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Responsable : ANDRIAMBOLOLONA Harinaivo

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Realization of a study of structural modification starting from measured data

Summary:

The purpose of this document is the description of the implementation of a study of structural modification starting from the measured data. The method used is based on the technique of under-structuring. The first substructure (initial structure) is obtained starting from in experiments identified clean modes and the second substructure (made modification) is modelled numerically by finite elements.

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1 Context

The detection of a too important level of vibration on a given material often causes a stop of use of the material in question, to avoid its ruin. Thus, the installation of solution specific to limit this phenomenon must be brought quickly to allow the good performance of the installation.

Two strategies can be considered. If the problem is generic, the clarification of a predictive model readjusted starting from measured information is the most reliable solution, but retiming is a tiresome stage, and does not allow to adapt calculation to the specificity of each structure. If the problem is specific to a particular material, one wishes to be able, without the stage of retiming of model, to envisage the effects dune modification on the modal characteristics of the structure. The technique presented here enters this second strategy.
In the majority of the cases, one tries to move the Eigen frequencies of the structure so that those are not in the waveband of excitation of the material concerned. The solution usually used consists in adding a mass or a stiffness at a place of the structure chosen beforehand. The method of estimate of the results of a structural modification described in this document, was proposed by Mr. Corus within the framework of his work of thesis [1]. It jointly uses the experimental results of measurement carried out on the initial structure and a digital model of the modification.

The sequence of the various operators is presented. The optimization of the localization and the mechanical characterization of the modification are left with the load of the user. Two manners of making are presented in this document: in section 3, initially developed method, reproduced exactly the method suggested by Mr. Corus in his thesis: the structure is described on modal basis, in generalized coordinates, and the modification on physical basis. This technique is used in the CAS-tests sdll137a and sdll137b. In section 4, the structure and the modification are described by their modal base. This technique, simpler to implement, was developed later on for the realization of a study of modification on a piping. This technique is used in the CAS-test sdll137e, on the same example; Another major interest of the setting in peuvre proposed is that the digital models of the structure and the modification do not need to have nodes coïncidents for the assembly. For information, the CAS-test sdll137c and sdll137d are identical to the versions has and B, but use the macro-order CALC_ESSAI for the realization of calculation.

2 Theoretical recall

This technique of structural modification is based on the method of under-structuring. The first substructure corresponds to the initial structure and the second substructure corresponds to the made modification.
The initial structure is modelled starting from its in experiments identified own modes. Except very particular case, the points of measurement are not at the level of the interface between the initial structure and the modification to be made. Before carrying out the coupling between these two substructures, it is thus necessary to pass by an intermediate stage which consists in condensing the information measured with the interfaces.

The various models which intervene during this calculation are: the model "measures", model "the support" and model "the modification". We will describe these various models hereafter.

To simplify the presentation, we adopt the following notations:
- the index mes is relating to the points of measurement,
- the index int is relating to the nodes interfaces,
- the exhibitor "+" indicates the reverse generalized of a matrix,
- L : matrix of localization (matrix of observability),
- y : field of displacement,
- Φ : matrix made up of the basic vectors of expansion defined on the model support,

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- η_{sup} : generalized coordinates associated with the base of expansion Φ
- ψ : modal matrix identified (deformed clean) on the initial structure,
- η_{test} : generalized coordinates associated with ψ

2.1 The model "measures"

We call model "measures" the modal model of the initial structure obtained starting from measured information. On this model a grid made up of the points of measurement is defined.

A field of measured displacement can be projected on a basis made up of the identified clean modes, that is to say:

$$y_{mes} = \psi \, \eta_{test} \tag{1}$$

One limits oneself to the case of structures little deadened (for which damping can be modelled mode by mode), for which the modal model of the initial structure is written:

$$\left\{ -\omega^2 [Id] + j\,\omega\,[\beta_{test}] + [\Omega_{test}^2] \right\} \eta_{test} = f_{\eta_{test}} \tag{2}$$

Where:

$[Id]$: matrix identity

$[\Omega_{test}^2]$: spectral matrix (diagonal matrix whose diagonal terms are the high own pulsations with square)

$[\beta_{test}]$: matrix of generalized depreciation

$f_{\eta_{test}}$: modal loading

ω : pulsation of excitation

2.2 Model "the support"

We call model "support", the simplified digital model of the initial structure.

This model must comprise the interfaces between the initial structure and the modification. It is used with the expansion and condensation of the information measured with the interfaces.

The expansion consists in finding a field defined on this model support, whose restriction on the points of measurement is nearest possible in experiments measured field. This field is obtained by minimizing the distance between measured information and the information estimated on the model support.

The field of estimated displacement $\tilde{y}_{mes}$ to the points of measurement is given by the following relation:

$$\tilde{y}_{mes} = L_{mes} \, \Phi \, \eta_{sup} \tag{3}$$

The estimated field $\tilde{y}_{mes}$ is of the same type as the measured field y_{mes}.

Generalized coordinates η_{sup}, unknown factors, are obtained by minimizing the distance between the measured field and the estimated field. By using the technique of least squares, one obtains:

$$\eta_{sup} = \left(L_{mes} \, \Phi \right)^+ y_{mes} \tag{4}$$

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One can thus estimate the field $\tilde{y}$ defined in the nodes of the model support, coherent with in experiments measured field.

$$\tilde{y} = \Phi \, \eta_{sup} = \Phi \left(L_{mes} \Phi \right)^{+} y_{mes} \tag{5}$$

The restriction of this field on the degrees of freedom interfaces is:

$$\tilde{y}_{int} = L_{int} \tilde{y} = L_{int} \Phi \left(L_{mes} \Phi \right)^{+} y_{mes} = T_{It} y_{mes} \tag{6}$$

T_{it} can be defined as being the matrix of passage between the points of measurement and the interface between the initial structure and the modification.

By replacing the measured field y_{mes} by his expression (1), one obtains:

$$\tilde{y}_{int} = T_{It} y_{int} = T_{It} \Psi \, \eta_{test} \tag{7}$$

That is to say:

$$\eta_{test} = \left(T_{It} \Psi \right)^{+} \tilde{y}_{int} \tag{8}$$

If one notes: $B = \left(T_{It} \Psi \right)^{+}$, one obtains:

$$\eta_{test} = B \, \tilde{y}_{int} \tag{9}$$

By multiplying the equation (2) on the left by B^{T}, and while replacing η_{test} by its expression (9), dynamic rigidity $\hat{Z}_{test}$ initial structure is given by the following relation:

$$\left[-\omega^2 B^T B + j \omega B^T [\beta_{test}] B + B^T [\Omega_{test}^2] B \right] \tilde{y}_{int} = \hat{Z}_{test} \tilde{y}_{int} = f_{int}^{I} \tag{10}$$

With: f_{int}^{I} : force applied to the interface

2.3   Model "modification"

We call model "modification", the digital model of the modification made to the initial structure.

If one notes Z_x, its dynamic rigidity, by partitionnant the unknown factors in internal degrees of freedom y_i and external degrees of freedom y_e (which is composed of degree of freedom interfaces), the model of the modification can be rewritten in the following way:

$$Z_x q = \begin{bmatrix} Z_{ii} & Z_{ie} \\ Z_{ei} & Z_{ee} \end{bmatrix} \begin{bmatrix} y_i \\ y_e \end{bmatrix} = \begin{bmatrix} f_i^{M} \\ f_e^{M} + f_{eext}^{M} \end{bmatrix} \tag{11}$$

The index i is relating to the internal degrees of freedom, the index e is relating to the external degrees of freedom and f_{eext}^{M} indicate the external force applied to the external degrees of freedom.

2.4   Coupling of the two substructures

The dynamic rigidity of the coupled model is obtained by considering the continuity of displacements to the interfaces:

$$\tilde{y}_{int} = y_e \tag{12}$$

and balances it efforts with the interfaces:

$$f_{int}^{I} + f_e^{M} = 0 \tag{13}$$

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That is to say:

$$\begin{bmatrix} Z_{ii} & Z_{ie} \\ Z_{ei} & Z_{ee} + \hat{Z}_{test} \end{bmatrix} \begin{bmatrix} y_i \\ y_e \end{bmatrix} = \begin{bmatrix} f_i^M \\ f_{eext}^M \end{bmatrix}$$

(14)

The resolution of this system makes it possible to calculate the behavior of the modified structure.

Note: in section 4, the equations of compatibility to the interface are written in modal base, i.e. the equations (12) and (13) are not checked exactly: they are projected on penny-space made up of the base of the extend modes of the structures:

$$\Phi^T \tilde{y}_{int} = \Phi^T y_e$$ (15)

$$\Phi^T f_{int}^I + \Phi^T f_e^M = 0$$ (16)

Since there are in general more degrees of freedom of interface than of clean modes used, the relations (15) and (16) cannot be exactly assured.

2.5 Retro-projection of the field on the points of measurement

One can evaluate the field at the points where the mesure was taken, by retro-projection of the field to the interfaces obtained on the coupled model.

By exploiting the relations (1), (9) and (12), the field at the points of measurement is written:

$$y_{mes} = \Psi \eta_{test} = \Psi B \tilde{y}_{int} = \Psi B y_e$$ (17)

2.6 Quality control of the base of expansion

The quality of the results depends obviously on uncertainty to the measure, but also of the capacity of the base of expansion to represent the behavior of the real structure and the transmission of information on the level of the interface.

The physical direction of the user intervenes on the choice of this base of expansion. It is difficult to know a priori the size of the base of expansion making it possible to obtain the best estimate of the coupled behavior. The quality of the base of expansion can be measured by reappraising the field with the interface by static expansion on the initial model starting from the field resulting from the coupled model.

This indicator does not make it possible to directly estimate the quality of the results got on the coupled model, but it indicates the relevance of the reconstruction of the field to the interface.

3 Implementation of the calculation of structural modification, example of the CAS-tests sdll137a and sdll137b

The data input of calculation are:
*   clean modes (generalized frequencies, deformations, masses) identified on the initial structure,
*   the model with the finite elements simplified of the initial structure (model "support"),
*   the model with the finite elements of the modification suggested (model "modification").

In this section, described method reproduced exactly that proposed by Mr. Corus in his thesis
To illustrate the presentation, we take as example the case test sdll137 [V2.02.137]. We present only the principal stages of modeling.

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3.1 The model "measures"

The model "measurement" makes it possible to define the localization of the points of measurement. The nodes of the grid can be connected to each other by discrete elements, for example, to facilitate the visualization of measured information. The mechanical characteristics that one assigns to this model do not influence the results, they make it possible the model to accommodate the identified clean modes.

That is translated on the level Aster in the following way:

Reading of the grid sensor (points of measurement):

```
MAILEXP=LIRE_MAILLAGE (UNITE=22);

MODLEXP=AFFE_MODELE (MAILLAGE=MAILEXP,
                AFFE=_F (TOUT=' OUI',
                        PHENOMENE=' MECANIQUE',
                        MODELISATION=' DIS_TR',),);
```

Reading of the identified clean modes:

```
MODMESU=LIRE_RESU (TYPE_RESU=' MODE_MECA',
                FORMAT=' IDEAS',
                MODELE=MODLEXP,
                UNITE=21,
                NOM_CHAM=' DEPL',
                MATR_RIGI =KASSEXP,
                MATR_MASS =MASSEXP,
                FORMAT_IDEAS=_F (NOM_CHAM=' DEPL',
                        NUME_DATASET=55,
                        RECORD_6= (1,2,3,8,2,6,),
                        POSI_ORDRE= (7.4,),
                        POSI_NUME_MODE= (7.4),
                        POSI_FREQ= (8.1,),
                        POSI_MASS_GENE= (8.2),
                        POSI_AMOR_GENE= (8.3),
                        NOM_CMP= ('DX', 'DY', 'DZ',
                                'DRX', 'DRY MARTINI', 'DRZ'),),
            TOUT_ORDRE=' OUI',);
```

One can possibly carry out a selection on the modes identified in order to keep only the clean modes most interesting to exploit.

```
MODEIDE=EXTR_MODE (FILTRE_MODE=_F (MODE=MODMESU,
                            NUME_MODE= (1,2,3,4,5,),),);
```

3.2 Model "the support"

Model "the support" is used for the expansion of measurement on the degrees of freedom interfaces. It must contain the nodes interfaces between the initial structure and the modification. On this model, a base of expansion is defined which makes it possible to pass from the degrees of freedom sensors to the degrees of freedom interfaces. This base of expansion can be made up of clean modes, or static answers, or of clean modes of the model support condensed on the degrees of freedom interfaces and degrees of freedom sensor [1]. The quality of the results depends on the faculty of this base to reproduce the real behavior of the structure. The geometrical characteristics and mechanics assigned to this model are not inevitably the exact mechanical characteristics (readjusted) of the real structure,

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but they must be closest possible to physical reality. Indeed, more the model is close to reality, better will be the results of the expansion.

Reading of the grid of model "the support":

```
MAILSUP=LIRE_MAILLAGE (UNITE=20);

MODLSUP=AFFE_MODELE (MAILLAGE=MAILSUP,
                    AFFE= (_F (GROUP_MA= ('BEAM', 'VISUAL',),
                              PHENOMENE=' MECANIQUE',
                              MODELISATION=' POU_D_E',),),),)
```

Definition of the basic vectors of expansion:

```
MODESUP=CALC_MODES (MATR_RIGI=KASSUP,
                   MATR_MASS=MASSUP,
                   OPTION=' PLUS_PETITE',
                   CALC_FREQ=_F (NMAX_FREQ=20,
                               SEUIL_FREQ=1.E-4,),
                   VERI_MODE=_F (SEUIL=1.E-05,
                               STOP_ERREUR=' OUI',),
                  );

MODSTSUP=MODE_STATIQUE (MATR_RIGI=KASSUP,
                      FORCE_NODALE= (_F (GROUP_NO=' CAPTEUR',
                                       AVEC_CMP= ('DY', 'DZ',),),),);

BASEMO=DEFI_BASE_MODALE (RITZ= (_F (MODE_MECA=MODESUP, NMAX_MODE=0,),
                             _F (MODE_STAT=MODSTSUP, NMAX_MODE=8,),),
                       NUME_REF=NUMSUP,);
```

Expansion of the information measured on the model support:

```
PROJ=PROJ_MESU_MODAL (MODELE_CALCUL=_F (MODELE=MODLSUP,
                                     BASE=BASEMO,),
                    MODELE_MESURE=_F (MODELE=MODLEXP,
                                    MESURE=MODEIDE,
                                    NOM_CHAM=' DEPL',),
                    RESOLUTION=_F (METHODE=' SVD',
                               EPS=1.E-5),);
```

Condensation of measurement on the degrees of freedom interfaces (here the degrees of freedom interfaces are selected as being the degrees of freedom "external" of the macronutrient):

```
SSEXP = MACR_ELEM_STAT (DEFINITION=_F (MODELE=MODLSUP,
                                    PROJ_MESU=PROJ,
                                    MODE_MESURE=MODEIDE,
                                    CARA_ELEM =CHCARSUP,
                                    CHAM_MATER=CHMATSUP,),
                      EXTERIEUR=_F (GROUP_NO = ('EXTERNAL',),),
                      RIGI_MECA=_F (),
                      MASS_MECA=_F (),);
```

Creation of the "super-mesh" including the nodes interfaces:

```
MAILCOND=DEFI_MAILLAGE (DEFI_SUPER_MAILLE=_F (MACR_ELEM_STAT = SSEXP,
                                           SUPER_MAILLE=' SUMAIL',),
                      DEFI_NOEUD=_F (ALL = 'YES', INDEX = (1,0,1,8,),),),);
```

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3.3   Coupling of measurement and the modification

Before carrying out the coupling of the substructures, it should be made sure that the grids of the various substructures are coherent (grids expressed in the same frame of reference,…).
The coupling consists in assembling the two models (initial structure condensed with the nodes interfaces and modification) in only one model. The principle is identical to that of the under-structuring.

Reading of the grid of the modification:

```
MAILX=LIRE_MAILLAGE (UNITE=24);
```

Assembly of the two grids (super-mesh + modification):

```
MAILCPL=ASSE_MAILLAGE (MAILLAGE_1=MAILCOND,
                       MAILLAGE_2=MAILX,
                       OPERATION=' SOUS_STR',);


MODLCPL=AFFE_MODELE (MAILLAGE=MAILCPL,
                 AFFE= (_F (GROUP_MA= ('BEAM',),
                        PHENOMENE=' MECANIQUE',
                        MODELISATION=' POU_D_E',),),
                   AFFE_SOUS_STRUC=_F (SUPER_MAILLE = 'SUMAIL',
                                  PHENOMENE=' MECANIQUE',),);
```

3.4   Calculation on the coupled model

After creation and assembly of the elementary matrices, (here, the assembled matrices are KASCPL and MASCPL) one can carry out a modal calculation on the model coupled in order to evaluate the effect of the modification on the first Eigen frequencies of the modified structure.

```
MODECPL=CALC_MODES (MATR_RIGI=KASCPL,
                MATR_MASS=MASCPL,
                OPTION=' PLUS_PETITE',
                CALC_FREQ=_F (NMAX_FREQ=2,
                        SEUIL_FREQ=1.E-4,),
                VERI_MODE=_F (SEUIL=1.E-05,
                        STOP_ERREUR=' OUI',),
                );
```

3.5   Retro-projection on the model measures

It is about a postprocessing which consists in going back to the initial points of measurement. That makes it possible to appreciate the effect, of the modification made compared to initial measurement.

```
MODERETR=DEPL_INTERNE (DEPL_GLOBAL=MODECPL, SUPER_MAILLE=' SUMAIL')
```

3.6   Quality control of the base of expansion

It is always interesting to check the quality of the expansion of measurement. One can check it by using an indicator which gives an account two estimates different from the field to the interface of the coupled model.

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It is a question of comparing the field with the interface by static expansion on the model support starting from the field resulting from the model coupled and the field with the interface of the coupled model.

To be able to make this comparison, one can create a fictitious model containing only the interface. The idea consists in extracting the fields with the interfaces in order to be able to compare them by carrying out a calculation of MAC (Modal Criterion Insurance).

Reading of the grid of the interface:

```
MAILINT=LIRE_MAILLAGE (UNITE=26);

MODLINT=AFFE_MODELE (MAILLAGE=MAILINT,
                 AFFE=_F (GROUP_MA=' VISUAL',
                       PHENOMENE=' MECANIQUE',
                       MODELISATION=' DIS_TR',),);
```

Calculation of the static answer on the model support:

```
MODSTINT=MODE_STATIQUE (MATR_RIGI=KASSUP,
                   FORCE_NODALE= (_F (GROUP_NO=' CAPTEUR',
                              AVEC_CMP= ('DY', 'DZ',),),),);
```

Definition of the base for the static expansion:

```
BASEINT=DEFI_BASE_MODALE (RITZ= (_F (MODE_MECA=MODESUP, NMAX_MODE=0,),
                        _F (MODE_STAT=MODSTINT, NMAX_MODE=4,),),
                     NUME_REF=NUMSUP,);
```

Static expansion of the field at the points of measurement obtained at the time of the resolution at the total level:

```
PROJMS=PROJ_MESU_MODAL (MODELE_CALCUL=_F (MODELE=MODLSUP,
                                BASE=BASEINT,),
                   MODELE_MESURE=_F (MODELE=MODLEXP,
                                MESURE=MODERETR,
                                NOM_CHAM=' DEPL',),
                   RESOLUTION=_F (METHODE=' SVD',
                           EPS=1.E-5),);

DEPLPR=REST_GENE_PHYS (RESU_GENE=PROJMS,
                  TOUT_ORDRE=' OUI',
                  NOM_CHAM=' DEPL');
```

Field with the interfaces obtained by static expansion:

```
DEPLINT=PROJ_CHAMP (METHODE=' ELEM',
                RESULTAT=DEPLPR,
                MODELE_1=MODLSUP,
                MODELE_2=MODLINT,
                NOM_CHAM=' DEPL',
                TOUT_ORDRE=' OUI',
                NUME_DDL=NUMINT,);
```

Field with the interfaces obtained at the time of the resolution at the total level:

```
DEPLXINT=PROJ_CHAMP (METHODE=' ELEM',
```

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```
                    RESULTAT=MODECPL,
                    MODELE_1=MODLCPL,
                    MODELE_2=MODLINT,
                    NOM_CHAM=' DEPL',
                    TOUT_ORDRE=' OUI',
                    NUME_DDL=NUMINT,);
```

The base of expansion is acceptable if the two fields defined in the interfaces are very close. The distance between the two fields can be measured by calculating the scalar product between these two vectors by a calculation of MAC (Modal Criterion Insurance).

```
MACINT=MAC_MODES (BASE_1=DEPLINT,
                  BASE_2=DEPLXINT,
                  INFORMATION  =2,);
```

This matrix of MAC must be possible nearest matrix identity. A matrix of MAC very different from the matrix identity indicates that the base of selected expansion does not make it possible to rebuild information with the interfaces well. In this case, it is advised to choose another base for the expansion of measurement.

One can also evaluate the distance between the two vectors by calculating energy criterion IERI (Indicating Energetics of Regularity of Interface). This criterion utilizes the matrix of mass or the matrix of rigidity of the structure.

```
IERIK = MAC_MODES (BASE_1=DEPLINT,
                   BASE_2=DEPLXINT,
                   MATR_ASSE=KASMAC,
                   IERI=' OUI',
                   INFORMATION  =2,);

IERIM = MAC_MODES (BASE_1=DEPLINT,
                   BASE_2=DEPLXINT,
                   MATR_ASSE=MASMAC,
                   IERI=' OUI',
                   INFORMATION  =2,);
```

4   Implementation of the calculation of structural modification, example of the CAS-test sdll137e

The method presented here differs slightly from that proposed in the preceding section. Here, the two structures are described by their modal base, whereas in section 3, the modification is described by its physical coordinates (model finite element). The implementation of this method is much simpler, because it is based largely on the techniques of under-structuring described in following documentations:
   •   reference material on the R4.06.02 under-structuring
   •   documentation of use for the installation of a dynamic calculation of under-structuring: U2.07.05.
Another advantage (essential) of this methodology is that the digital models of the structure and the modification do not need to have nodes coïncidents. The assembly of the two substructures is done by using the operator of projection of grid to the interface (techniques identical to what is made for the option `LIAISON_MAIL` of `AFFE_CHAR_MECA` and in `PROJ_CHAMP`)

One does not present here the details of the implementation of a calculation by under-structuring, but one has specificities of this CAS-test, adapted if the model of the basic structure is not readjusted.

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4.1 Experimental model of the structure

One created an experimental model on the grid on which measurement was carried out, and into important the base of modes identified via a software of modal identification. The reading of the modes is made with LIRE_RESU. The detail of the method is given in section 3, and in Doc. U2.07.06.

```
MODMtmp=LIRE_RESU (TYPE_RESU=' MODE_MECA',
                FORMAT=' IDEAS',
                MODELE=MODLEXP,
                UNITE=21,
                NOM_CHAM=' DEPL',
                FORMAT_IDEAS=_F (NOM_CHAM=' DEPL',
                                NUME_DATASET=55,
                                RECORD_6= (1,2,3,8,2,6,),
                                POSI_ORDRE= (7.4,),
                                POSI_NUME_MODE= (7.4,),
                                POSI_MASS_GENE= (8.2,),
                                POSI_AMOR_GENE= (8.3,),
                                POSI_FREQ= (8.1,),
                                   NOM_CMP= ('DX', 'DY', 'DZ', 'DRX', 'DRY
MARTINI', 'DRZ',),),
                MATR_A=KASSEXP,
                MATR_B=MASSEXP,
                TOUT_ORDRE=' OUI',);
```

4.2 Model support

The model support is a model finite elements of the same structure, not readjusted. That means for example, that its Eigen frequencies do not correspond at all to the Eigen frequencies of the real structure.

```
MAILSUP=LIRE_MAILLAGE (UNITE=20,);

MAILSUP=DEFI_GROUP (reuse=MAILSUP, MAILLAGE=MAILSUP,
                CREA_GROUP_NO=_F (NOM=' CAPT2',
                                DIFFE= ('SENSOR', 'EXTERNAL'),),);

MODLSUP=AFFE_MODELE (MAILLAGE=MAILSUP,
                AFFE=_F (GROUP_MA= ('SIMPLE', 'VISUAL',),
                        PHENOMENE=' MECANIQUE',
                        MODELISATION=' POU_D_E',),);

MATSUP=DEFI_MATERIAU (ELAS=_F (E=2.1E11,
                            NU=0.3,
                            RHO=7800.,),);

MATDBL=DEFI_MATERIAU (ELAS=_F (E=4.2E11,
                            NU=0.3,
                            RHO=15600.,),);

# 'SIMPLE': group not amending. 'VISUAL': group
# supporting the modification
CHMATSUP=AFFE_MATERIAU (MAILLAGE=MAILSUP,
                    MODELE=MODLSUP,
                    AFFE= (_F (GROUP_MA=' SIMPLE',
                        MATER=MATSUP,),
                       _F (GROUP_MA=' VISUAL',
                        MATER=MATDBL,),),);
```

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```
            CHCARSUP=AFFE_CARA_ELEM (MODELE=MODLSUP,
                               POUTRE=_F (GROUP_MA=' POUTRE',
                                     SECTION=' RECTANGLE',
                                     CARA= ('HY', 'HZ',),
                                     VALE= (9E-3,38E-3,),),
                               ORIENTATION=_F (GROUP_MA=' POUTRE',
                                       CARA=' VECT_Y',
                                       VALE= (0. , 0. , 1. ,),),),);


            CONDLSUP=AFFE_CHAR_MECA (MODELE=MODLSUP,
                            DDL_IMPO= (_F (GROUP_NO=' FIXE',
                                       LIAISON=' ENCASTRE')));


    ASSEMBLY (MODELE=MODLSUP,
             CHAM_MATER=CHMATSUP,
             CARA_ELEM=CHCARSUP,
             CHARGE=CONDLSUP,
             NUME_DDL=CO ('NUMSUP'),
             MATR_ASSE= (_F (MATRICE=CO ('KASSUP'),
                       OPTION=' RIGI_MECA',),
                      _F (MATRICE=CO ('MASSUP'),
                       OPTION=' MASS_MECA',),),);


    BAMO=MODE_STATIQUE (MATR_RIGI=KASSUP,
                   MATR_MASS=MASSUP,
                   FORCE_NODALE= (_F (GROUP_NO= ('CAPT2', 'EXTERNAL'),
                             AVEC_CMP= ('DY', 'DZ',),),),),);
```

NB: in the method suggested above, one calculates the static statements corresponding to the degrees of freedom of the sensors. For little that the grid is sufficiently fine, there exist always nodes of the grid support "close relations" of the position of the sensors. IF it is not the case, a method is proposed in the CAS-test sdlll137e, using an external routine python (called `calc_modestat_capteurs`), to calculate the statements statics corresponding rigorously to the position of the sensors. This method "seeks" the nodes close to the sensors, and calculates the static statement corresponding by sum balanced of the statements on these nodes.

4.3   Expansion of the experimental modes

Experimental modes identified on the structure and imported on model in section 4.1 are interpolated on the model support via the methods of expansion presented in section 2. The base of expansion is made up of the static statements calculated previously (the base BAMO), reorthonormalized via the following operations:

```
PROJ_BASE (BASE=BAMO,
         STOCKAGE=' PLEIN',
         MATR_ASSE_GENE= (_F (MATRICE=CO ('KPROJ'),
                         MATR_ASSE=KASSUP,),
                        _F (MATRICE=CO ('MPROJ'),
                         MATR_ASSE=MASSUP,),),);


nbmod_expans = 5
MODGENE=CALC_MODES(MATR_RIGI=KPROJ,
               MATR_MASS=MPROJ,
               OPTION=' PLUS_PETITE',
               CALC_FREQ=_F (NMAX_FREQ=nbmod_expans,),
               VERI_MODE=_F (STOP_ERREUR=' NON'),
             );
```

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```
MODREPHY=REST_GENE_PHYS (RESU_GENE=MODGENE, NOM_CHAM=' DEPL')
```

Modes of `MODREPHY` generate the same subspace as `BAMO`, but its components are classified by increasing Eigen frequencies. By choosing the parameter well `nbmod_expans`, one can control the regularity of the base of extend modes generated. The choice of this parameter is determining for the quality of calculation, and several methods are proposed, in particular in the thesis of Mr. Corus, to choose the best compromise.

The expansion is done in the two following stages:

```
# bases extend modes for the structure
tmp=PROJ_MESU_MODAL (MODELE_CALCUL=_F (MODELE=MODLSUP,
                                       BASE=MODREPHY,),
                     MODELE_MESURE=_F (MODELE=MODLEXP,
                                       MESURE=MODMESU,),);


# bases extend modes for the structure
MODEET=REST_GENE_PHYS (RESU_GENE=tmp)
```

4.4 Creation of the macronutrient associated with the structure

The base of extend modes in the following orders is `BAMOSTRU`. The macronutrient is manufactured while giving to `MACR_ELEM_DYNA` :
*   this base of deformations,
*   the modal characteristics identified on the model measures (called here `freq`, `amor` and `farmhouse`)

```
INTSTRU=DEFI_INTERF_DYNA (NUME_DDL=NUMSUP,
                          INTERFACE=_F (NAME = 'INTSTRU',
                                        TYPE = 'MNEAL',
                                        GROUP_NO = 'EXTERNAL'))

BAMOSTRU=DEFI_BASE_MODALE (RITZ=_F (MODE_MECA = MODEET),
                           NUME_REF=NUMSUP,
                           INTERF_DYNA=INTSTRU)



freq = MODMESU.LISTE_PARA () ['FREQ']
amor = MODMESU.LISTE_PARA () ['AMOR_REDUIT']
farmhouse = MODMESU.LISTE_PARA () ['MASS_GENE']

MACELSTR=MACR_ELEM_DYNA (BASE_MODALE=BAMOSTRU,
                         MODELE_MESURE=_F (FREQ=freq,
                                           MASS_GENE=mass,
                                           AMOR_REDUIT=amor,));
```

4.5 Model modification

The model of the modification is entirely digital (in general much simpler, the stage of retiming is not necessary). In the CAS-test sdll137e, one proposes to create the macronutrient who simply describes it with the macro-order `CREA_ELEM_SSD`.

```
MACELMOD = CREA_ELEM_SSD (
                MODEL = MODMODI,
```

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```
                         LOAD = CONDMODI,
                         CHAM_MATER = CHMAMODI,
                         CARA_ELEM = CARAMODI,
                         INTERFACE = _F (NAME = 'INTMODI',
                                         TYPE = 'CRAIGB',
                                         GROUP_NO = 'EXTERNAL'),
                         BASE_MODALE = _F (STANDARD = 'RITZ',
                                           TYPE_MODE = 'STATIC',
                                           ),
                         CALC_FREQ = _F (OPTION=' SANS'),);
```

4.6 Assembly of the substructures, and calculation of the Eigen frequencies of the modified structure

The assembly is done also simply by using the macro-order ASSE_ELEM_SSD.

```
ASSE_ELEM_SSD (RESU_ASSE_SSD = _F (
                                 MODEL = CO ('MODEGE'),
                                 NUME_DDL_GENE = CO ('NUMEGE'),
                                 RIGI_GENE = CO ('RIGGEN'),
                                 MASS_GENE = CO ('MASGEN'),
                                 ),
               SOUS_STRUC = (_F (NAME = 'MODIFICATION',
                                 MACR_ELEM_DYNA = MACELMOD,),
                              _F (NAME = 'STRUCT',
                                 MACR_ELEM_DYNA = MACELSTR,),),
               LIAISON=_F (SOUS_STRUC_2=' STRUCT',
                           INTERFACE_2=' INTSTRU',
                           SOUS_STRUC_1=' MODIFICATION',
                           INTERFACE_1=' INTMODI',
                           GROUP_MA_MAIT_2=' toto',
                           OPTION=' REDUIT'),
               VERIF = _F (STOP_ERREUR = 'YES',
                           PRECISION = 1.E-6,
                           CRITERION = 'RELATIVE'),
               METHOD = 'ELIMINATES',
               );
```

Note: the use of the keyword GROUP_MA_MAIT_2 allows to declare the direction of the master-slave relation for projections of nodes of a substructure on the other. It is not necessary to specify the group of meshs used, because, with the option REDUCED, the code uses by default the group which was declared in the definition of the interface in DEFI_INTERF_DYNA.
Calculation of the Eigen frequencies of the assembled structure:

```
RESGEN=CALC_MODES(MATR_RIGI=RIGGEN,
                  MATR_MASS=MASGEN,
                  OPTION = 'BAND',
                  CALC_FREQ=_F (FREQ = (1.0, 1000.0),),
                  SOLVEUR_MODAL=_F (DIM_SOUS_ESPACE=10,),
                  VERI_MODE=_F (STOP_ERREUR=' NON',
                                STURM=' NON',),
                  SOLVEUR=_F (METHODE=' MUMPS'),
                  );

FREQ=RECU_TABLE (CO=RESGEN, NOM_PARA=' FREQ')
```

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It should be noted that here, contrary to the other CAS-tests, no method of checking of the quality of calculation is proposed by retro-projection on the sensors of the structure. One could plan to add this procedure. The results of the CAS-tests are appreciably equal to those obtained for sdll137a and B.

5   Conclusion

The procedure of calculation of structural modification presented here is based on the joint exploitation of the measured data and the digital model of the modification. It uses the principle of the under-structuring for the coupling of the two models.

This technique should not be used like a black box. The user must intervene on the choice of the base of expansion so that this one is most relevant possible. He must also find the modification the most adapted to the constraint imposed by the environment where is the initial structure.

One never insists enough on the importance of the implementation of experimental measurement. Indeed, uncertainties on the experimental data are propagated throughout calculation and can lead to an important error on the final results. It is highly advised that the person who makes the mesure is the same one as that which implements digital modeling. It is ready to exploit the measured data, and more with same to carry out the coupling between measurement and calculation.

6   Bibliography

[1]   Mr. CORUS, Thesis ECP n° 2003-23, Improvement of the methods of structural modification per use of techniques of expansion and reduction of model.

[2]   Handbook of validation (V2.02.137): SDLL137 – structural Modification of a beam.

[3]   B. GROULT, Thesis ECP n° 2008-14, Extension of a method of structural modification for the design of dissipative devices integrating of viscoelastic materials.