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FLUID STRUCTURE INTERACTION IN TUBE BUNDLES

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ABSTRACT

A lot of industrial components contain tube bundles immersed in a fluid. The mechanical analysis of such systems requires the study of the fluid structure interaction in the tube bundle.

Simplified methods, based on homogeneization methods, have been developed to analyse such phenomenon and have been validated through experimental results. Generally, these methods consider only the fluid motion in a plan normal to the bundle axis.

This paper will analyse, in a first part, the fluid structure interaction in a tube bundle through a 2D finite element model representing the bundle cross section. The influence of various parameters like the bundle size, and the bundle confinement will be studied. These results will be then compared with results from homogeneization methods.

Finally, the influence of the 3D fluid motion will be investigated, in using simplified methods.

NOMENCLATURE

$A = a\bar{\bar{I}}$	: Diagonal matrix characterising the acoustic permeability of the bundle.
$\bar{\bar{I}}$	: Unit matrix.
B, D	: Diagonal matrices characterising the homogeneous medium :

$$B = |Y^*|\bar{\bar{I}} - A = b\bar{\bar{I}}$$

$$D = |Y|\bar{\bar{I}} - A = d\bar{\bar{I}}$$

$$a = \left(\frac{c_{eq}}{c}\right)^2 |Y^*|$$

$\|Y^*\|$	: Fluid area in the elementary cell divided by ε^2
$\|Y\|$	: Assembly cross section divided by ε^2
ε	: Bundle pitch
e	: Gaps between two adjacent tubes
δ	: Flat to flat dimension (or diameter of the tubes) $\varepsilon = \delta + e$
c	: Sound velocity in the fluid at rest
c_{eq}	: Equivalent sound velocity taking into account the bundle
f_t	: Tube's eigenfrequency in air ($\omega_t = 2\pi f_t$)
m_t	: Tube's mass
k_t	: Tube's stiffness
p	: Pressure in the homogeneous medium
$\bar{s}$	: Subassembly displacement in the homogneous medium
ρ_0	: Fluid density
grad	: Gradient operator
l	: Length of the subassemblies
$\bar{y}$	: Equivalent displacement
Δ	: Laplacian operator
R	: Surrounding vessel's radius
N	: Ring number in the bundle

η : confinement parameter

$$\eta = \frac{2R}{(2N+1)\varepsilon}$$

R_i : Mean radius of the ith ring

$$R_i = i\varepsilon$$

R_i^+ : External radius of the ith ring

$$R_i^+ = i\varepsilon + \frac{\delta}{2}$$

R_i^- : Internal radius of the ith ring

$$R_i^- = i\varepsilon - \frac{\delta}{2}$$

1 - INTRODUCTION

A lot of industrial structures contain tube bundles (reactor cores, steam generators, heat exchangers). The mechanical behaviour of such structures is strongly influenced by the fluid structure interaction occurring between the tubes and the surrounding fluid. The structural analysis of such components requires the modelization of this interaction.

Though finite elements exist for both tubes and fluid, the development of a finite element model including both tubes and fluid is difficult : in order to obtain an acceptable accuracy, a refined modelization at the scale of the elementary cell (one tube and the surrounding fluid) should be required and that would lead to a large size of equations difficult to solve, even on large computers.

To avoid this difficulty, simplified methods based on homogeneization techniques have been developed (Sanchez-Palencia, 1980 ; Benner et al., 1981 ; Planchard et al. 1982 ; Preumont et al., 1989 ; Brochard et al., 1991). They aim to replace the physical heterogeneous medium by an homogeneous equivalent medium which macroscopic properties are deduced from the mechanical properties of the tubes and from the bundle geometry. The results got with these methods have been compared with experimental results (Planchard et al. 1982 ; Brochard et al. 1990). These methods allow only to represent the tubes global motions and they are generally limited to the study of the bundle cross section (2D models).

In a first part, this paper will focus on the analysis the fluid structure interaction in a tube bundle in using a 2D finite element model including an explicit representation of both tubes and flluid. The frequency of the fluid coupled eigenmodes will be determined and the corresponding mode shapes will be analysed in pointing out the modes which could be highly excited by a global support motion (seismic excitation). The influence of parameters like the bundle size (i.e. the number of rings) and the confinement (the distance between the surrounding vessel and the bundle) will be investigated. These results will be compared with results got from homogeneization methods.

In a second part, the influence of the 3D fluid motion will be investigated and especially the influence of a free surface (or a great fluid volume) located at the upper bound of the bundle. This analysis will be performed in using a simplified approach.

2 - BIDIMENSIONNAL (2D) FINITE ELEMENT MODEL

2-1 - Objectives

The aim of this analysis is to characterize the dynamical behaviour of a bundle composed of identical tubes immersed in a fluid through its fluid coupled eigenmodes. Such bundle constitutes a complicated three dimensionnal structure, including various support systems (plates for example) and various boundary conditions for the fluid (free surface, great fluid volumes).

In order to keep a reasonnable size for the problem, the physical 3D problem is reduce to a 2D problem in a plan orthogonal to the bundle axis (bundle cross section) in assuming that :

- the motion of each tube is a translation in a plan normal to its axis,
- the fluid motion parallely to the bundle axis is neglected.

Such assumptions are convenient for long bundles for which boundary conditions on the fluid and on the tubes have only slight influence. The proposed model is equivalent to study a unit length bundle slice.

Moreover, the gaps between the tubes will be choosen small enough to get an important effect of the fluid. This aspect reinforces the interest of such calculation as the experiment in that case becomes difficult and sometimes impossible because, due to a dynamical excitation, shocks between the tubes may occur, inducing a non linear behaviour of the bundle.

The fluid coupled eigenmodes will be classified according to their seismic excitability (modal masses) and their mode shapes (flowering motion, etc.)

2-2 - Description of the model

a - Tube properties

It has been choosen that the bundle was composed of identical hexagonal tubes in triangular arrangement. This arbitrary choice (with respect to bundles containing circular tubes in square or triangular arrangements) influences only the numerical results but has no influence on the qualitative results. Moreover the hexagonal configuration is used in an important industrial structure : the Fast Breeder Reactor cores.

The cross section of the tubes used in the model is the cross section of the FBR core mock-up RAPSODIE fuel assemblies (Brochard et al., 1990) and the tube vibratory characterisctics are an approximation of the 1st bending mode of these fuel assemblies. These characteristics are :

- flat to flat dimension $\delta = 49.8$ mm
- bundle pitch $\varepsilon = 50.8$ mm (gap e = 1 mm)
- mass per unit length : $m_t = 12$ kg
- eigenfrequency in air $f_t = 8$ Hz

b - Finite element model description

The finite element model represents a quarter of a cross section of the bundle (for small number of rings, models representing a half cross section has been also used). It includes :

- a mesh of each tube using shell elements. The tubes Young's modulus has been taken great enough in order to avoid any lose of shape of the tubes cross section. Each tube can move according to X and Y direction. To simulate the tube stiffness, two springs are linked on the tubes (see on figure 1)

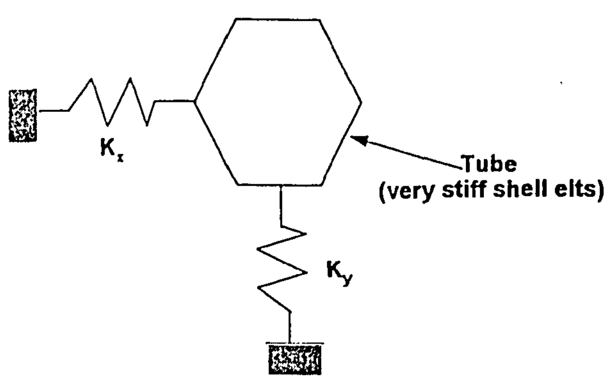

Figure 1 : Tube model

- a fluid mesh as seen on figure 2
- a cylindrical surrounding vessel (assumed to be fixed) radius R.

To assume the link between the fluid and the structure, specific link elements are introduced at the border between the tubes, the vessel and the fluid.

The number of rings N and the vessel radius R are parameters, the influence of which has been investigated.

All calculations have been performed with the computer code CASTEM 2000 developed by CEA.

2-3 - Results

a - Discretization

The first calculations aim to determine what refinement in the discretization was necessary to get a good accuracy. After a parametric study, it appears that a discretization with 3 finite elements on each side of the tube was sufficient.

b - Eigenmodes spectrum

To illustrate what can be observed in the eigenmodes spectrum, the case of a bundle composed of one central tube surrounded by two rings (N=2) and the confinement parameter η=1.4 is presented. 38 eigenmodes have been calculated (see table 1) :

- the first bending mode at 2.69 Hz corresponds to an axisymmetric flowering motion of all tubes in the same sense, the pressure field presents also the same axisymmetry (figure 3),
- a second axisymmetric mode with a motion in opposite sense of the two rings is observed at 3.08 Hz,
- two modes have an important modal mass (one for each direction X and Y) representing 87% of the total structural mass. These modes correspond to a translation of the tubes along each direction (figure 4). The pressure field is very similar to what is observed for the translation of one tube alone. Their frequency is equal to 6.6 Hz which is very close to the bundle's frequency obtained when all tubes are linked together (6.67 Hz), but it is smaller than the frequency of one tube alone in an infinite fluid domain (7.3 Hz). This point will be discussed in the next paragraph.
- the last mode at 7.9 Hz is a sort of "rotation" of the rings around the bundle axis (figure 5).

Some of the previous results are always observed independantly of the ring numbers :

- the mode shape of the first mode is an axisymmetric flowering response,
- the existence of some modes having great modal masses the frequencies of which are close to the frequency got when all tubes are linked together.
- the last mode has always the same specific shape with its frequency higher than the

frequency of oneassembly alone in an infinite fluid domain.

- Table 1 -
Bundle eigenmodes (2 rings)

Mode numbe r	frequen-cy (Hz)	mode type	percent of mass (dir.X)	percent of mass (dir.Y)
1	2.694	s/s	0	0
2	2.811	s/a	0.025	0
3	2.814	a/s	0	0.026
4	2.939	a/s	0	0
5	2.970	s/s	0	0
6	2.970	a/a	0	0
7	3.082	s/s	0	0
8	3.116	s/a	0.038	0
9	3.122	a/s	0	0.038
10	3.504	s/a	≅0	0
11	6.576	s/s	0	0
12	3.581	a/a	0	0
13	4.666	s/a	0.2	0
14	4.669	a/s	0	0.2
15	4.749	a/a	0	0
16	5.742	s/s	0	0
17	5.747	a/a	0	0
18	5.977	s/a	9.7	0
19	5.985	a/s	0	10.1
20	6.106	a/s	0	≅0
21	6.467	a/a	0	0
22	6.467	s/s	0	0
23	6.523	s/s	0	0
24	6.611	s/a	86.8	0
25	6.612	a/s	0	86.4
26	6.795	s/a	≅0	0
27	6.905	a/s	0	≅0
28	7.022	a/a	0	0
29	7.071	s/s	0	0
30	7.081	a/a	0	0
31	7.131	s/a	2.3	0
32	7.136	a/s	0	2.3
33	7.287	s/a	≅0	0
34	7.376	s/s	0	0
35	7.387	a/a	0	0
36	7.567	s/a	0.9	0
37	7.571	a/s	0	0.9
38	7.870	a/a	0	0

s/a : mode shape symmetric/X antisymmetric/Y
a/s : mode shape antisymmetric/X symmetric/Y
s/s : mode shape symmetric/X symmetric/Y
a/a : mode shape antisymmetric/X antisymmetric/Y

c - Influence of the bundle size

The influence of the bundle size (i.e.the ring number) is presented on figure 6 for a constant confinement ($\eta = 1.1$) :

- the frequency of the first mode (axisymmetric flowering motion) decreases slightly from 3.2 Hz for one ring to 2.7 Hz for 2 rings and remain constant when the ring number increases,
- the frequency of the highest mode does not depend on the ring number
- the frequency of the mode corresponding to the motion of all tubes linked together (which is an approximation of the modes with the highest modal mass) depends slightly on the ring number and increases with it, which is due to the bundle porosity (for a given confinement i.e. when the distance between the bundle and the vessel remains constant).

d - Influence of the confinement

The figure 7 presents the influence of η. The first and the last mode does not depend on η, which is related with the fact that the pressure in the fluid surrounding the bundle remains rather constant for these two modes.

On the contrary, the modes having important modal masses depend strongly on η The added mass effect decreases when η increases, the frequency tends to the value corresponding to a tube alone in an infinite fluid domain (7.3 Hz) (figure 8). This phenomenon is well known and is exactly the same as what is observed for the evolution of the fluid effect for two concentric cylinders (Gibert, 1989)

2-4 - Comparison with homogeneization method

a -Principle of the method

The homogeneization methods aim to evaluate the fluid effect for a global motion of the bundle. These methods which have been already used for numerous industrial problems (porous medium, soil, reinforced concrete,etc., Sanchez-Palencia, 1980) aim to replace the physical medium by an equivalent homogeneous medium in order to describe the mean evolution of the problem's main parameters (displacement, pressure, velocity...).

In the case of the fluid structure interaction in the tube bundles, the variables of interest are the tubes displacements and the fluid pressure.The mathematical method to derive the homogeneous equations may vary according to the different authors : macroelement method (Preumont et al., 1989), asymptotic expansion for the pressure and the displacement using locally periodic functions (Benner et al. 1981, Planchard et al.,1982, Brochard et al., 1991a and 1994), expansion at the first order of the tube motion (Shinoara, 1981).

In the present application, we shall use the method described in Brochard et al., 1991a. The homogeneous medium equations may be written :

$$\begin{cases} \dfrac{1}{|Y|}\operatorname{div}\left(A\,\overrightarrow{\operatorname{grad}}\,p\right)-\dfrac{\lambda}{c^2}\dfrac{\partial^2 p}{\partial t^2}=\rho_0\operatorname{div}\left(D\ddot{\vec{s}}\right) & (1-1)\\ \left(\dfrac{m_t}{\varepsilon^2}+\rho_0 B\right)\ddot{\vec{s}}+\dfrac{k_t}{\varepsilon^2}\vec{s}=-D\,\overrightarrow{\operatorname{grad}}\,p & (1-2)\end{cases}$$

b - Application for the translation of all tubes

Let's approximate the bundle by a circular domain (radius R_h) immersed in a fluid domain (radius R) and consider that the tube displacement may be expressed in polar coordinates by :

$$\vec{s}(r,\theta,t)=s(r,t)\left(\cos\theta\,\vec{u}_r-\sin\theta\,\vec{u}_t\right)$$

$\vec{u}_r$ (resp. $\vec{u}_t$) : radial (resp. orthoradial) unit vector

This expression corresponds to a translation along the direction X of the tubes.

The resolution of equation 1-1 and 1-2 (in neglecting the compressibility effects) leads to the following expression for the bundle eigenfrequency.

$$f_h=f_{air}\sqrt{\frac{1}{1+\dfrac{\rho_0\varepsilon^2}{m}\left(b+\dfrac{d^2}{a+|Y|\dfrac{R^2-R_h^2}{R^2+R_h^2}}\right)}}$$

For $\eta \gg 1$ (i.e. $\dfrac{R^2-R_h^2}{R^2+R_h^2}\cong 1$) f_h is equal to 7.17 Hz which is coherent with the finite element model results (discrepancy < 1%).

c - Application for the axisymmetric flowering motion

Equations 1-1 and 1-2 may be also solved in considering that both displacements and pressure do not depend on the azimuthal position. Moreover, as it was observed on the finite element calculations that the pressure remains constant in the surrounding fluid, the previous equations are solved only for the homogenized domain with an imposed pressure equal to 0 at the boundary ($r = R_h$). Then the eigenfrequency may be expressed :

$$f_{fl}=f_{air}\sqrt{\frac{1}{1+\dfrac{\rho_0\varepsilon^2}{m}\left(b+\dfrac{d^2}{a}\right)}}$$

For the considered bundle, $f_{fl} = 2.5$ Hz. The agreement with the finite element results is good (4% discrepancy).

d - Remarks

The agreement observed on the eigenfrequencies between the homogeneization method and the finite element model was foreseeable, considering the numerous comparisons of homogeneous calculations with experiments, even if these comparisons were mainly based on time histories including sometimes non linear effects (Planchard 1982, Brochard et al. 1991a and 1994). More precisely, the axisymmetric flowering modes have been calculated by the homogeneization, the dynamic and non linear calculations using them were in good agreements with the experiments but these modes have not been measured (Brochard et al. 1994). The above presented finite element calculations confirm the existence of such modes and the validity of the homogeneization method for this type of problem.

3 - EFFECT OF THE FLUID AXIAL MOTION

3-1 - Background

In real industrial structures, the bundle length is not necessarily very important in comparison with its diameter. Commonly, ratio values of the length versus the diameter about 5 are observed (and sometimes less). In such a case, the previous approach based on a pure horizontal fluid motion may overestimate the fluid effect, especially if there is a fluid free surface or a great fluid volume at the upper extremity of the bundle.

Taking into acount the 3D fluid motion is not easy as a 3D model would lead to a very large size problem.

A simplified method has been proposed (Gibert 1989) to estimate the fluid added mass for 3D problems. It consists in replacing the 3D problem by a set of two 2D problems in two orthogonal plans, these plans being themselves normal to the vibrating shells. These two problems allow to determine 2 added masses m1 and m2. Then the global added mass may be estimated :

$$\frac{1}{m_{3D}} = \frac{1}{m_1} + \frac{1}{m_2}$$

This method leads to 10% discrepancy with exact solution for simple cases (rectangular plates, cylindrical shells).

For the tube bundle, the two 2D problems may be defined as :

- the horizontal problem above presented
- a problem in a vertical plan (meridian plan), the fluid motion is then supposed to be purely vertical.

3-2 - Bundle model for the vertical fluid motion

For that purpose, the bundle is modeled by a set of circular rings separated by thin fluid sheets. This study is limited to two different types of tube motion :

- axisymmetric radial motion (flowering motion)
- horizontal translation.

The ith-ring is characterised by :

- its mass : $m_i = 6\,i\,m$
- its frequency : f_t
- its mean radius : $R_i = i\,\varepsilon$
- its thickness : δ
- its length : l

To determine the fluid action, it is necessary to solve the fluid equations in each fluid sheet. For the sheet between the rings i and i+1 these equations may be written :

$$\begin{cases} \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial p}{\partial r}\right) + \frac{\partial^2 p}{\partial z^2} = 0 & \\ \frac{\partial p}{\partial r} = -\rho_0 \ddot{s}_i & \text{for } r = R_i^+ \\ \frac{\partial p}{\partial r} = -\rho_0 \ddot{s}_{i+1} & \text{for } r = R_{i+1}^- \\ \frac{\partial p}{\partial z} = 0 & \text{for } z = 0 \\ p = 0 & \text{for } z = l \end{cases} \qquad (2)$$

The last two boundary conditions are introduced to take into account the presence of a plate at the bundle bottom and the fact that there is a fluid free surface or a great fluid volume above the bundle.

The resolution of equations 2 is performed in assuming that the pressure variation on the thickness of the fluid sheet may be neglected. Then the fluid forces acting on the rings are calculated and the fluid added and coupling masses are determined (table 2).

	axisymmetric flowering motion	translation motion
added mass ring i	$\frac{4}{3}\pi\rho_0\frac{R_i l^3}{e}$	$\frac{2}{3}\pi\rho_0\frac{R_i l^3}{e}$
coupling mass rings i and i-1	$-\frac{2}{3}\pi\rho_0\frac{R_i^- l^3}{e}$	$-\frac{1}{3}\pi\rho_0\frac{R_i^- l^3}{e}$
coupling mass rings i and i-1	$-\frac{2}{3}\pi\rho_0\frac{R_i^+ l^3}{e}$	$-\frac{1}{3}\pi\rho_0\frac{R_i^+ l^3}{e}$

Table 2 : Fluid vertical motion - Added and *Coupling masses for the ith ring*

3-3 - Results

Calculations have been performed in considering a tube length equal to 1 m. Then the fluid coupled eigenmodes have been calculated.

a - Axisymmetric flowering motion

The calculations show that the mode associated with a motion in the same sense of all tubes has the highest frequency (on the contrary, it was the smallest one when the horizontal fluid motion was only considered). The frequency of this mode increases almost proportionnally with the ring numbers (figure 9). This result can be derived analytically, in assuming that the mode shape amplitude for each ring is proportionnal to the ring's radius.

For large bundles (bundles for which the ratio R/H of its radius to its height is about 2), the eigenfrequency associated with a vertical fluid motion may be greater than the frequency obtained in considering only the horizontal fluid motion. It shows the great influence of this phenomenon.

More precisely, for a bundle with H/R about 5 (which corresponds to N = 4 in our geometry), the decrease of the added mass in considering the 3D effect is about 10% for $\eta = 1.1$ and 22% for $\eta = 2$ with respect to the horizontal calculation. It corresponds respectively to 4% and 11% increase of the eigenfrequency. For larger bundles the effect is much more important : 50% decrease of the added mass is obtained for $\eta = 1.1$ and N = 12 or $\eta = 2$ and N = 10 (i.e. $H/R \cong 2$).

The frequency associated to the vertical fluid motion problem increases of 20 % when η increases from 1.1 to 1.5. For higher values of η, the frequency variations are small (figure 10).

For modes involving motion in opposite sense of the rings, according to the previous remarks on their frequencies, the influence of the 3D fluid motion will be smaller than for the previous global mode.

b - Global translation of the bundle

In that case, the mode associated with a motion in the same sense of all tubes has the highest frequency, in the same way as in the horizontal calculation. The frequency of this mode (fluid vertical motion) increases also proportionnally with the ring number (for a given η), (figure 11). This frequency increases with η (especially for $\eta<1.3$).

Nevertheless, the decrease of the added mass due to the 3D fluid motion is smaller than for the axisymmetric flowering case. The 50% decrease of of the added mass with respect to the horizontal calculation is got only for very large bundles ($N > 20$ i.e. bundles for which $R/H < 1$). For bundles with $H/R \cong 5$, the variation of the added mass is small (2%). The influence of the 3D fluid motion has not been analysed for the other modes.

These results concerning the 3D fluid effect are coherent with results on similar study concerning cylindrical shells (Gibert 1989).

4 - CONCLUSION

The bundle 2D finite elements model allows the calculation of the fluid coupled eigenmodes and has confirmed the existence of axisymmetric flowering modes. Thus it contributes to the validation of the homogeneization method.

The influence of the 3D fluid motion may be important, especially for axisymmetric flowering motion. The translation modes are comparatively less sensitive to this phenomenon. Nevertheless, this study constitutes only a first step and further analyses are necessary. First, it should be useful to validate, for the bundle geometry, the method used to take into account the 3D effect. This validation should be made on the basis of 3D calculations. Then studies with more realistic bending mode shapes are necessary, especially when the free surface is in the zone where the bending mode shape is maximal (for example cantilever tubes like in FBR cores) ; the 3D fluid effect could be there more important than in the case presented in this paper.

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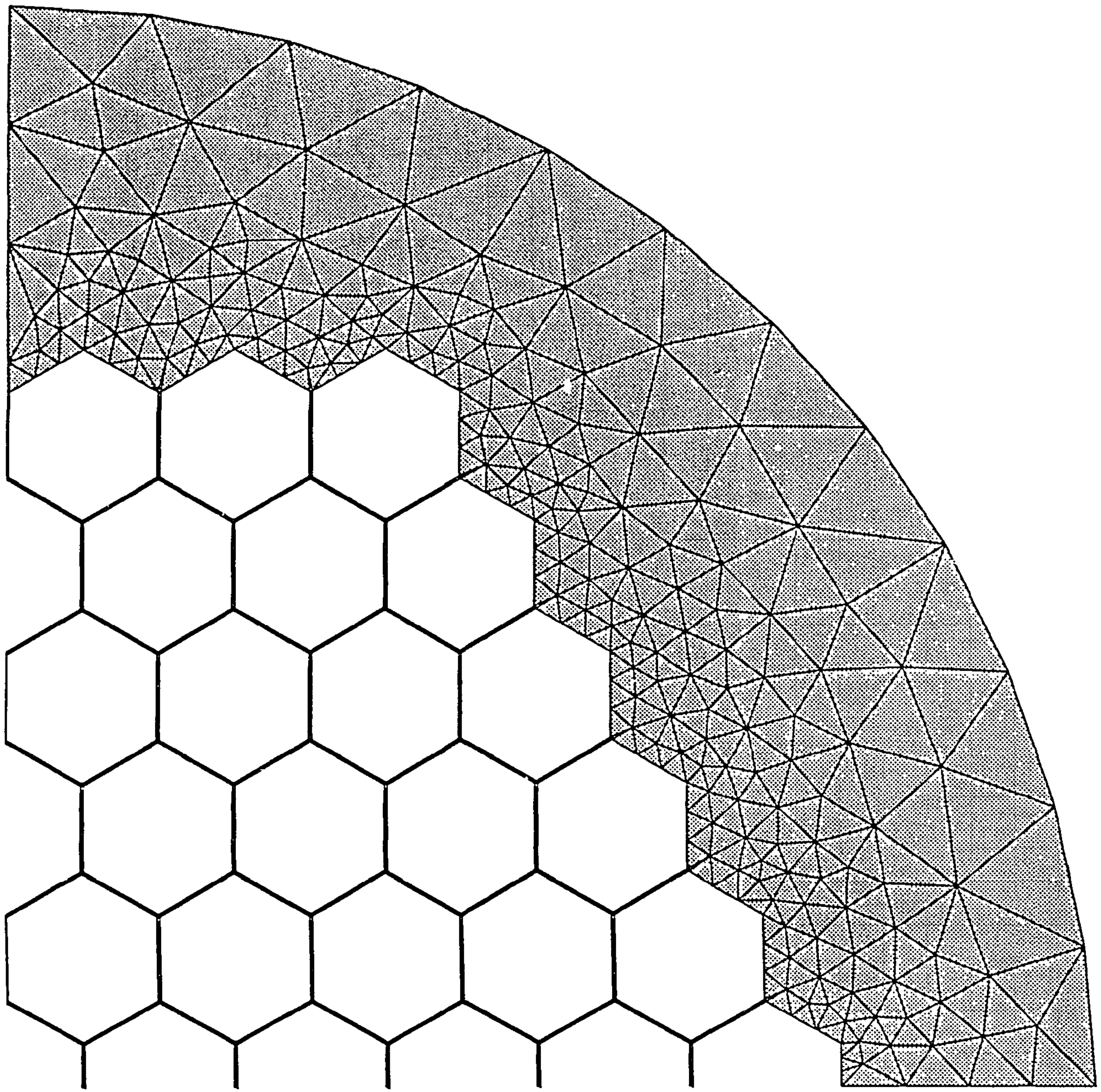


Figure 2 : 2D model mesh

Figure 3 : 2D model -axisymmetric flowering mode

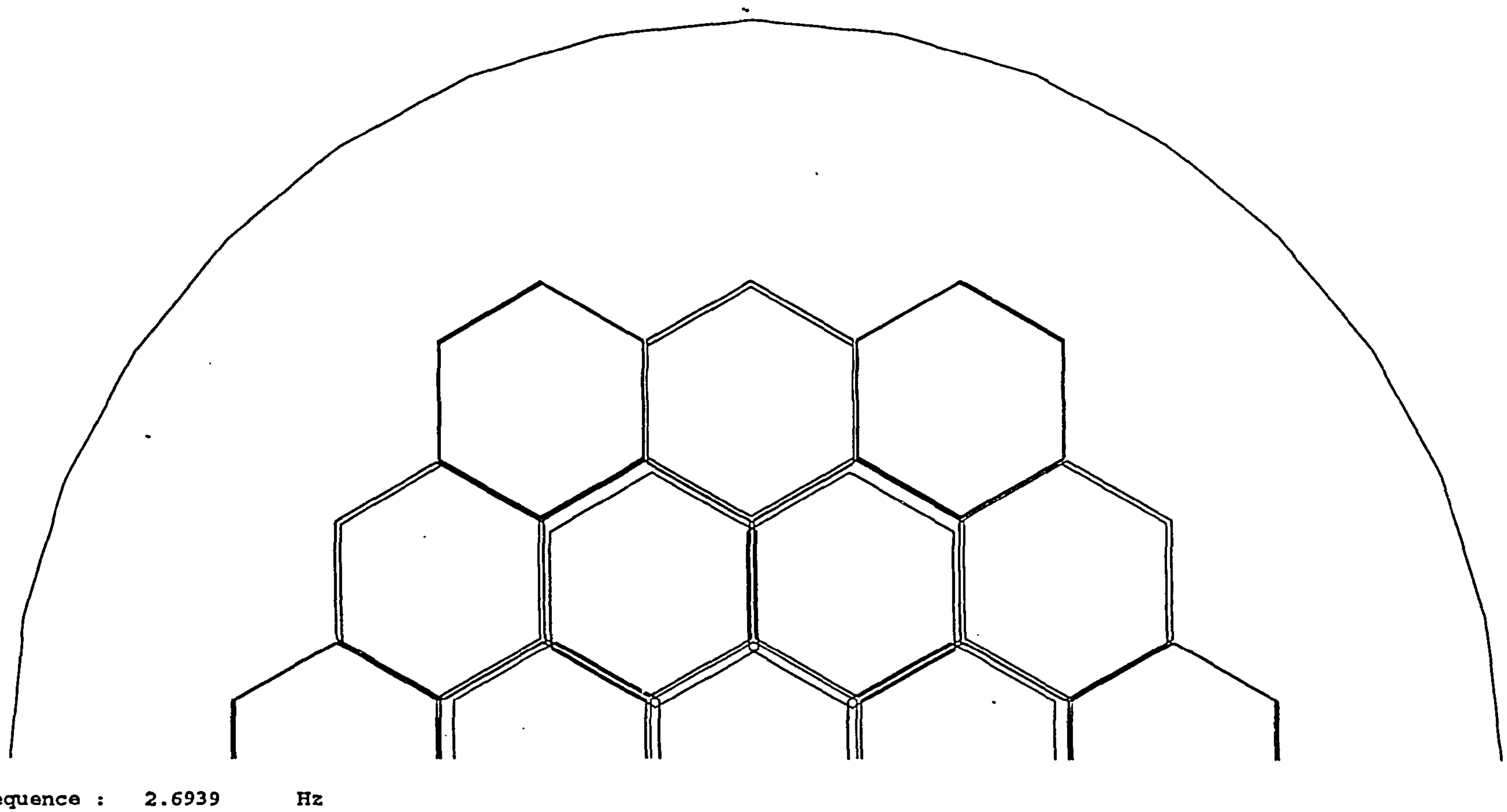
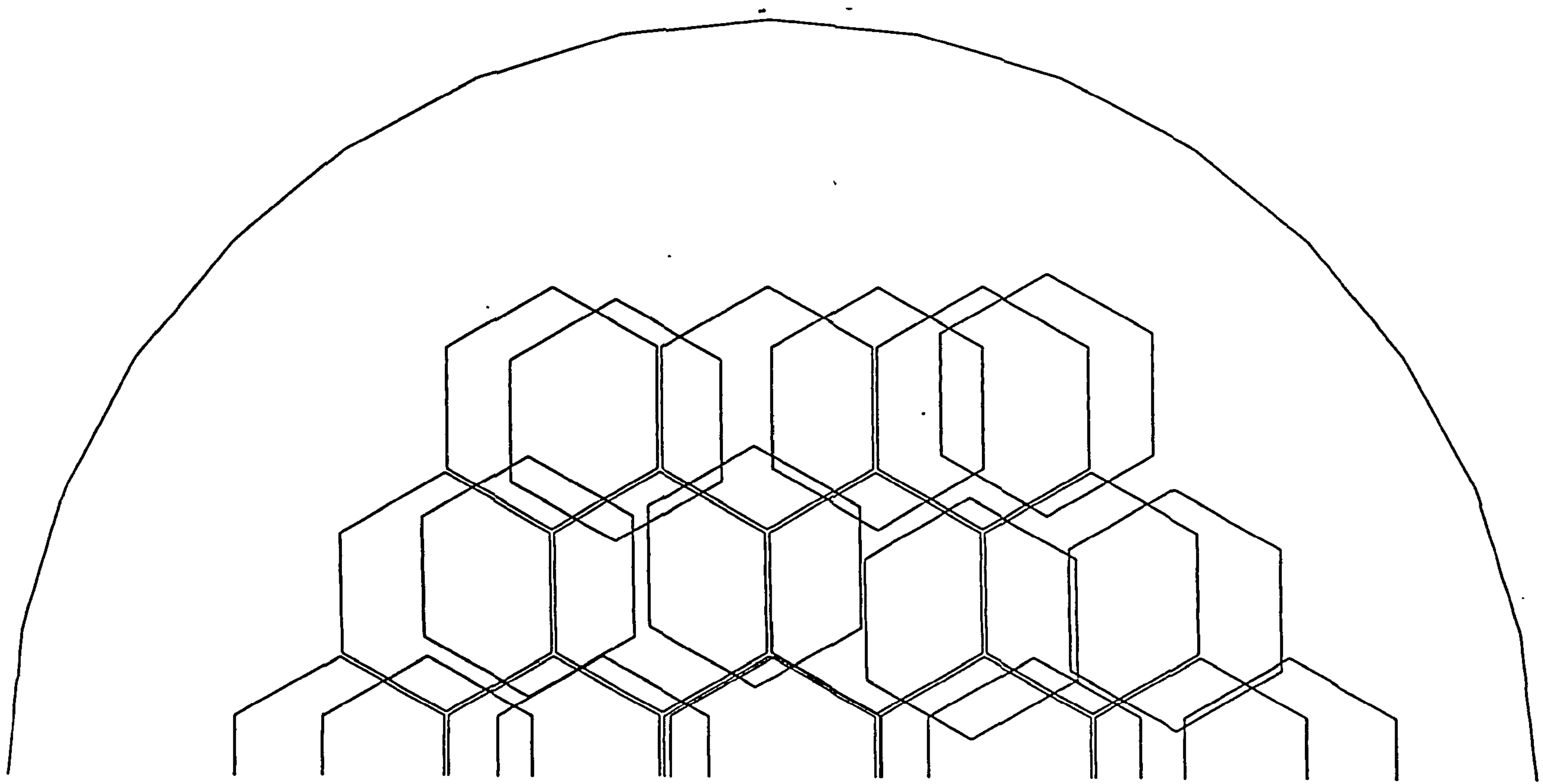
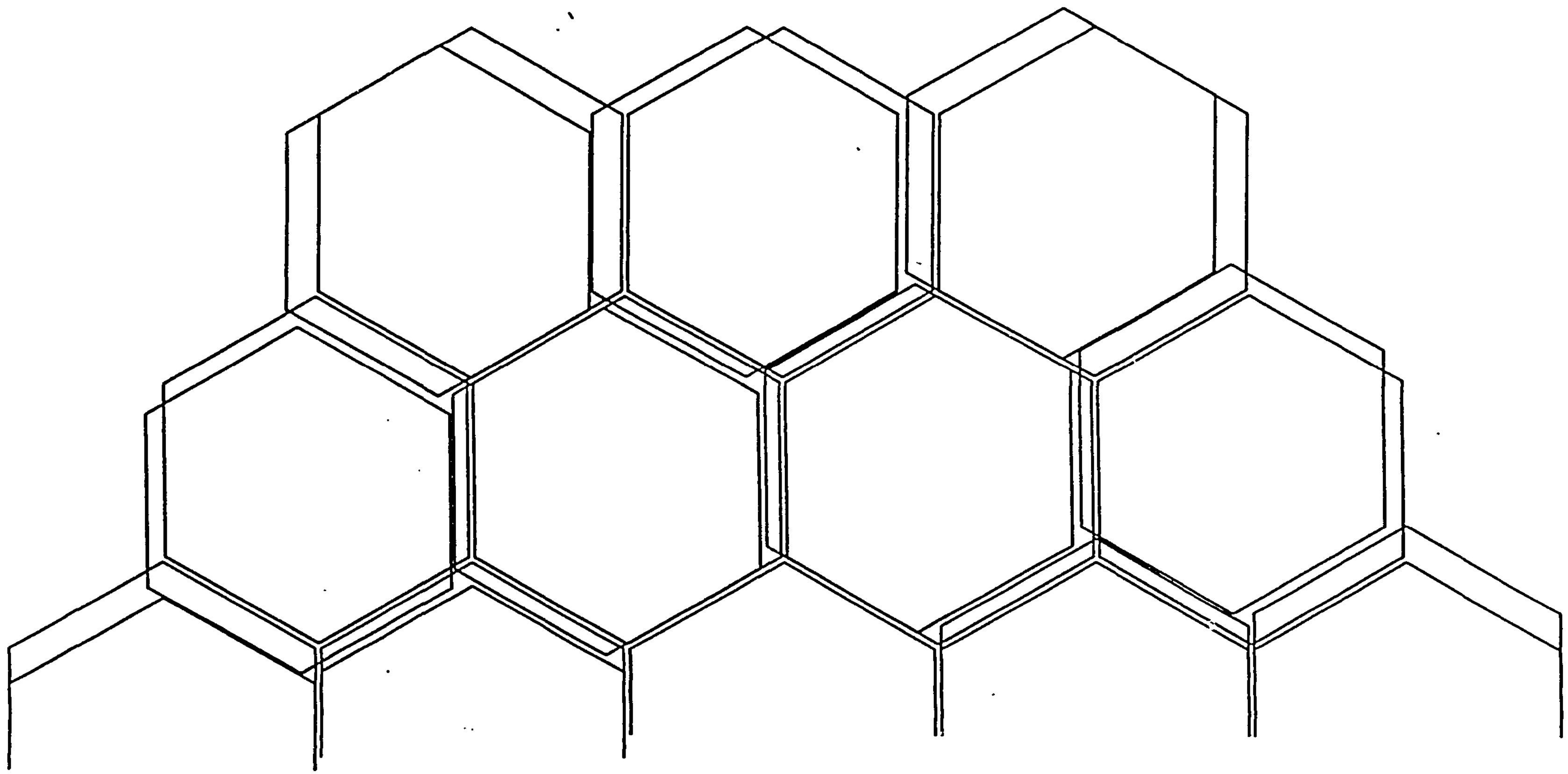


Figure 4 : 2D model horizontal translation mode



Frequence : 6.6109 Hz

Figure 5 : 2D model highest mode



Frequence : 7.8701 Hz

Figure 6 : 2D horizontal model influence of the ring number

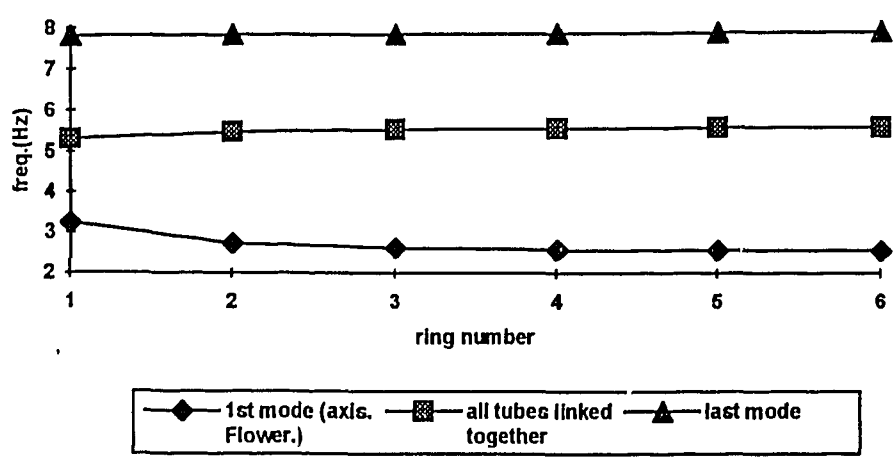


Figure 7 : 2D horizontal model - Influence of eta (1ring)

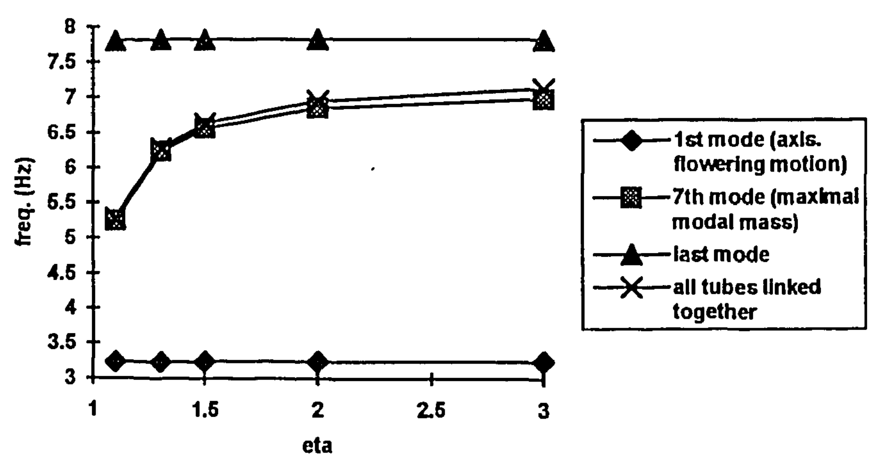


Figure 8 : 2D horizontal model
All tubes linked together

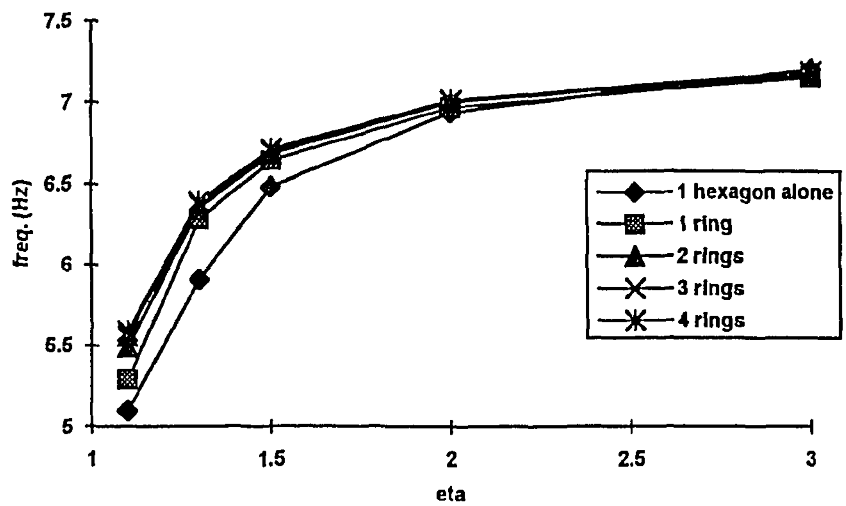


Figure 9 : Fluid vertical motion
axisymmetric flowering motion

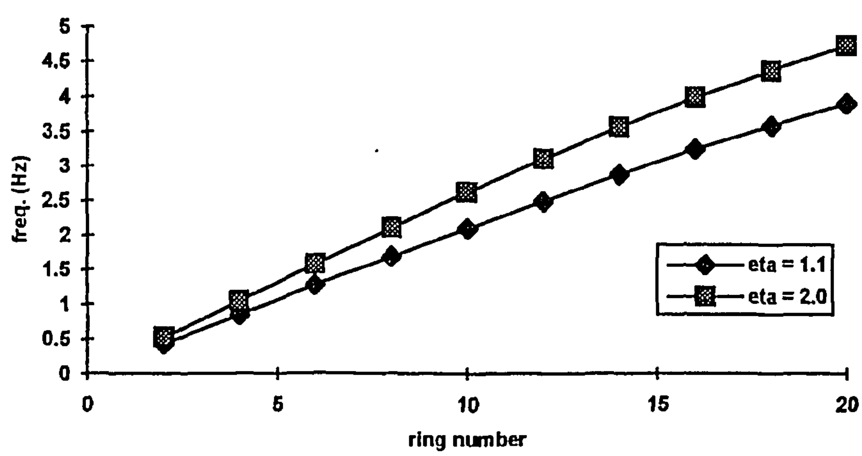


Figure 10 : Fluid vertical motion
Axisymmetric flowering motion
Influence of eta

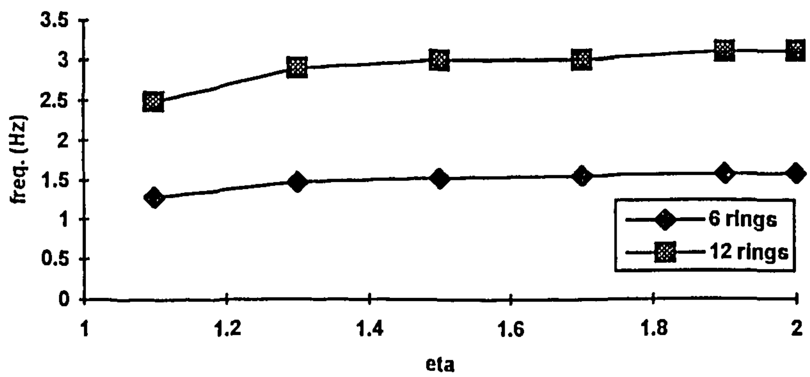


Figure 11 : Fluid vertical motion
Bundle translation
Influence of the rings number

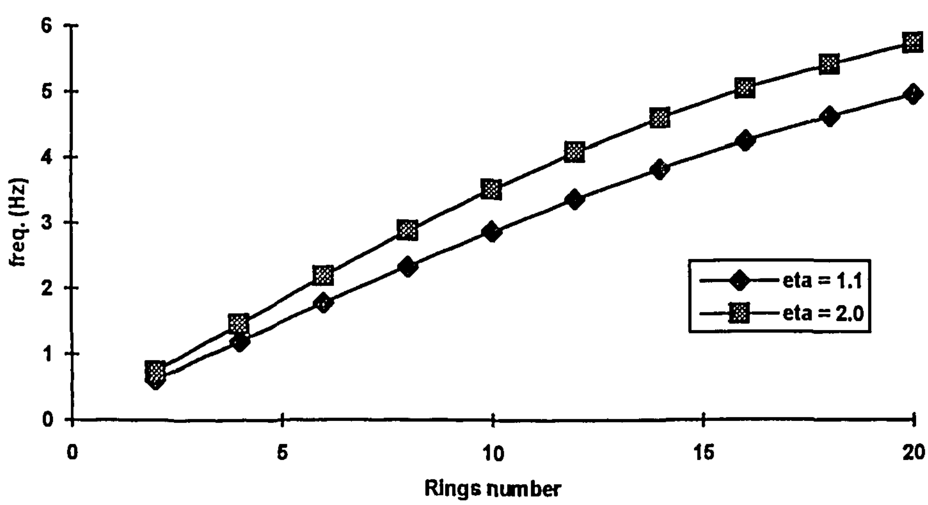


Figure 12 : Fluid vertical motion
Bundle translation
Influence of eta