
GRAV	Value of the gravity load