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L. Szabados

L. M. Kovács

# RKVI, COMPUTER PROGRAM TO DETERMINE VIBRATION CHARACTERISTICS OF FUEL RODS IN PARALLEL FLOW

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# RKVI - COMPUTER PROGRAM TO DETERMINE VIBRATION CHARACTERISTICS OF FUEL RODS IN PARALLEL FLOW

L. Szabados - L.M. Kovács

Central Research Institute for Physics, Budapest, Hungary
Reactor Research Department

SUMMARY

RKVI is a digital computer program for ICL-1905 computer in FORTRAN language. The code considers an isolated rod supported by two adjacent spacer grids, and calculates some important characteristics of rod vibrations induced by a single-phase fluid. These calculated parameters which are required to the engineering design of spacer grids can be summarized as follows: fundamental frequencies, maximum vibration amplitudes, end slopes,"and fixity" parameters, transverse deflection functions, transverse reaction forces, relative axial displacements and bending moment functions.

ÖSSZEFOGLALÁS

Az RKVI kód az ICL-1905 digitális számológépre kifejlesztett FORTRAN nyelvü program. A kód meghatározza az egy fázisu folyadék által előidézett rudvibráció legfontosabb paramétereit két szomszédos távolságtartó rács közötti rudszakaszra vonatkozóan. A távolságtartó rácsok mérnöki tervezéséhez szükséges számitott vibrációs paraméterek az alábbiakban foglalhatók össze: fundamentális frekvenciák, maximális vibrációs amplitudók, rudvég szögelfordulások, rudvég befogásra jellemző paraméterek, transzverzális lehajlási függvények, transzverzális reakcióerők, relativ axiális elmozdulások és hajlitó nyomaték függvények.

РЕЗЮМЕ

Код RKVI представляет собой программу, разработанную для ЭВМ ICL-1905 и написанную на языке FORTRAN . Код определяет основные параметры вызванного однофазной жидкостью колебания одного самосостоятельного стержня между двумя соседними дистанционирующими решетками. С помощью кода могут быть вычислены следующие вибрационные характеристики, необходимые для конструирования дистанционирующих решеток: собственные частоты, предельные вибрационные амплитуды, углы наклона концов стержня, параметры, характеризующие крепление концов стержня, функции поперечного изгиба, поперечные силы реакции, относительные осевые перемещения и функции изгибающего момента.

## 1. INTRODUCTION

Heterogeneous water-cooled reactors are often designed for high-power density and hence present a problem in the removal of heat from the core. The problem is generally resolved by employing high water velocities to improve the heat transfer. Measurements performed during the last ten years have proved, however, that high-velocity coolant flowing through a reactor core is a source of energy that can induce and sustain vibration in reactor core components. Both individual rod vibration and composite bundle vibration has the potential for causing component failure by fretting, wear and fatigue. Recently a number of experimental and theoretical studies [1-14] have been conducted in order to predict the amplitude of vibration, to understand the mechanism of parallel-flow induced vibration, and to obtain design fixes to eliminate it.

Earlier studies of parallel-flow induced vibration of flexible rods can be divided into two groups: those involving a deterministic approach [1-11] , and those involving a probabilistic approach [12-15]. In the first group, no complete solution to the equation of motion has been presented, and analyses are hampered by the lack of a complete description of the forcing functions. Several empirical expressions based on postulated causes of self-excitation, cross flow, secondary circulation etc.have been correlated, yet the real forces exciting the vibration remain unknown. The second group offers an alternative approach to the problem, by postulating that vibration is excited by random pressure fluctuations in the turbulent flow.

The best analytical approach to the study of rod displacement statistics due to pressure fluctuations in turbulent boundary layers has been worked out at the Argonne National Laboratory [15] , [17] . This probabilistic approach is essentially the same as that of Reavis [12] , but the equation of motion is that of Paidoussis [4] , which accomodates the effects of added mass, damping, axial force and the flow velocity on natural frequencies.

The purpose of the present paper is to calculate some important characteristics of single-phase fluid induced rod vibrations between two adjacent spacers which are required for the design of fuel spacer grids. These vibration parameters are calculated by the RKVI program, which was developed for ICL-1905 computers in FORTRAN language. The values of the fundamental frequencies, the vibration amplitudes, the end slopes, the "end fixities", the transverse deflection functions, the transverse reaction forces, and the reaction moments and relative axial displacements of an isolated rod supported by two adjacent spacer grids can be determined by the program.

The main features of the RKVI program can be summarized as follows:

a./ It is supposed that each rod is supported by two adjacent spacer grids for arbitrary support "end fixities" represented by a torsional spring /see Fig.1/.

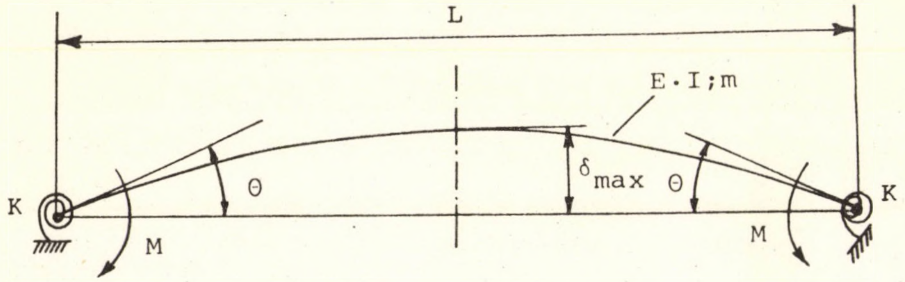


Fig.1

Model of fuel rod.

These torsional springs at both ends of the rod provide a restoring moment in proportion to the actual end slope. The "end fixity" values can be determined by both static and dynamic methods.

b./ Experiments [1-9] have shown that the flow velocity has a great influence on the amplitude of the vibrations, but does not effect the frequency, which is the natural frequency of the rod and remains constant. The differential equation for the transverse free vibrations of a rod can therefore be used, in order to calculate the fundamental frequencies and the end slope per unit amplitude. These frequency values are corrected in the program for the effect of axial spring loading and of viscous damping in water.

c./ The correlations between the vibration amplitude and the fundamental frequency are calculated by four different semi-empirical approximations / [2] , [4] , [12] , [1] /. The actual end slope values are determined from the slope per unit amplitude by means of the effective values of the vibration amplitude.

d./ Finally the program calculates the transverse deflection functions, the transverse reaction forces and the reaction moments, the relative axial displacement between the fuel rod and the spacer grids, and the axial distributions of the bending moments.

## 2. GENERAL DESCRIPTION OF THE CODE

1./ <u>Fundamental equations</u>:

a./ <u>"End fixity" calculations</u>:

The "end fixity" value can be calculated by a static load test. The equation relating the deflection of the rod loaded by a concentrated weight at the mid-point to the "end fixity" of the rod / [1] , [9] / is:

$$Y_{conc} = \frac{1}{4} \cdot \frac{\alpha \cdot L + 8}{\alpha \cdot L + 2} \cdot \frac{P_{conc} \cdot L^3}{48 \cdot I \cdot E} \qquad /1a/$$

The equation relating the deflection of the rod loaded by a uniformly distributed weight to the "end fixity" of the rod / [2] , [3] / is:

$$Y_{dist} = \frac{\alpha \cdot L + 10}{\alpha \cdot L + 2} \cdot \frac{P_{dist} \cdot L^4}{384 \cdot I \cdot E} , \qquad /1b/$$

where

$$\alpha \cdot L = \frac{K \cdot L}{I \cdot E} \qquad K = \frac{M}{\Theta} \qquad /2/$$

If an axial end spring is inserted, then the measured value of deflection will have to be corrected for the effect of axial loading /$P_{spring}$/ using the following formula [9] :

$$Y_{corrected} = Y_{measured} \cdot \frac{\xi^3}{3(tg\xi - \xi)} \qquad /3/$$

where

$$\xi = \frac{L}{2} \cdot \sqrt{\frac{P_{spring}}{E \cdot I}} \qquad /4/$$

b./ Fundamental frequency calculations

The differential equation for the transverse free vibration of the rod with elastically built-in ends shown in Fig. 1 is / [10] , [13] ; [15] /:

$$m \cdot \frac{\partial^2 y}{\partial t^2} + E \cdot I \cdot \frac{\partial^4 y}{\partial x^4} = 0 \qquad /5/$$

The solution of the differential equation can be obtained as follows [10] :

$$y = \Phi(x) \cdot \sin(\omega t) \qquad /6/$$

where

$$\Phi(x) = A \cdot \sin(\beta x) + B \cdot sh(\beta x) + C \cdot \cos(\beta x) + D \cdot ch(\beta x) \qquad /7/$$

$$\beta^4 = \frac{m \cdot \omega^2}{E \cdot I} \qquad /8/$$

$$\omega = 2 \cdot \pi \cdot f \qquad /9/$$

The fundamental frequencies are obtained from equations /8/ and /9/:

$$f = \frac{(\beta \cdot L)^2}{2 \cdot \pi} \cdot \sqrt{\frac{E \cdot I}{m \cdot L^4}} \qquad /10/$$

The ends of the rod are assumed to be elastically built in, with the angle of rotation proportional to the applied moment. This is the common type of linear torsional elasticity expressed as

$$M = K \cdot \Theta \ .$$

The differential equation /5/ was solved with the boundary conditions / [10] , [11] , [3] /:

$$K \cdot \frac{\partial \Phi}{\partial x} = E \cdot I \cdot \frac{\partial^2 \Phi}{\partial x^2} \qquad \text{at} \qquad x = 0 \qquad /11/$$

$$K \cdot \frac{\partial \Phi}{\partial x} = -E \cdot I \cdot \frac{\partial^2 \Phi}{\partial x^2} \qquad \text{at} \qquad x = L \qquad /12/$$

The values of $\beta \cdot L$ , as eigenvalues of the above boundary value problem, can be determined by solving the following transcendental equation for $\beta \cdot L$ / [10] , [11] /:

$$\cos(\beta L).\mathrm{ch}(\beta L) + 2 \cdot \frac{E \cdot I}{K \cdot L} \cdot (\beta \cdot L) \cdot \left[\mathrm{sh}(\beta L) \cdot \cos(\beta L) - \sin(\beta L) \cdot \mathrm{ch}(\beta L)\right] -$$

$$2 \cdot \left(\frac{E.I}{K.L}\right)^2 \cdot (\beta L)^2 \cdot \sin(\beta L) \cdot \mathrm{sh}(\beta L) = 1 \qquad /13/$$

The frequency equations give the relationship between the "end fixity" and the fundamental frequencies and are obtained from equation /13/ / [3] , [9] /:

$$\alpha \cdot L = \frac{-2 \cdot \beta \cdot L}{\mathrm{tg}\left(\frac{\beta L}{2}\right) + \mathrm{th}\left(\frac{\beta L}{2}\right)} \qquad /14/$$

$$\alpha \cdot L = \frac{2 \cdot \beta \cdot L}{\mathrm{cotg}\left(\frac{\beta L}{2}\right) - \mathrm{coth}\left(\frac{\beta L}{2}\right)} \qquad /15/$$

Equations /14/ and /15/ refer to the symmetrical and antisymmetrical modes of vibration, respectively, and these functions are plotted in Fig. 2 / [3] , [9] /. The limits of $\beta \cdot L$ are $\pi$ /pin ended beam/ and 4.730 /built-in beam/, corresponding to $K = 0$ and $K = \infty$ , respectively.

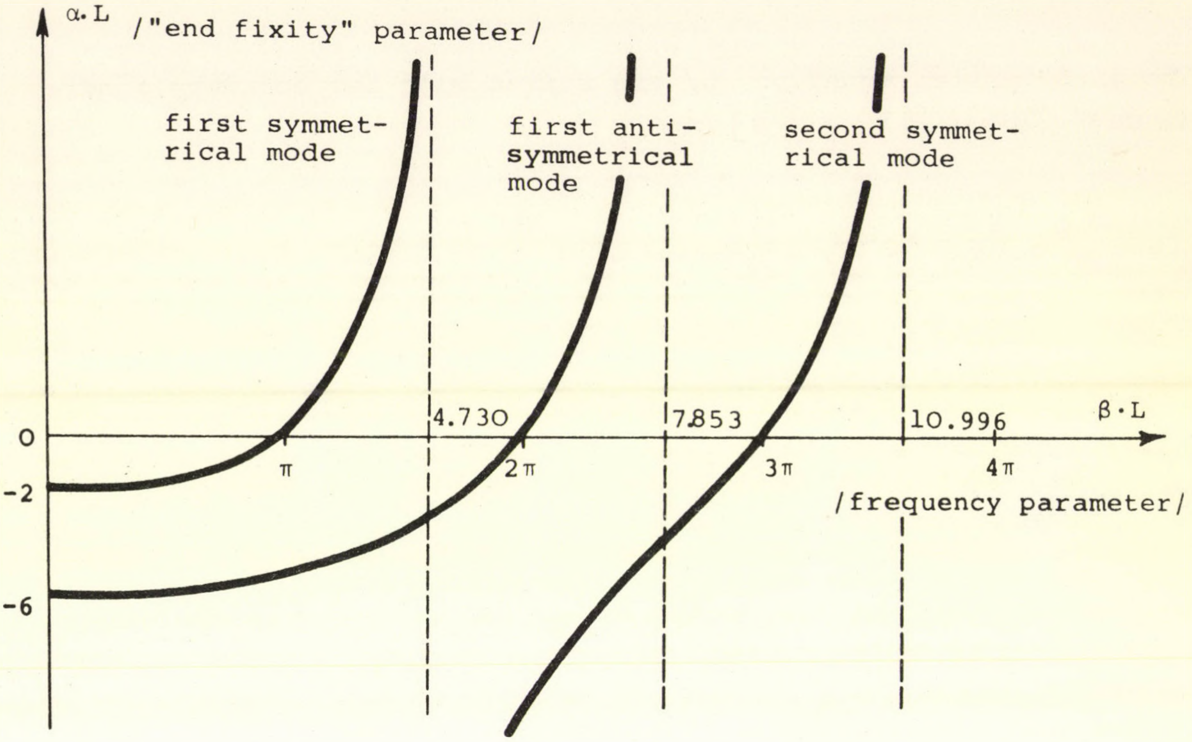


**Fig. 2**

**The symmetrical and the anti-symmetrical modes of vibration.**

c./ <u>End slope per unit amplitude</u>

The end slopes per unit amplitude are obtained by differentiating the function $y(x)/\delta_{max}$ / [10] /:

$$\left.\frac{\partial\left(y(x)/\delta_{max}\right)}{\partial x}\right|_{x=0} = \frac{\Theta}{\delta_{max}} = -2 \cdot \frac{C}{\delta_{max}} \cdot (\beta \cdot L)^2 \cdot \frac{E \cdot I}{K \cdot L^2} \qquad /16/$$

where

$$y(x)/\delta_{max} = \Phi(x)/\delta_{max} = \frac{A}{\delta_{max}}\left[\sin(\beta x) - sh(\beta x)\right] +$$

$$\frac{C}{\delta_{max}}\left[\cos(\beta x) - ch(\beta x) - 2 \cdot \frac{E \cdot I}{K \cdot L} \cdot (\beta L) \cdot sh(\beta x)\right] \qquad /17/$$

d./ Frequency correction calculations

The influence of the axial spring load on the fundamental frequency is theoretically represented by / [1] , [9] /:

$$f_{spring} = f \cdot \sqrt{1 - \frac{P_{spring} \cdot L^2}{C_1 \cdot E \cdot I}} \qquad /18/$$

The frequency values will be corrected by the effect of viscous damping in water / [1] , [7] /:

$$f_{water} = f_{air} \cdot \frac{1}{\sqrt{1 + C_3 \cdot \frac{M_{water}}{m}}} \qquad /19/$$

e./ Amplitude predictions

In order to calculate vibration amplitudes various authors have proposed semi-empirical treatments of the problem based on the dynamic equilibrium equation of the rod:

$$m \cdot \frac{\partial^2 y}{\partial t^2} + E \cdot I \cdot \frac{\partial^4 y}{\partial x^4} = P - R \qquad /20/$$

This simplified equation represents the balance between elastic reactions, mass forces, the forces P causing the movement, and the damping forces R. Various hypotheses have been proposed for P and R, and various empirical vibration amplitude relations have been deduced which contain constants determined by the tests. The RKVI program calculates four different amplitude relations.

i./ Correlation proposed by Burgreen / [2] , [3] /:

$$\left(\frac{\delta_{max}}{\delta_{hydr}}\right)^{1.3} = 0.83 \cdot 10^{-10} \cdot k_1 \cdot \Gamma^{0.5} \cdot \Omega \qquad /21/$$

where the dimensionless parameters are

$$k_1 = \frac{\alpha \cdot L + 10}{\alpha \cdot L + 2} \qquad /22/$$

$$\Gamma = \frac{\rho_{water} \cdot V^2 \cdot L^4}{E \cdot I} \qquad /23/$$

$$\Omega = \frac{\rho_{water} \cdot V^2}{\mu_{water} \cdot \omega} \qquad /24/$$

$$d_{hydr} = \frac{2 \cdot \sqrt{3}}{\pi} \cdot \frac{t^{\Delta}_{lattice}}{D_{rod}} - D_{rod} \qquad /25/$$

ii./ Correlation proposed by Paidoussis / [4] , [5] /:

$$\frac{\delta_{max}}{D_{rod}} = C_2 \cdot \left(\beta_{water} \cdot L\right)^{-4} \cdot \frac{\left(u^2 \cdot Re \cdot e^2\right)^{0.8}}{1 + 2 \cdot u^2} \cdot \frac{r^{2/3}}{1 + 4 \cdot r} \qquad /26/$$

where the dimensionless parameters are

$$u^2 = \frac{M_{water} \cdot V^2 \cdot L^2}{E \cdot I} \qquad /27/$$

$$Re = \frac{V \cdot d_{hydr}}{\nu_{water}} \qquad /28/$$

$$e = \frac{L}{D_{rod}} \qquad /29/$$

$$r = \frac{M_{water}}{M_{water} + m} \qquad /30/$$

iii./Westinghouse vibration correlation /W.V.I/ / [12] /:

$$\delta_{max} = C_{emp} \cdot \eta_{d_{hydr}} \cdot \eta_{D_{rod}} \cdot \eta_L \cdot \frac{D_{rod} \cdot L \cdot N^{0.5}_{rod} \cdot V \cdot \rho_{water} \cdot \nu^{0.5}_{water}}{W_{rod} \cdot f^{1.5}_{water} \cdot \xi^{0.5}} \qquad /31/$$

where the empirical dimensionless factor is

$$C_{emp} = C_{44} \cdot \left(\frac{d_{hydr}}{L}\right)^{D_{44}} \qquad /32/$$

and the dimensionless scale factors are

$$\eta_{d_{hydr}} = C_{11} \cdot \left( \frac{f_{water}}{V} \cdot d_{hydr} \right)^{D_{11}} \qquad /33/$$

$$\eta_{D_{rod}} = C_{22L} \cdot \left( \frac{f_{water}}{V} \cdot D_{rod} \right)^{D_{22L}} \quad \text{if} \quad \frac{f_{water}}{V} \cdot D_{rod} \leqq 0.4 \qquad /34a/$$

$$\eta_{D_{rod}} = C_{22G} \cdot \left( \frac{f_{water}}{V} \cdot D_{rod} \right)^{D_{22G}} \quad \text{if} \quad \frac{f_{water}}{V} \cdot D_{rod} > 0.4 \qquad /34b/$$

$$\eta_{L} = C_{33L} \cdot \left( \frac{f_{water}}{V} \cdot L \right)^{D_{33L}} \quad \text{if} \quad \frac{f_{water}}{V} \cdot L \leqq 0.4 \qquad /35a/$$

$$\eta_{L} = C_{33G} \cdot \left( \frac{f_{water}}{V} \cdot L \right)^{D_{33G}} \quad \text{if} \quad \frac{f_{water}}{V} \cdot L > 0.4 \qquad /35b/$$

iv./ Euratom vibration correlation /E.U.R/ / [1] /:

$$\frac{\delta_{max}}{D_{rod}} = 10^{-9} \cdot \frac{Re^{0.5}}{S_o} \cdot e^{1.5} \cdot \phi^{0.5} \cdot \left( \frac{\rho_{water}}{\rho_{rod}} \right)^{0.25} \qquad /36/$$

where the Strouhal number is:

$$S_o = \frac{f_{air} \cdot D_{rod}}{V} \qquad /37/$$

and

$$\phi = \frac{f_{air}}{f_{water}} = \sqrt{1 + C_3 \cdot \frac{M_{water}}{m}} \qquad /38/$$

f./ <u>The actual end slope</u>

The actual end slope values are obtained from the end slopes per unit amplitude / [10] /:

$$\Theta = \left( \frac{\Theta}{\delta_{max}} \right) \cdot \delta_{max} = -2 \cdot \left( \frac{C}{\delta_{max}} \right) \cdot (\beta L)^2 \cdot \frac{E.I}{K.L^2} \cdot \delta_{max} \qquad /39/$$

g./ Transverse deflection function

The transverse deflection function of a rod between two adjacent spacer grids at the moment of maximum amplitude is obtained from equation /17/:

$$\Phi(x) = \left[\frac{\Phi(x)}{\delta_{max}}\right] \cdot \delta_{max} = \left\{\left(\frac{A}{\delta_{max}}\right) \cdot \left[\sin(\beta x) - sh(\beta x)\right] + \right.$$

$$\left.\left(\frac{C}{\delta_{max}}\right) \cdot \left[\cos(\beta x) - ch(\beta x) - 2 \cdot \frac{E.I}{K \cdot L} \cdot (\beta L) \cdot sh(\beta x)\right]\right\} \cdot \delta_{max} \qquad /40/$$

h./ Transverse reaction forces and reaction moments

The transverse reaction force between rod and spacer can be calculated from the inertial force of the cylinder:

$$R = -\frac{1}{2} \cdot \int_{o}^{L} m \cdot \frac{\partial^2 y(x,t)}{\partial t^2} \cdot dx \qquad /41a/$$

The following approximation is obtained by substituting $y(x,t)$ from equations /6/ and /40/ into /41a/:

$$R = -\frac{1}{2} \cdot m_{rod,total} \cdot \omega^2_{water} \cdot \left(\frac{\delta_{average}}{\delta_{max}}\right) \cdot \delta_{max} \qquad /41b/$$

where

$$\left(\frac{\delta_{average}}{\delta_{max}}\right) = P_3\left[1 - \cos\left(\frac{\beta L}{2}\right)\right] + P_4\left[1 - ch\left(\frac{\beta L}{2}\right)\right] + P_5\left[\sin\left(\frac{\beta L}{2}\right) - sh\left(\frac{\beta L}{2}\right)\right]$$

$$P_3 = \frac{2}{\beta L} \cdot \left(\frac{A}{\delta_{max}}\right)$$

$$P_4 = \frac{2}{\beta L} \cdot \left[\left(\frac{A}{\delta_{max}}\right) + 2 \cdot \frac{\beta}{\alpha} \cdot \left(\frac{C}{\delta_{max}}\right)\right]$$

$$P_5 = \frac{2}{\beta L} \cdot \left(\frac{C}{\delta_{max}}\right)$$

$$m_{rod,tot} = m \cdot L$$

The axial distribution of the bending moments can be easily determined knowing the transverse deflection function:

$$M(x) = -E \cdot I \cdot \frac{\partial^2 y(x,t)}{\partial x^2} = \left\{ P_1 \cdot \left[ \sin(\beta x) + sh(\beta x) \right] + \right.$$

$$\left. P_2 \cdot \left[ \cos(\beta x) + ch(\beta x) + 2 \cdot \frac{\beta}{\alpha} \cdot sh(\beta x) \right] \right\} \cdot \delta_{max} \qquad /42/$$

where

$$P_1 = \beta^2 \cdot E \cdot I \cdot \left( \frac{A}{\delta_{max}} \right)$$

$$P_2 = \beta^2 \cdot E \cdot I \cdot \left( \frac{C}{\delta_{max}} \right)$$

i./ Relative axial displacement between rod and spacer

The relative displacement between rod and spacer in the axial direction, which can cause "fretting corrosion", are obtained as the difference of the curved and even rod lengths:

$$RD = S - L$$

where

$$S = \sum_{n=1}^{N_{div}} \sqrt{\Delta x^2 + \left( y_n - y_{n-1} \right)^2} \qquad /44/$$

$$n = 1,2,3,\ldots\ldots\ldots\ldots N_{division}$$

$$\Delta x = \left( x_n - x_{n-1} \right) = \frac{L}{N_{div}}$$

2./ Special features of RKVI

The program contains eight options offering different program choices. These logical parameters are:

a./ Torsional spring constant determination /LP1/;
b./ Determination of the amount of new INPUT data /LP2/;
c./ Transverse deflection function and bending moment distributions calculation /LP3/;
d./ Calculation of relative axial displacements between rod and spacer at four different amplitude correlations /LP4, LP5,LP6, LP7/;
e./ The end of INPUT information /IVEGE/.

## 3. USER'S MANUAL

### 1./ INPUT preparation

Input data are punched on paper tape or on cards. The expression "card" will be used for one record /i.e. one line/ of the paper tape.

Identification card: FORMAT /9A8/

The headings provide information for the user and machine operator. This card should follow the DATA card and precede each problem of a problem block.

Parameter card: FORMAT /I2/

Char. 2: LP2 Logical parameter determining the amount of new data.

Operating cards for entire INPUT: FORMAT /5E13.6/

| | | |
|---|---|---|
| Card 1. | DUA | diameter of the fuel rod |
| | DBB | inner diameter of the rod canning |
| | DBK | outer diameter of the rod canning |
| | RACS | distance of the triangular lattice |
| | E | Young's modulus of elasticity |
| Card 2. | ROUA | density of the fuel rod |
| | ROB | density of the rod canning |
| | ROV | density of the water |
| | VISZKK | kinematic viscosity of the water |
| | PAX | axial spring load |
| Card 3. | C1 | constant in equation /18/ |
| | C2 | constant in equation /26/ |
| | C3 | constant in equation /19/ |
| | DAMP | critical damping ratio |
| | SEB | mean flow velocity parallel to the axis of the cylinder |
| Card 4. | YKONCR | measured rod deflection caused by concentrated weight at static load test |
| | PKONC | concentrated weight at static test |
| | YMOSZLR | measured rod deflection caused by uniformly distributed weight at static load test |

| | | |
|---|---|---|
| | PMOSZL | uniformly distributed weight at static test |
| | RUGO | torsional spring constant |
| Card 5. | RUDHOS | length of the rod between two adjacent spacer grids |
| | C11 | coefficient in equation /33/ |
| | D11 | exponent in equation /33/ |
| | C22L | coefficient in equation /34a/ |
| | D22L | exponent in equation /34a/ |
| Card 6. | C22G | coefficient in equation /34b/ |
| | D22G | exponent in equation /34b/ |
| | C33L | coefficient in equation /35a/ |
| | D33L | exponent in equation /35a/ |
| | C33G | coefficient in equation /35b/ |
| Card 7. | D33G | exponent in equation /35b/ |
| | C44 | coefficient in equation /32/ |
| | D44 | exponent in equation /32/ |

<u>Operating card for simplified INPUT</u> FORMAT /3E13.6/

| | |
|---|---|
| SEB | mean flow velocity parallel to the axis of the cylinder |
| RUDHOS | length of the rod between two adjacent spacer grids |
| RUGO | torsional spring constant |

<u>INPUT constants</u> FORMAT /7/I2,1X/,I4/

| | |
|---|---|
| LP1 | logical parameter for torsional spring constant determination |
| N | number of rods in a bundle |
| LP3 | logical parameter for transverse deflection function and bending moment distribution calculation |
| LP4, LP5, LP6, LP7, | options for calculation of relative axial displacements between rod and spacer in the Burgreen, Paidoussis, Westinghouse and Euratom amplitude correlations, respectively |
| NNN | number of subdivisions of the half rod for the calculation of the relative axial displacement between rod and spacer. |

End - of - data card:

At the end of each set of data for a RKVI problem, a card is written to indicate the end of INPUT information. The card must have an integer 8 in column 2, if another problem is to follow, or an integer 9 in column 2, if there are no more problems.

2./ Code OUTPUT

The OUTPUT of RKVI is self-explanatory for those who are familiar with its algorithm. Therefore, a brief summary of OUTPUT results is sufficient. First, all INPUT data are reproduced in the OUTPUT. The second group of calculated data includes the transverse reaction forces between rod and spacer. The third group contains the transverse deflection function and the axial distribution of the bending moments. /These functions are calculated at the 21 printing points of the half rod./ The fourth group includes the relative axial displacement between the rod and the spacer.

The most important results are printed out in a separate group as follows:

| | |
|---|---|
| ROATL | average density of the rod |
| AI | moment of inertia of rod canning |
| SP6 | flexural rigidity of the rod canning |
| RUDM | mass of the rod displaced per unit length |
| VIZM | virtual mass of the fluid per unit length |
| DH | hydraulic diameter of the test section |
| DCELLA | equivalent diameter of the triangular lattice cell |
| RE | Reynolds number, based on the hydraulic diameter |
| YKONC | corrected rod deflection caused by concentrated weight at static load test |
| RUGO | torsional spring constant |
| YMOSZL | corrected rod deflection caused by uniformly distributed weight at static load test |
| ALFA | "end fixity" parameter |
| AL | dimensionless "end fixity" parameter |
| BETAL | frequency parameter in air without axial spring |
| BETAV | frequency paramter in water without axial spring |
| BETARL | frequency parameter in air with axial spring |
| BETARV | frequency parameter in water with axial spring |
| FREQL | frequency in air without axial spring |
| FREQV | frequency in water without axial spring |
| FREQRL | frequency in air with axial spring |
| FREQRV | frequency in water with axial spring |
| TETAEGY | end slope per unit amplitude |

AMPL1, AMPL2, AMPL3, AMPL4 maximum vibration amplitude /half peak to peak/ in the Burgreen, Paidoussis, Westinghouse and Euratom amplitude correlations, respectively

TETA1, TETA2, TETA3, TETA4 actual end slope in the Burgreen, Paidoussis, Westinghouse and Euratom amplitude correlations, respectively

B1L = BETAL . RUDHOS dimensionless frequency parameter in air without axial spring

B2L = BETAV . RUDHOS dimensionless frequency parameter in water without axial spring

B3L = BETARL . RUDHOS dimensionless frequency parameter in air with axial spring

B4L = BETARV . RUDHOS dimensionless frequency parameter in water with axial spring

## 3./ Machine requirements

RKVI program is written for ICL-1905 computers. The code requires a memory capacity of 8200 words. The running time is determined by the complexity of the problem and the desired options, and is about 1-5 minutes.

## Symbols and definitions

The unit system used for RKVI computations follows the normally accepted engineering system of Anglo-Saxon countries:

| | |
|---|---|
| Unit of mass | = pounds |
| Unit of length | = feet |
| Unit of time | = seconds |
| Unit of temperature | = Fahrenheit |

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| Physical or Mathematical Symbol | FORTRAN Symbol | Units | Definitions and remarks |
|---|---|---|---|
| 1 | 2 | 3 | 4 |
| LP1 | LP1 | - | Logical parameter for torsional spring constant determination.<br>LP1 = 0 torsional spring constant is calculated from equation /1a/<br>LP1 = 1 torsional spring constant is calculated from equation /1b/<br>LP1 = 2 torsional spring constant known from INPUT data |
| LP2 | LP2 | - | Logical parameter determining the amount of new data<br>LP2 = 1 read entire INPUT<br>LP2 $\neq$ 1 read simplified INPUT |
| LP3 | LP3 | - | Logical parameter for calculation of transverse deflection function and bending moment distribution.<br>LP3 = 0 transverse deflection function and bending moment calculation is omitted.<br>LP3 $\neq$ 0 transverse deflection function and bending moment are calculated from equations /40/ and /42/. |
| LP4, LP5<br><br>LP6, LP7 | LP4, LP5<br><br>LP6, LP7 | -<br><br>- | Logical parameter for calculation of relative axial displacements between rod and spacer in the Burgreen, Paidoussis, Westinghouse and Euratom amplitude correlations, respectively.<br>LP4 = 0, LP5 = 0, LP6 = 0, LP7 = 0 relative axial displacement calculation is omitted.<br>LP4 $\neq$ 0, LP5 $\neq$ 0, LP6 = Ø, LP7 $\neq$ 0 relative axial displacement is calculated from equation /42/. |
| IVEGE | IVEGE | - | Logical parameter indicating the end of INPUT information for a problem.<br>IVEGE = 8 if another problem is to follow.<br>IVEGE = 9 if there are no more problems. |

| 1 | 2 | 3 | 4 |
|---|---|---|---|
| $d_{ua}$ | DUA | ft | Diameter of the fuel rod |
| $d_{bb}$ | DBB | ft | Inner diameter of the rod canning |
| $D_{Rod}$ | DBK | ft | Outer diameter of the rod canning |
| $d_{hydr}$ | DH | ft | Hydraulic diameter of the test section |
| $d_{cella}$ | DCELLA | ft | Equivalent diameter of the triangular lattice cell |
| L | RUDHOS | ft | Length of the rod between two adjacent spacer grids |
| $\rho_{ua}$ | ROUA | $lbm/ft^3$ | Density of the fuel rod |
| $\rho_{burk}$ | ROB | " | Density of the rod canning |
| $\rho_{water}$ | ROV | " | Density of the water |
| $\rho_{aver}$ | ROATL | " | Average density of the total rod |
| I | AI | $ft^4$ | Moment of inertia of the rod canning |
| E | E | $lb_{f/ft^2}$ | Young's modulus of elasticity |
| E.I | SP6 | $lb_f \cdot ft^2$ | Flexural rigidity of the rod canning |
| m | RUDM | $lbm/_{ft}$ | Mass of the rod displaced per unit length |
| $M_{water}$ | VIZM | " | Virtual mass of the fluid per unit length |
| $t_{lattice}$ | RACS | ft | Distance of the triangular lattice |
| $\nu_{water}$ | VISZKK | $ft^2/_{sec}$ | Kinetic viscosity of the water |

| 1 | 2 | 3 | 4 |
|---|---|---|---|
| $\mu_{water}$ | - | $lbm/_{sec.ft}$ | Dynamic viscosity of the water $\mu_{water} = \rho_{water} \cdot \nu_{water}$ |
| $P_{spring}$ | PAX | $lb_f$ | Axial spring load |
| $\xi$ | DAMP | - | Critical damping ratio |
| V | SEB | $ft/_{sec}$ | Mean flow velocity parallel to the axis of the cylinder |
| K | RUGO | $lb_f.ft/_{rad}$ | Torsional spring constant |
| $Y_{conc,corr}$ | YKONC | ft | Corrected rod deflection caused by concentrated weight at static load test |
| $Y_{conc,meas}$ | YKONCR | ft | Measured rod deflection caused by concentrated weight at static load test |
| $Y_{dist,corr}$ | YMOSZL | ft | Corrected rod deflection caused by uniformly distributed weight at static load test |
| $Y_{dist,meas}$ | YMOSZLR | ft | Measured rod deflection caused by uniformly distributed weight at static load test |
| $N_{rod}$ | N | - | Number of rods in a bundle |
| $N_{division}$ | NNN | - | Number of division of the half-length rod at the calculation of the relative axial displacement between rod and spacer |
| Re | RE | - | Reynolds number, based on the hydraulic diameter |
| $\alpha$ | ALFA | $1/_{ft}$ | "end fixity" parameter |
| $\alpha.L$ | AL | - | Dimensionless "end fixity" parameter. |
| $\beta_{air}$ | BETAL | $1/_{ft}$ | Frequency parameter in air without axial spring |
| $\beta_{water}$ | BETAV | $1/_{ft}$ | Frequency parameter in water without axial spring |

| 1 | 2 | 3 | 4 |
|---|---|---|---|
| $\beta_{air,spring}$ | BETARL | $1/_{ft}$ | Frequency parameter in air with axial spring |
| $\beta_{water,spring}$ | BETARV | $1/_{ft}$ | Frequency parameter in water with axial spring |
| $f_{air}$ | FREQL | $1/_{sec}$ | Frequency in air without axial spring |
| $f_{water}$ | FREQV | $1/_{sec}$ | Frequency in water without axial spring |
| $f_{air,spring}$ | FREQRL | $1/_{sec}$ | Frequency in air with axial spring |
| $f_{water,spring}$ | FREQRV | $1/_{sec}$ | Frequency in water with axial spring |
| $\Theta/\delta_{max}$ | TETAEGY | rad/ft | End slope per unit amplitude |
| $\delta_{max}$ | AMPL1, AMPL2<br>AMPL3, AMPL4 | ft | Maximum vibration amplitude /half-peak to peak/ in the Burgreen, Paidoussis, Westinghouse and Euratom amplitude correlations, respectively |
| $\Theta$ | TETA1, TETA2<br>TETA3, TETA4 | rad | Actual end slope in the Burgreen, Paidoussis, Westinghouse and Euratom amplitude correlations, respectively |
| $B_{1L}$ | B1L | - | Dimensionless frequency parameter in air without axial spring |
| $B_{2L}$ | B2L | - | Dimensionless frequency parameter in water without axial spring |
| $B_{3L}$ | B3L | - | Dimensionless frequency parameter in air with axial spring |
| $B_{4L}$ | B4L | - | Dimensionless frequency parameter in water with axial spring |
| M | ANYOM1, ANYOM2<br>ANYOM3, ANYOM4 | $lb_f.ft$ | Restoring bending moment in the Burgreen, Paidoussis, Westinghouse and Euratom amplitude correlations, respectively |
| $C_1$ | C1 | - | constant in equation /18/ $C_1 = \pi^2$ for pin ended beam<br>$C_2 = 42$ for built-in beam |
| $C_2$ | C2 | - | Constant in equation /26/<br>C2 depends primarily on the ratio of cross-flow velocity to axial flow velocity, and is approximately equal to $10^{-6}$ for a system with minimum flow disturbance and $5.10^{-5}$ for highly disturbed flow conditions |
| $C_3$ | C3 | - | Constant in equation /19/<br>$C_3$ varies from 1 to 3 depending on the geometry |

| 1 | 2 | 3 | 4 |
|---|---|---|---|
| $C_{11}$ | C11 | - | Coefficient in equation /33/ |
| $D_{11}$ | D11 | - | Exponent in equation /33/ |
| $C_{22L}$ | C22L | - | Coefficient in equation /34a/ |
| $C_{22G}$ | C22G | - | Coefficient in equation /34b/ |
| $D_{22L}$ | D22L | - | Exponent in equation /34a/ |
| $D_{22G}$ | D22G | - | Exponent in equation /34b/ |
| $C33_L$ | C33L | - | Coefficient in equation /35a/ |
| $D_{33L}$ | D33L | - | Exponent in equation /35a/ |
| $C_{33G}$ | C33G | - | Coefficient in equation /35b/ |
| $D_{33G}$ | D33G | - | Exponent in equation /35b/ |
| $C_{44}$ | C44 | - | Coefficient in equation /32/ |
| $D_{44}$ | D44 | - | Exponent in equation /32/ |
| $t$ | - | sec | Time |
| $x$ | X | ft | Longitudinal coordinate |
| $y$ | YFX1/X/,YFX2/X/ YFX3/X/,YFX4/X/ | ft | Transverse deflection function of the cylinder in the Burgreen, Paidoussis, Westinghouse and Euratom amplitude correlations, respectively. |
| $P_{conc}$ | PKONC | $lb_f$ | Concentrated weight at static load test |
| $P_{distr}$ | PMOSZL | $lb_{f/ft}$ | Uniformly distributed weight at static load test |
| $y/\delta_{max}$ | YPAFX/X/ | - | Transverse deflection function per unit amplitude |

| 1 | 2 | 3 | 4 |
|---|---|---|---|
| $\omega$ | OMEGAL, OMEGAV<br>OMEGARL, OMEGARV | rad/sec | Circular frequency of oscillation of the cylinder in air without axial spring, in water without axial spring, in air with axial spring and in water with axial spring, respectively. |
| A, B, C, D | | - | Integral constants in equation /7/ |
| $A/\delta_{max}$, $C/\delta_{max}$ | APERA, CPERA | - | Integral constants in equation /17/ |
| $S_o$ | STROU | - | Strouhal number /as a function of $f_{air}$/ |
| R | REAK1, REAK2<br>REAK3, REAK4 | $lb_f$ | Transverse reaction force between rod and spacer in the Burgreen, Paidoussis, Westinghouse and Euratom amplitude correlations, respectively. |
| RD | ROVID1, ROVID2<br>ROVID3, ROVID4 | ft | Relative axial displacement between rod and spacer in the Burgreen, Paidoussis, Westinghouse and Euratom amplitude correlations, respectively. |
| S | S1, S2<br>S3, S4 | ft | Length of the curved rod in the Burgreen, Paidoussis, Westinghouse and Euratom amplitude correlations, respectively. |
| M/x/ | AMFX1/X/, AMFX2/X/<br>AMFX3/X/, AMFX4/X/ | $lb_f$.ft | Axial distribution of the bending moments in the Burgreen, Paidoussis, Westinghouse and Euratom amplitude correlations, respectively. |

Kiadja a Központi Fizikai Kutató Intézet
Felelős kiadó: Szabó Ferenc, a KFKI
Reaktorkutatási Tudományos Tanácsának elnöke
Szakmai lektor: Kosály György
Nyelvi lektor: T. Wilkinson
Példányszám: 180 Törzsszám: 72-6478
Készült a KFKI sokszorosító üzemében,
Budapest
1972. április hó