

Dynamic Analysis with

VecTor2

This bulletin describes the dynamic analysis facilities within VecTor2. Details of VecTor2 and FormWorks can be found in the ‘VecTor2 and FormWorks Manual’ (Vecchio and Wong, 2003). Details of the dynamic analysis methodology and algorithms employed by VecTor2 can be found in Saatci (2007).

It should be noted that modelling for dynamic analysis with VecTor2 is largely done using standard static analysis features, with the addition of dynamic properties such as structural mass, damping and dynamic loading. In other words, structural modelling, such as mesh creation and material model selection, is identical as for static analysis, which can be completed with FormWorks. On the other hand, some parameters required for dynamic analysis have to be introduced manually by modifying the input text files created with FormWorks. The following sections give the details of the required input modifications based on the input fields. [Note that the input files created by FormWorks are ASCII type text files, which can be opened and edited manually by common applications such as MS Windows Notepad®.] In the following discussions, the parameters in the FormWorks input fields are denoted by `Courier` typeface.

1. Job Data

To initiate a dynamic analysis in FormWorks, the `Analysis Mode` in the `JOB CONTROL` tab of `DEFINE JOB` window has to be set to one of the two ‘Dynamic Nonlinear’ options. ‘Dynamic Nonlinear – General’ is used for impact and impulse load analysis, as well as ground acceleration analysis when the ground acceleration data is input through `APPLY GROUND ACCELERATION` data input

facility of FormWorks. 'Dynamic Nonlinear - EQ Record' is used when a VECTOR.EQR file is used for ground acceleration input. See Section 2.4 for details.

VecTor2 employs a step-by-step numerical integration method for the numerical evaluation of the dynamic response. Therefore, the load stages and resulting load stage output files in static analysis correspond to a time and the response at that time in dynamic analysis, respectively.

The time-step size for the analysis is specified in the first load case parameters. The first load case, and the corresponding load case file specified, should contain the dynamic mass information (see Section 2.1). The initial and final load factor coefficients are ignored for the first load case in dynamic analysis. Note that, if there are static loads present in the first load case file (such as self weight), their load factor is taken as 1.0 automatically. The load step increment, `Inc.Factor`, is the time increment between the recorded output files. `Repetitions` specifies the number of time subdivisions between two output files (Note that Load Type should be set to 'Cyclic' to enable `Repetitions` input). In other words, the actual time-step used for numerical integration is determined by $\text{Inc.Factor}/\text{Repetitions}$. For example, in the example given in Figure 1, the time-step size used for numerical integration is $0.001/10 = 0.0001$ s, whereas an output file is created at every 0.001 s rather than every time-step. This feature is mostly used to avoid a large number of output files if the analysis requires a very short time-step.

The total number of output files recorded, hence the total duration of the analysis, is determined by `No.of load stages`. In dynamic analyses with VecTor2, the first load stage is set for 0.0 s, in the rest condition, corresponding to the response under static loads. Therefore, in the example shown in Figure 1, the duration of the analysis is $(300-1) \times 0.001 \text{ s} = 0.299$ s, which is achieved in 2990 time-steps of 0.0001 s length, and an output file is created at every 10th time-step totalling 299 output files, excluding the first output file for the static loads.

The time-step size is an important parameter directly affecting the stability and the accuracy of the solution. Issues regarding the time-step size selection are discussed in Saatci (2007) in detail. One approach for assuring a sufficiently short time-step size is repeating the analysis with a reduced the time-step size and checking if the two solutions with different time-steps yield near-identical response. If they do not, the time-step size must be reduced. Another approach is to check the energy balance as explained in Saatci (2007). Such a feature for assisting the time-step size selection will be adopted in the future versions of VecTor2.

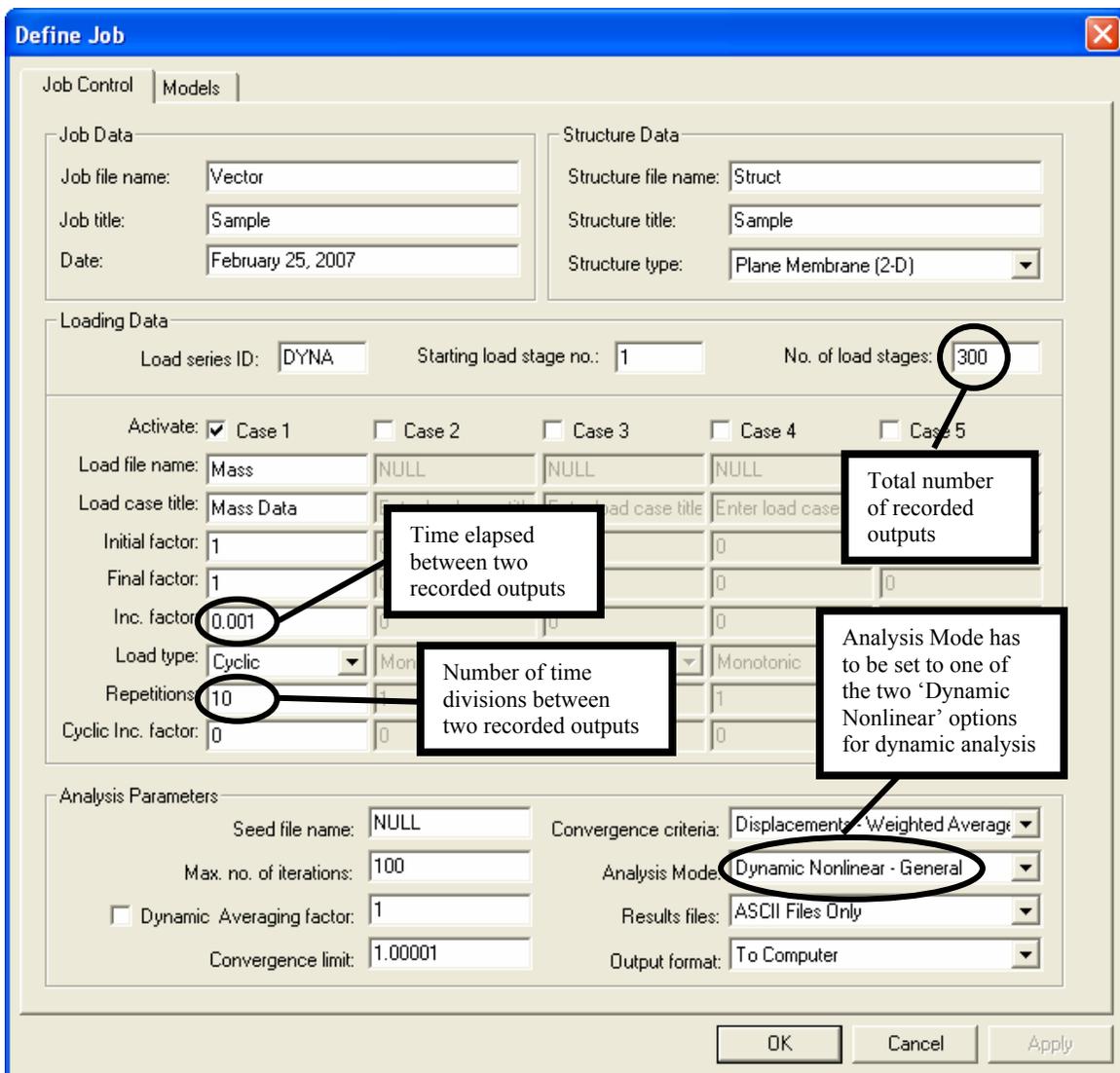


Figure 1. Sample job definition

2. Load Data

The majority of the dynamic loads are introduced using the load definition provisions within FormWorks; i.e., in specifying *Lumped Masses*, *Impulse Forces*, and *Ground Accelerations*. The following sections provide details for introducing the mass and dynamic loads that can be considered in VecTor2.

2.1 Structural Mass

Structural masses in VecTor2 are lumped at the nodes. Details of the methodology used for establishing mass matrix can be found in Saatci (2007).

Nodes with lumped masses should be declared with the `APPLY LUMPED MASSES` facility within FormWorks. The mass data required for each node is as follows:

NODE	Node number
DOF-X	1 if the mass is activated in x-direction. 0, otherwise.
DOF-Y	1 if the mass is activated in y-direction. 0, otherwise.
MASS	Nodal mass in kilograms.
GF-X	Multiplier for static load in x-direction. Nodal mass is converted to force, multiplied with this coefficient and applied as a superimposed static load in x-direction. This feature is intended mostly for the consideration of the self-weight when specified as 1 or -1. Gravitational acceleration, g , is assumed as 9.81 m/s for conversion.
GF-Y	Multiplier for static load in y-direction.
VO-X	Initial velocity of the mass in x-direction. (See impact loads)
VO-Y	Initial velocity of the mass in y-direction. (See impact loads)
#NODE	Number of nodes to be produced with identical properties (optional)
d(NODE)	Node number increment for additional nodes with identical properties (optional)

A common approach to determine the nodal masses is calculating the mass of an element and dividing it equally to the element's nodes. The total nodal mass is then determined by summing the contributing masses found from the elements intersecting at the same node. It should be noted that, in the current version of VecTor2, the density data entered in the Concrete Material Properties section are not converted to nodal masses automatically. However, the density data entered in the concrete materials definition are converted and included as static self-weight loads. Therefore, attention is required not to double-count the self-weight if density data is specified in the Concrete Material Properties definition and a non-zero GF-X or GF-Y is specified in the LUMPED MASSES input. It should be noted that a default concrete density ($=2400 \text{ kg/m}^3$) is assumed if density data is entered equal to or less than zero in structure data. Therefore, a very small positive density, such as 0.1 kg/m^3 , is recommended to avoid incorrect self-weight if the mass data is entered in load case with non-zero static load multipliers.

2.2 Impact Loads

When the mass and the contact velocity of the impacting body are known, impact loads are introduced by assigning the contact velocity as an initial velocity, V_0-X or V_0-Y , to the lumped masses representing the impact object. Depending on the specifics of the problem, this approach may require the use of some particular modelling techniques for accurately representing the actual impact problem. For example, modelling the impact of a free-falling drop-weight on a reinforced concrete beam, as presented in Saatci (2007), required the use of compression-only truss bars, as shown in Figure 2. In this problem, the drop-weight was modelled using four rigid rectangular elements connected to the specimen by five compression-only truss bars, so that when the drop-weight bounced back, it would not pull up on the specimen. These truss bars were assigned very high stiffness properties to represent a hard impact. Note that, in the case of a soft impact, stiffness of these truss bars can be assigned with the stiffness properties of the drop-weight.

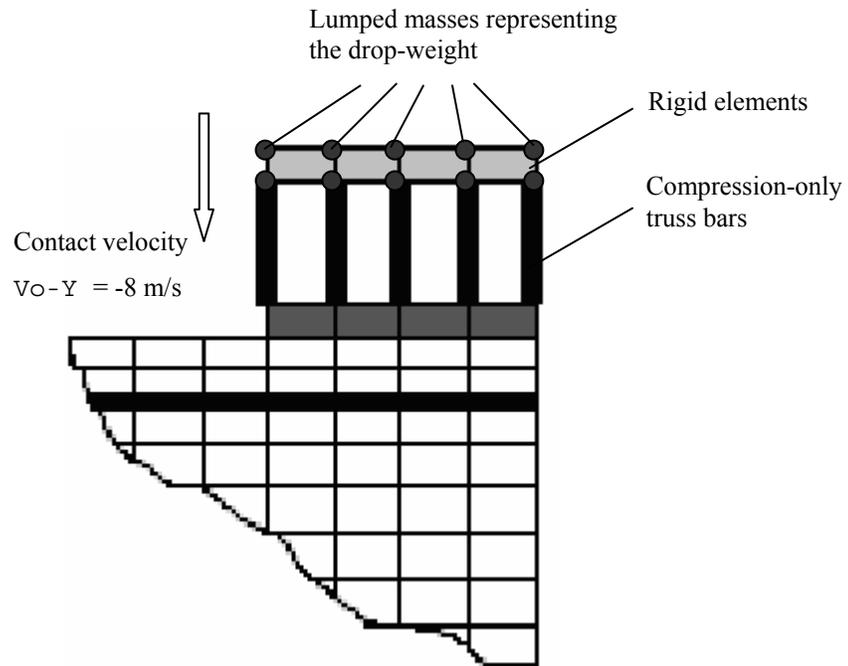


Figure 2. Modelling the impact (Saatci 2007)

Also note that, in some impact problems, the force-time history of the impact forces may be known in advance. In such cases, impact problem can be modelled by using impulse forces as explained in the following section.

2.3 Impulse Forces

Impulse forces are typically described as short-duration, high-intensity forces. In VecTor2, such forces can be applied to specific nodes in the finite element mesh through the `APPLY IMPULSE FORCES` data input facility of FormWorks.

The impulse force applied to a node may have a trilinear variation in time. Four force-time points are entered for each node to specify the impulse force history. VecTor2 assumes a linear variation between these points. Note that the impulse force is assumed to drop to zero after the last point (Figure 3). Impulse force data is entered in the following order for each node.

NODE Node number
 DOF 1 if the force is applied in x-direction.
 2 if the force is applied in y-direction.
 T1 , F1 , T2 ,
 F2 , T3 , F3 ,
 T4 , F4 Impulse force data points (see Figure 3).
 #NODE Number of nodes to be produced with identical force (optional)
 d (NODE) Node number increment for additional nodes with identical force (optional)

Impulse forces can be used in impact problems if the impact load-time history is known. In case of blasts, complementary software, such as VecTor-Blast, can be used to determine the impulse forces acting on various locations of a structure.

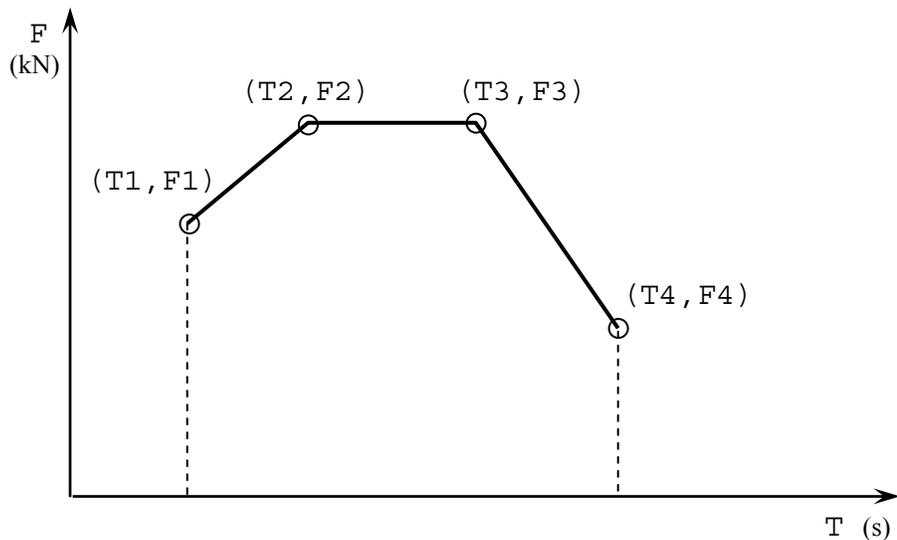


Figure 3. Variation of impulse forces in VecTor2

2.4 Ground Acceleration

Ground acceleration can be introduced in VecTor2 in two ways: through APPLY GROUND ACCELERATION data input facility of FormWorks, or through a VECTOR.EQR file.

Ground Acceleration as FormWorks Input Data

Ground acceleration data can be input manually in FormWorks using the APPLY GROUND ACCELERATION LOAD input facilities. Here, ground acceleration is entered as follows:

TIME	Time in seconds.
ACC-X	Ground acceleration in x-direction, in terms of gravitational acceleration, $g = 9.81 \text{ m/s}^2$.
ACC-Y	Ground acceleration in y-direction, in terms of gravitational acceleration, $g = 9.81 \text{ m/s}^2$.

Note that the ground acceleration can be introduced by its x- and y-components. If the acceleration is only in one direction, the other component should be specified as zero. Data should be entered in time-wise ascending order. The time for the last entry should be greater than or equal to 999, as a marker for the end of the record.

Ground Acceleration in VECTOR.EQR File

Most earthquake records are available on the internet as downloadable text files. The most common file formats used for distributing these records can be used directly as ground acceleration data in VecTor2 with minor edits. A list of some popular internet earthquake record databases can be found at the end of this bulletin.

The text file containing the earthquake record should be renamed as VECTOR.EQR, and the file has to be placed in the same folder with the other input files. The VECTOR.EQR file must have the following format.

```

4
"NORTHRIDGE EARTHQUAKE - SANTA MONICA, CITY HALL GROUNDS"
"JANUARY 17, 1994, 04:31 PST"
"CORRECTED ACCELEROGRAM, CHANNEL 1, 90 DEGREES, CDMG QN94A538"
"SOURCE: NISEE, U.C. BERKELEY, CALIFORNIA"
3000 0.02 8 CM
3000 0.02 8 CM
3000 0.02 8 CM
3000 POINTS OF ACCEL DATA EQUALLY SPACED AT .020 SEC. (UNITS: CM/SEC/SEC)
2.321 1.647 .854 -.188 -1.492 -.155 1.559 1.468
1.468 .234 -1.725 -.507 .331 .014 1.031 1.911

```

- ① Number of following lines to be skipped containing supplementary information
- ② Lines to be skipped containing supplementary information
- ③ *Total number of data points, time increment, number of data points in a row, data unit (M for m/s², CM for cm/s², MM for mm/s²)*
- ④ Lines to be skipped containing supplementary information, exactly 3 lines
- ⑤ Acceleration data in row-wise order

Note that the direction of the applied ground acceleration record is specified in the VT2.AUX file, which is explained in the following section. When a VECTOR.EQR file is used, no Ground Acceleration Record should be specified in FormWorks.

3. Auxiliary Data (AUX) File

The Auxiliary Data File VT2.AUX contains various analysis parameters that are not set by FormWorks. Some dynamic analysis parameters are also contained in this file. Details of these parameters are described below.

NEWMARK BETA FACTOR, NEWMARK GAMMA FACTOR

These parameters are the constants β and γ used for Newmark's direct numerical integration method. Details of this method, and its application in VecTor2, are described in Newmark (1959) and Saatci (2007). Typically, the γ -value is commonly set to 0.5, since any other value introduces artificial numerical damping into the solution (Newmark 1959). The β -value determines how the acceleration changes within a time-step. $\beta = 1/4$ is

used when the acceleration is constant within a time-step (constant acceleration method), and $\beta = 1/6$ is used when the acceleration changes linearly from the beginning to the end of a time-step (linear acceleration method). Other values are also possible, but special care is required since they may have severe effects on the accuracy and the stability of the solution. The constant acceleration method, with $\beta = 1/4$, is found to yield accurate and stable results with the analyses carried out in Saatci (2007) using VecTor2, and therefore, is recommended.

MODAL FACTOR #1, MODAL FACTOR #2, DAMPING FACTOR #1, DAMPING FACTOR #2

As explained in Saatci (2007), VecTor2 uses the Rayleigh method of introducing damping to the system. Rayleigh damping assumes a certain calculated variation of damping ratios between the vibrational modes. In this method, the specific damping ratios are assigned to two selected vibrational modes, and damping ratios for the remaining modes are calculated accordingly (Figure 4). In VecTor2, MODAL FACTOR #1 and #2 corresponds to the selected modes of vibration for which the damping ratios are to be specified, and DAMPING FACTOR #1 and #2 are the damping ratios to be assigned to these two selected modes, respectively.

A detailed discussion on the selection of these damping parameters can be found in Saatci (2007). In the impact analyses carried out using VecTor2, MODAL FACTOR #1 and #2 were selected as 1 and 2, respectively. Then, these modes were assigned with minimal damping ratios, only to ensure a numerically stable solution. These damping ratios were found as a result of a series of repeated analyses. Damping ratios were reduced in consecutive analyses until the solution became unstable, and minimum damping ratios that yielded a stable solution were selected as final damping ratios. Note that this method of determining the damping ratios requires repeating the analysis several times with different damping ratios. However, it was found to be effective and successful in the analyses carried out in Saatci (2007).

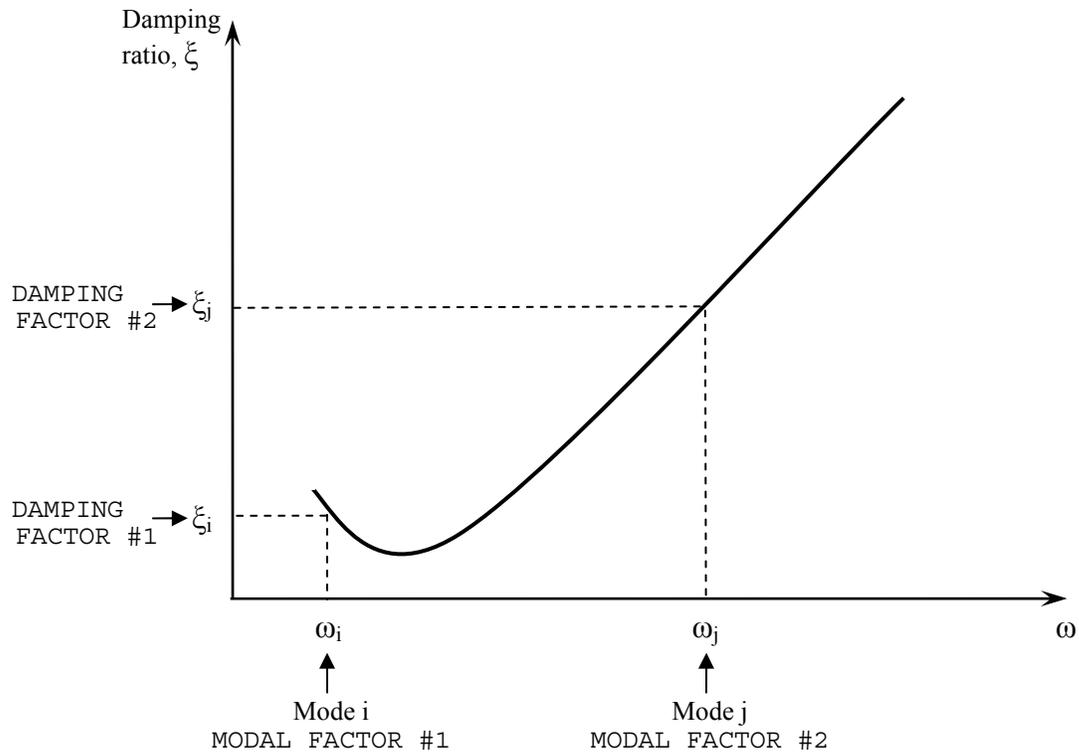


Figure 4. Variation of modal damping ratios with natural frequency

GROUND ACCELERATION IN X-DIRECTION / Y-DIRECTION

1 if the ground acceleration is applied in the respective direction.

0 otherwise.

Note that this parameter is only used if VECTOR.EQR file is used as ground acceleration input.

4. Eigen Analysis and EIGEN.TXT File

If a non-zero damping ratio is assigned for the two modes specified in AUX file, VecTor2 carries out an eigen analysis to determine the coefficients required for Rayleigh damping. Eigen analysis is carried out at the end of the first load step, prior to starting the dynamic time-step analysis, and the results are stored in an EIGEN.TXT file. EIGEN.TXT file

contains modal vibrational periods and the damping ratios calculated for each mode according to Rayleigh damping. An examination of the modal periods can give an indication of the effects of the vibrational periods on the system, i.e. if the structure has a single dominant vibrational mode, or if it has several contributing modes that affect the response significantly. If the system has several effectively contributing modes, some analysis choices may have to be revised, such as the mesh size, time-step size, and damping ratios.

References

Newmark, N. M. (1959). "A method of computation for structural dynamics." Journal of the Engineering Mechanics Division, ASCE, Vol.85, pp.67-94.

Saatci, S. (2007). "Behaviour and modelling of reinforced concrete structures subjected to impact loads." Ph.D. Thesis, University of Toronto, Department of Civil Engineering. (Downloadable at <http://www.civ.utoronto.ca/vector/>)

Vecchio, F. J. and Wong, P. (2002). VecTor2 and Formworks Manual, University of Toronto, Department of Civil Engineering Publication, Publication No.2002-02.

Earthquake Record Databases

Pacific Earthquake Engineering Research Center - Ground Motion Database
<http://peer.berkeley.edu/smcat/>

Pacific Earthquake Engineering Research Center: NGA Database
<http://peer.berkeley.edu/nga/>

Incorporated Research Institutions for Seismology
<http://www.iris.edu/>

Cosmos Virtual Data Center
<http://db.cosmos-eq.org>

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