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Space systems — Dynamic and static analysis — Exchange of mathematical models

*Systèmes spatiaux — Analyse dynamique et statique — Échange de
modèles mathématiques*



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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 14954 was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

Space systems — Dynamic and static analysis — Exchange of mathematical models

1 Scope

This International Standard normalizes the exchange of mathematical models between payload contractors (PLC) and launch service providers (LSP). It identifies standard methods for modelling the dynamic behaviour of both launch vehicles (LV) and payload (PL), particularly when they are coupled prior to launch and during the early moments of the launch phase.

In standard mode, the delivered models represent dynamic and static behaviour at the launcher interface. The requirements provided in this International Standard are the minimum necessary for dynamic coupled analysis. They may not be sufficient for stress analysis. The payload models are full integrated models from the different parts of the payload under the payload contractor authority, including also their own adapter to LV interface in the case that the adapter is a part of the payload.

This International Standard does not include the validation of PL models.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO/IEC 646, *Information technology — ISO 7-bit coded character set for information interchange*

3 Terms, definitions, symbols, and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1.1

payload

system that is launched by a launch vehicle

EXAMPLES Satellite, spacecraft, space probe.

3.1.2

payload contractor

organization in charge of a payload

3.1.2

launch service provider

organization that conducts a launch with a launch vehicle

3.2 Abbreviated terms

ATM	acceleration transformation matrix
CoG	centre of gravity
DoF	degree of freedom
DTM	displacement transformation matrix
EOF	end of file
ICD	interface control document
LSP	launch service provider
LTM	load transformation matrix
LV	launch vehicle
OTM	output transformation matrix
PL	payload
PLC	payload contractor
SI	International System of Units

3.3 Symbols

A	acceleration transformation matrix
C	damping matrix
D	displacement transformation matrix
K	stiffness matrix
K_R	stiffness matrix of rigid body modes, $K_R = \phi_R^T K \phi_R$
L	load transformation matrix
M	mass matrix
M_R	mass matrix of rigid body modes, $M_R = \phi_R^T M \phi_R$
S_e	strain energy
q_{is}	internal degrees of freedom
q_j	degrees of freedom of the interface
ϕ_R	matrix of rigid body modes
η_k	modal coordinates

4 General description of models

4.1 Matrices

The mathematical model of a PL shall be made of three matrices [mass matrix (M), stiffness matrix (K), and damping matrix (C)]. It shall be sufficient to characterize the dynamic and static behaviour of the structure, assuming that no external forces are applied to the payload except through the LV-PL interface.

A modal synthesis method is a typical procedure used to generate a reduced mathematical model.

Additional matrices may be provided in order to reconstitute acceleration, displacement or load in the PL.

These matrices are identified as OTMs in the following clauses.

4.2 Types of models

4.2.1 Physical models

Physical models shall be represented by matrices, the dynamic and static behaviour of which is described solely by the DoFs related to physical displacement at nodal points, including all interface points.

4.2.2 Modal models

Modal models shall be represented by matrices, the dynamic and static behaviour of which is described solely by a mix of physical and modal DoFs (representing the modes of the structure fixed at previous physical DoFs). Only interface DoFs are physical DoFs.

4.2.3 Hybrid models

Hybrid models are extensions of modal models for which internal physical DoFs other than the interface DoFs are included.

4.3 Units

All numerical input and output data shall be expressed in SI. Acceleration may be expressed in g , where $g = 9,81 \text{ m/s}^2$.

Use of units other than those of SI is an exception that shall be submitted for the approval of the LSP.

5 General requirements

5.1 Modelling codes

The software (name and version) and the type of finite elements used for the modelling of the PL shall be indicated.

The condensation procedure applied to the original dynamic model shall be described.

5.2 Co-ordinate systems

A reference co-ordinate system for the PL model shall be defined. A drawing of the PL ensemble with its co-ordinate system shall be included in the written report.

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The orientation of the PL axes with respect to the LV shall be defined by the LSP, based on compliance with requirements of clearance between PL and LV structures, on pad access to the PL, and on mechanical and electrical interfaces as stipulated in the ICD.

The same reference system shall be used for the geometrical description of the PL and for the definition of the DoFs in the mass and stiffness matrices.

The axis system shall be cartesian.

A local co-ordinate system may be used but shall be clearly defined. For interfaces, all reference shall be made to the reference co-ordinate system.

5.3 Theoretical aspects for modelling

5.3.1 General modelling

The model shall describe the complete, dynamic, three-dimensional PL behaviour in free-free conditions and also clamped at its interface with the launch vehicle. The model shall be representative up to a frequency specified by the LSP.

5.3.2 Liquid modelling

If the payload contains significant liquid propellant mass, the model shall describe the slosh motions of these liquids, neglecting the surface tension and assuming that the equilibrium surface is perpendicular to the liquid's quasi-static net acceleration vector, when required by the LSP.

The effects of fluid-structure interaction shall be taken into account in the prescribed frequency range.

Typical values of quasi-static acceleration shall be provided by the LSP for loading cases to be considered.

5.3.3 Damping modelling

Damping is usually based on approximations derived from engineering judgement and tests. It may be defined at the PL level, in which case a PL damping matrix shall be a part of the mathematical model.

Damping may be defined at the system level by agreement between PLC and LSP, in which case no damping matrix is required. However, if necessary, the dependence of damping on frequency may be provided.

5.3.4 Interface modelling

When the interface between the PL and the LV may be considered rigid, as approved by both the PLC and the LSP, the interface can be condensed to one node with six DoFs.

Modelling of the PL-LV interface shall require greater accuracy when the flexibility of the interface might induce higher loads on the PL. This issue shall be discussed by both parties prior to the preliminary coupled analysis cycle.

6 Condensation methods

6.1 Condensed physical model

6.1.1 General

The choice of method of condensation is left to the discretion of the writer of the model. The condensed model shall be compliant with requirements given in Clause 7.

The nodal points and DoF shall be defined as in 6.1.2.

6.1.2 Requirements

6.1.2.1 Unless otherwise specified, each physical nodal point of the interface shall have six DoFs in the reference co-ordinate system:

$$T_X = \text{DoF 1}, T_Y = \text{DoF 2}, T_Z = \text{DoF 3}, R_X = \text{DoF 4}, R_Y = \text{DoF 5}, R_Z = \text{DoF 6}$$

where T is translation, R is rotation and X, Y, Z are the axes.

6.1.2.2 The DoFs shall be ordered in the matrices first according to the numbering of the nodes and second according to the numbering of the DoFs as listed in 6.1.2.1.

6.1.2.3 A local co-ordinate system may be used but shall be defined. In general, local co-ordinates are excluded for the interface DoFs.

6.1.2.4 Nodal point co-ordinates shall be expressed in the reference system of the PL.

6.1.2.5 As a result of these rules, the mass, stiffness and damping matrices may have a size less than $6N \times 6N$, where N is the number of nodal points.

6.1.2.6 The OTMs may be supplied with related user instructions. The output parameters shall be linearly dependent on the acceleration and/or displacement of nodal points.

Thus, the OTMs are likely to have the same number of columns as the stiffness and mass matrices and P rows, where P is the number of output parameters.

6.2 Modal model

6.2.1 General

The dynamic behaviour of the PL shall be described by the reduced stiffness, mass and damping matrices, relative to the elastic modes (modal co-ordinates, η_k) and the interface nodes (the interface DoF, q_j).

This size of the stiffness and mass matrices (and the damping matrix if provided) is Q rows \times Q columns, such that

$$Q = Q_I + Q_m$$

where:

$$Q_I = \text{number of degrees of freedom of the interface}$$

$$Q_m = \text{number of elastic modes}$$

6.2.2 Requirements

6.2.2.1 Unless otherwise specified, each physical nodal point of the interface shall have six DoFs in the reference co-ordinate system:

$$T_X = \text{DoF 1}, T_Y = \text{DoF 2}, T_Z = \text{DoF 3}, R_X = \text{DoF 4}, R_Y = \text{DoF 5}, R_Z = \text{DoF 6}$$

where T is translation, R is rotation and X, Y, Z are the axes.

6.2.2.2 The DoFs shall be ordered in the matrices first according to the numbering of the nodes and second according to the numbering of the DoFs as listed in 6.2.2.1.

The modal DoFs shall be numbered differently from the interface nodes because they are considered to have only one degree of freedom. The modal DoFs shall be ordered in the matrices according to the numbering of the modes.

6.2.2.3 Local co-ordinate systems may be used but shall be defined. In general, local co-ordinates are excluded for the interface DoFs.

6.2.2.4 Nodal point co-ordinates shall be expressed in the reference system of the PL.

6.2.2.5 The OTMs shall be delivered in order to reconstitute loads, accelerations and displacements of nodes and elements that will allow a verification of the payload design.

OTMs shall be separated according to the type of output:

$$\ddot{q}_a = [A] \begin{pmatrix} \ddot{\eta}_k \\ \ddot{q}_j \end{pmatrix}$$

where A is the acceleration transformation matrix (ATM);

$$q_d = [D] \begin{pmatrix} \eta_k \\ q_j \end{pmatrix}$$

where D is the displacement transformation matrix (DTM);

$$F = [L1] \begin{pmatrix} \ddot{\eta}_k \\ \ddot{q}_j \end{pmatrix} + [L2] \begin{pmatrix} \eta_k \\ q_j \end{pmatrix}$$

where $L1$ and $L2$ are the load transformation matrices (LTM1 and LTM2).

The size of these matrices is P rows \times Q columns, where Q is defined in 6.2.1 and represents the size of the mass or stiffness matrix, and P is the number of output transformation parameters.

NOTE P is not necessarily the same for each type of matrix.

For the modal model, if a damping matrix is provided it shall be defined as follows:

- damping relative to interface nodes shall be assumed to be 0, or shall be defined by agreement between LSP and PLC;
- damping relative to the elastic modes shall be modal damping.

6.3 Hybrid model

6.3.1 General

A hybrid model is an extended modal model with more physical DoFs than those solely for the interface. Its use is the same as for the modal model.

The dynamic behaviour of the PL shall be described by the reduced stiffness, mass and damping matrices, relative to the elastic modes (modal co-ordinates, η_k), the interface nodes (interface DoF, q_i), and completed by internal nodes (internal DoF, q_{is}) representing the static deformation of the PL when displacements are restricted to the chosen physical DoF, q_{is} .

The size of the stiffness and the mass matrices (and the damping matrix if provided) is Q rows \times Q columns, such that

$$Q = Q_k + Q_l + Q_m$$

where

Q_k = number of physical internal DoFs retained;

Q_l = number of interface DoFs;

Q_m = number of elastic modes.

6.3.2 Requirements

6.3.2.1 Unless otherwise specified, each physical nodal point of interface shall have six DoFs in the reference co-ordinate system:

$$T_X = \text{DoF 1}, T_Y = \text{DoF 2}, T_Z = \text{DoF 3}, R_X = \text{DoF 4}, R_Y = \text{DoF 5}, R_Z = \text{DoF 6}$$

where T is translation, R is rotation and X, Y, Z are the axes.

6.3.2.2 The DoFs shall be ordered in the matrices first according to the numbering of the nodes and second according to the numbering of the DoFs as listed in 6.3.2.1 for physical nodal points.

The modal DoFs shall be numbered differently from interface nodes and internal nodes because they are considered to have only one degree of freedom. They shall be ordered in the matrices according to the numbering of the modes.

To differentiate the interface nodes from the internal nodes, the interface nodes should be ordered first.

6.3.2.3 Local co-ordinate systems may be used but shall be defined. In general, local co-ordinates are excluded for interface DoFs.

6.3.2.4 Nodal point co-ordinates shall be expressed in the reference system of the PL.

6.3.2.5 The OTMs shall be delivered in order to reconstitute the loads, accelerations and displacements of nodes and elements, in order to allow a verification of the payload design.

OTMs shall be separated according to the type of output:

$$\ddot{q}_a = [A] \begin{pmatrix} \ddot{\eta}_k \\ \ddot{q}_j \\ \ddot{q}_{is} \end{pmatrix}$$

where A is the acceleration transformation matrix (ATM);

$$q_d = [D] \begin{pmatrix} \eta_k \\ q_j \\ q_{is} \end{pmatrix}$$

where D is the displacement transformation matrix (DTM);

$$F = [L1] \begin{pmatrix} \ddot{\eta}_k \\ \ddot{q}_j \\ \ddot{q}_{is} \end{pmatrix} + [L2] \begin{pmatrix} \eta_k \\ q_j \\ q_{is} \end{pmatrix}$$

where $L1$ and $L2$ are the load transformation matrices (LTM1 and LTM2).

The size of these matrices is P rows \times Q columns, where Q is defined above and is the size of mass or stiffness matrix, and P is the number of output transformation parameters.

NOTE P is not necessarily the same for each type of matrix.

7 Model delivery checks

7.1 General

The following checks shall be performed on the condensed model before delivery by using one copy of the files to be supplied. Check results shall be delivered with their data when requested.

7.2 Conformity check

7.2.1 Stiffness matrix

The stiffness matrix, K , shall be symmetric ($K^T = K$, where K^T is the transposed matrix), positive and semi-definite (for any vector X , $X^T K X$ shall be positive or null).

7.2.2 Mass matrix

The mass matrix, M , shall be symmetric and strictly positive (for any non-null vector X , $X^T M X$ shall be strictly positive).

7.2.3 Damping matrix

The damping matrix, C , shall be symmetric, positive, and semi-definite.

7.2.4 Rigid mode checks

The rigid-body modes ϕ_R are the displacements of the structure based purely on model geometry rather than stiffness or eigenvector calculations, with the hypothesis of small displacements. The origin for this rigid-body mode is the origin of the reference co-ordinate system. Six unit displacements and rotations are imposed on this node. For a nodal point with co-ordinates (X, Y, Z) , the displacements for the six rigid-body modes are as follows: (column 1 corresponds to the translation along X , ..., column 4, to a rotation around X axis, ...):

$$\begin{pmatrix} 1 & & & & Z & -Y \\ & 1 & & & -Z & X \\ & & 1 & & Y & -X \\ & & & 1 & & \\ & & & & 1 & \\ & & & & & 1 \end{pmatrix}$$

For modal co-ordinates, the displacements for rigid body modes are null. This leads to a matrix with six columns, one for each rigid mode.

7.3 Mass properties check

The rigid mass matrix of the condensed model shall give the correct mass (m), moments of inertia ($I_{XX}, I_{XY}, I_{XZ}, I_{YY}, I_{YZ}, I_{ZZ}$), and the correct values of the CoG ($X_{CoG}, Y_{CoG}, Z_{CoG}$).

The test to be performed is to calculate M_R as defined below:

$$M_R = \phi_R^T M \phi_R$$

This matrix M_R gives the desired values:

$$M_R = \begin{pmatrix} m & 0 & 0 & 0 & -mZ_{CoG} & mY_{CoG} \\ 0 & m & 0 & mZ_{CoG} & 0 & -mX_{CoG} \\ 0 & 0 & m & -mY_{CoG} & mX_{CoG} & 0 \\ 0 & mZ_{CoG} & -mY_{CoG} & I_{XX} & I_{XY} & I_{XZ} \\ -mZ_{CoG} & 0 & mX_{CoG} & I_{YX} & I_{YY} & I_{YZ} \\ mY_{CoG} & -mX_{CoG} & 0 & I_{ZX} & I_{ZY} & I_{ZZ} \end{pmatrix}$$

The difference between theoretically derived non-zero elements of the M_R matrix and the desired values shall be provided by PLC and submitted for approval by the LSP when requested.

Different approaches can be used to obtain positive products of inertia. If this is the case, it should be clearly stated.

7.4 Strain energy check

A constraint check shall be performed when the condensed model is in free-free configuration. The test to be performed consists of calculating the strain energy as defined below:

$$S_e = \frac{1}{2} K_R$$

The resulting K_R matrix shall be provided to the PLC and submitted to the LSP for approval when required.

For diagonal elements of K_R , verify that the three translation values are less than 10^{-2} and that the three rotation values are less than 10^{-1} (in the SI).

7.5 Free-free eigenfrequencies test

In order to check the stiffness and mass matrices without any constraint, a modal calculation in free-free configuration shall be performed with the condensed model, and the results shall be provided to the LSP.

There shall be exactly six eigenfrequencies for the rigid modes. These values shall be less than 10^{-3} and shall be submitted to the LSP for approval if this requirement is not met.

Mass and stiffness matrices shall be calculated in the SI.

7.6 Cantilevered modes

An analysis of the modes shall be performed for the condensed model in the configuration with the PL clamped to LV interface, in order to check the stiffness and mass matrices.

Results shall be provided to the LSP.

The effective masses or mass fractions for each mode within the range of frequencies accepted by the PLC and the LSP shall be delivered.

8 Requested outputs

Required outputs shall be defined by the PLC and the LSP.

These should include the modelling codes, the finite elements and the condensation procedure (see 5.1), the co-ordinates systems (see 5.2), the modelling description files (see 5.3 and Clause 6), the modelling delivery check results (see Clause 7), the files for the nodes, DoFs and matrices (see Clause 10), and may include other supporting information. The minimum basic requirements are given in the relevant sections.

9 Size limitations

Model size shall be defined by an agreement between the PLC and the LSP.

10 Delivery formats

10.1 General

The preferred formats are defined below. All other formats shall be agreed among LSP, PLC and other contracting parties.

All tables or matrices shall be delivered in separate ISO 7-bit files in accordance with ISO 646.

The following format shall be used:

- An integer (I) shall be written in 2 characters (FORTRAN format I2), 8 characters (FORTRAN format I8) or 20 characters, (FORTRAN format I20). In the following paragraphs, values with this format are denoted by "(I2)", "(I8)" or "(I20)".
- A real value (R) shall be written in the FORTRAN format E22.16. In the following paragraphs, values with this format are denoted by "(E22.16)".

EXAMPLE `-.2407199523591110E+01.`

- A text shall be written directly with a limited number of characters. This limitation is identified in the following paragraphs by A_i , where i is the limiting value. A60 for example indicates a text of 60 characters.

NOTE ARIANE and NASTRAN are two file formats that have been used widely for this purpose.

10.2 File header record

Each file shall begin with a header record, containing information about the model concerned, the date of creation and references.

10.3 Node definition file: Node.def

A file shall contain the list of nodes or modal degrees of freedom and their co-ordinates in the reference co-ordinate system defined in 5.2.

For the modal degrees of freedom, the co-ordinates are taken (1 000,0; 0,0; 0,0). The numbering of nodes shall be compliant with Clause 6.

The DoFs existing in the matrix shall be described.

The format is the following.

- a) One record containing the global number N (I20) of nodes and modal degrees of freedom, and then a title.

EXAMPLE Co-ordinate of the nodes (A60).

- b) One record for each nodal point or each modal degree of freedom containing

- the number (I20) of the nodal point or modal degree of freedom,
- the co-ordinates (3 times E22.16).

- c) One record for end of file containing

- a negative integer (I20),
- the word "EOF" (A3) to indicate the end of the file.

10.4 Degree of freedom definition file: DoF.def

A file shall contain the list of DoFs that exist in the stiffness and mass matrices. The DoFs shall be ordered as defined in Clause 6. For each nodal point or modal degree of freedom, a value of 1 shall designate the existing degrees of freedom, a value of 0 for the others.

The format is the following.

- a) One record containing the global number N (I20) of nodes and modal degrees of freedom.

EXAMPLE Degrees of freedom definition (A60),

- b) One record for each nodal point or each modal degree of freedom containing

- the numbering (I20) of the nodal point or modal degree of freedom,
- six values (I2): 1 if the degree of freedom exists, 0 otherwise.

For the modal DoFs, only the first value exists and it shall be set to 1.

- c) One record for end of file containing
 - a negative integer (I20),
 - the word “EOF” (A3) for the end of the file.

10.5 Matrix files: *****.mat**

10.5.1 Format

All matrices shall be delivered with the same format.

The format is the following:

- a) one record containing the size of the matrix: number of columns (I20), number of rows (I20) and then a title.

EXAMPLE Mass matrix for spacecraft ISO¹⁾ (A40).

- b) one record for each non-null column:
 - the numbering(I20) of the column, IC,
 - the numbering (I20) of the row of the first non-zero value, IR1,
 - the numbering (I20) of the row of the last non-zero value, IR2,
 - a matrix of the values (E22.16) for row IR1 to IR2 inclusive, e.g. (IR2 – IR1 + 1) values.
- c) one record for end-of-file containing
 - a negative integer (I20),
 - the word “EOF” (A3) for the end of the file.

All matrices shall have the same number of columns.

NOTE Mass and stiffness matrices can be provided in the format of the NASTRAN OUTPUT 4 software, under the condition that DIGIT of the OUTPUT 4 function is set to 16 (E22.16 format).

10.5.2 Matrices provided

The following matrices shall be provided:

- stiffness matrix: STIFFNES.mat;
- mass matrix: MASS.mat;
- damping matrix: DAMPING.mat (if requested).

1) ISO is a payload launched on 16 November, 1995.

The following matrices may be delivered:

- acceleration transformation matrix: ACCETM.mat;
- displacement transformation matrix: DISPTM.mat;
- load transformation matrix 1: LOADTM1.mat;
- load transformation matrix 2: LOADTM2.mat.

Any other OTMs may be provided with the agreement of the LSP.

10.6 Output transformation description files: *****.des**

For each OTM, a file describing each output transformation parameter shall be provided. The file name shall have the same root as the matrix file with an extension of “des” (instead of “mat”). The file names shall be “ACCETM.des”, “DISPTM.des”, “LOADTM1.des”, “LOADTM2.des”.

The format of the file shall be the following:

- a) one record containing the number (I20) of output transformation parameters for this type and then a title
 EXAMPLE Description of acceleration restitution (A60).
- b) one record for the description of each parameter containing
 - the numbering (I8) of the corresponding row in the matrix *****.OTM** (in ascending order),
 - an integer (1, 2 or 3) (I2) corresponding to the following:
 - 1 = only minimum and maximum values are requested;
 - 2 = minimum and maximum values and time history plot are requested;
 - 3 = minimum and maximum values, a time-history plot, and a shock spectra plot (quality factor of 10, 20 and 50) are requested.
 - a description (A40) of the output transformation parameter.
- c) one record for end of file containing
 - a negative integer (I20),
 - the word “EOF” (A3) for end of the file.

