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FLOW INDUCED VIBRATION IN THE SUPERPHENIX HEAT EXCHANGER BUNDLES

by F. AXISA

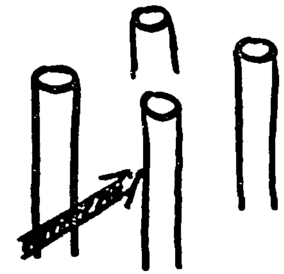
I BASIC DATA USED IN PREDICTIVE ANALYSES

II APPLICATION TO I.H.X AND COMPARISON WITH TEST RESULTS OF A HYDROELASTIC MODEL

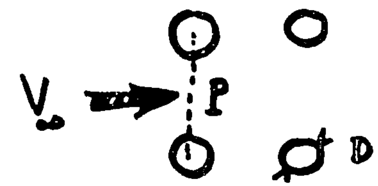
III APPLICATION TO S.G. AND TEST RESULTS OF A HYDROELASTIC MODEL

IV CONCLUDING REMARKS AND FUTURE WORK

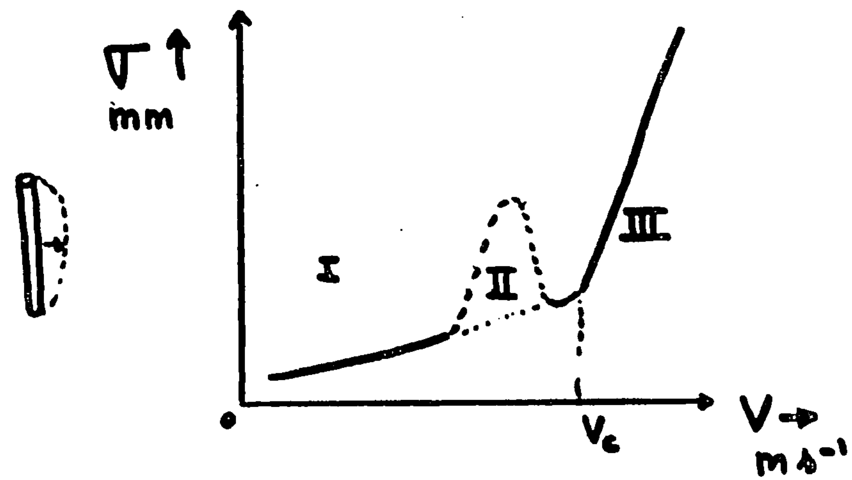
⊥ FIV in TUBE ARRAYS



CROSS FLOW



$$V = V_\infty \frac{P}{P-D}$$



I EXCITATION BY TURBULENCE

II "PERIODIC WAKE SHEDDING"

III FLUIDELASTIC INSTABILITY

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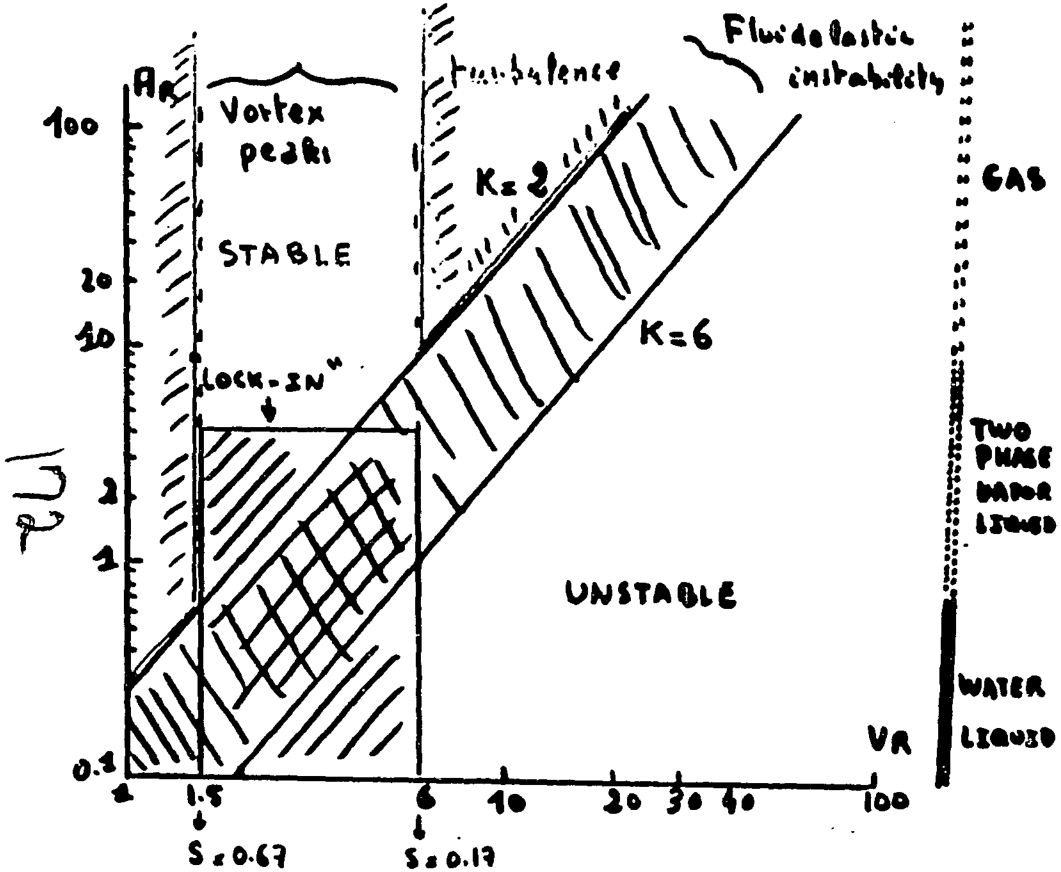

$A_R = \dfrac{2\pi m \zeta}{\rho D^2}$ $\quad V_R = \dfrac{fD}{V_g}$ $\quad V_g$: gap flow velocity

$V_{Rc} = K\sqrt{A_R}$ $\quad$ K depend upon pitch and array pattern

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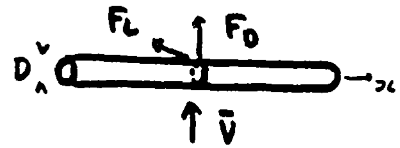
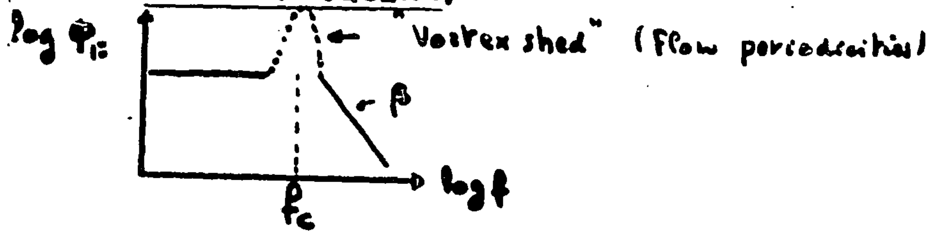
RESPONSE TO CROSS-FLOW TURBULENCE



1) FLUCTUATING FORCES ARE RANDOM IN TIME AND SPACE ALONG TUBE SPAN, CROSS-SPECTRUM:

$$\Psi_F(x_1,x_2,f) = \Phi_F(f) \times \exp - \frac{|x_1-x_2|}{\lambda_c}$$

2) AUTOCORRELATION SPECTRUM : BROAD BANDED WITH CUTOFF FREQUENCY



3) SINGLE PHASE FLOW SCALING PARAMETERS

$$\Phi_F(f) = \left[\frac{1}{2}\rho \bar V^2 D\right]^2 \frac{D}{\bar V}\, \tilde\Phi_F(f_R)$$

$$f_R = fD/\bar V$$

$$F = \frac{1}{2}\rho \bar V^2 D\, \tilde F$$

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DIVA RIG :

TEST SECTION

AIR FLOW UP TO 0.3 Kg/s

WATER FLOW UP TO 200 Kg/s

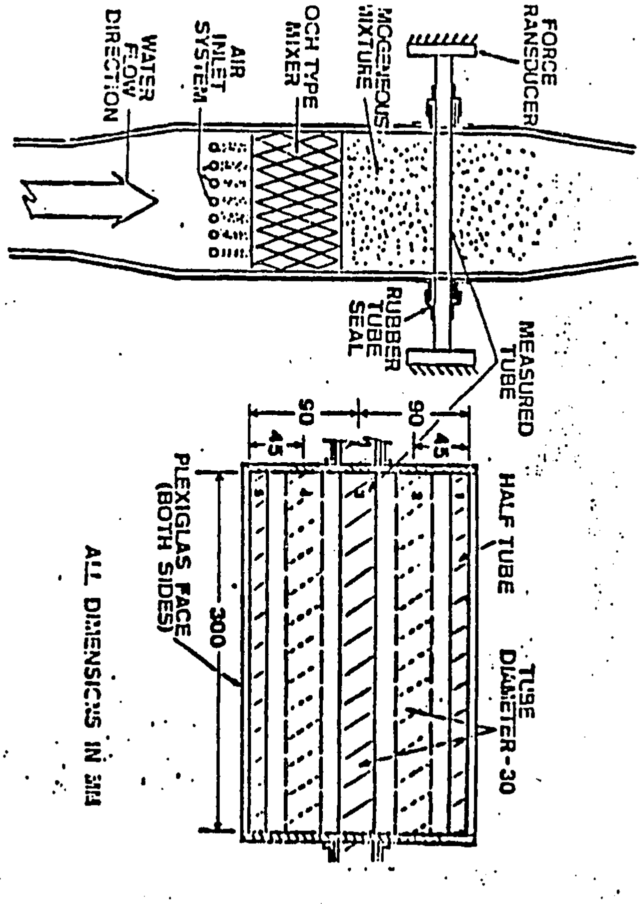

Fig 6

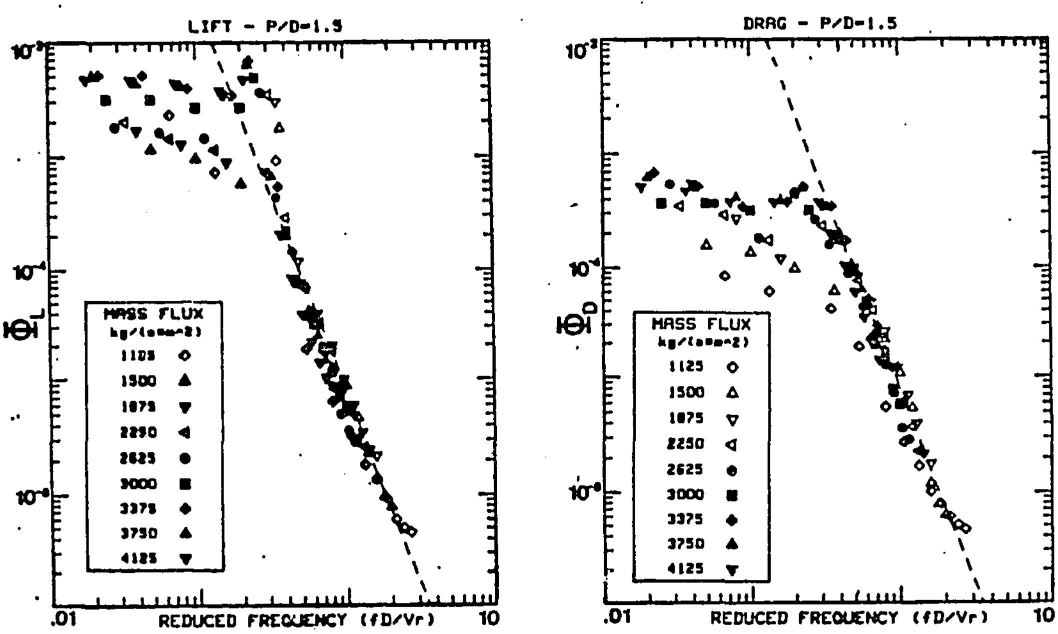

Figure 3.10 : Nondimensional power spectral densities for a tube row, with P/D=1.5, subjected to water cross flow

- Fig 2 -

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TUBE RESPONSE TO CROSS FLOW TURBULENCE

4) R.M.S DISPLACEMENT AT RESONANCE

$$\sigma_d(f_0,x) = \frac{1}{2}\bar{\rho}\,\bar{V}^2 D\,\frac{\varphi_0(x)}{8\pi^{3/2} M_0 f_0^2}\,\frac{1}{\xi^{1/2}}\left(\frac{f_0 D}{\bar{V}}\right)^{1/2} L_0\, x\,\left[\tilde{\Phi}_F(f_R)\right]^{1/2}$$

$$L_0^2 = \int_0^\ell\int_0^\ell \varphi(x_1)\,\varphi(x_2)\left[u(x_1)\,u(x_2)\right]^2 \exp - \frac{|x_1-x_2|}{\lambda_c}\,dx_1\,dx_2$$

5) PARAMETRIC TRENDS

MODAL PARAMETERS

$\sigma_d \propto f_0^{-\left(\frac{3+\beta}{2}\right)}$ Frequency

$\propto 1/\sqrt{\xi}$ damping

$\propto 1/M_0$ mass

FLOW PARAMETERS

$\sigma_d \propto \bar{V}^{\frac{3+\beta}{2}}$ Velocity

$\propto \bar{\rho}$ density

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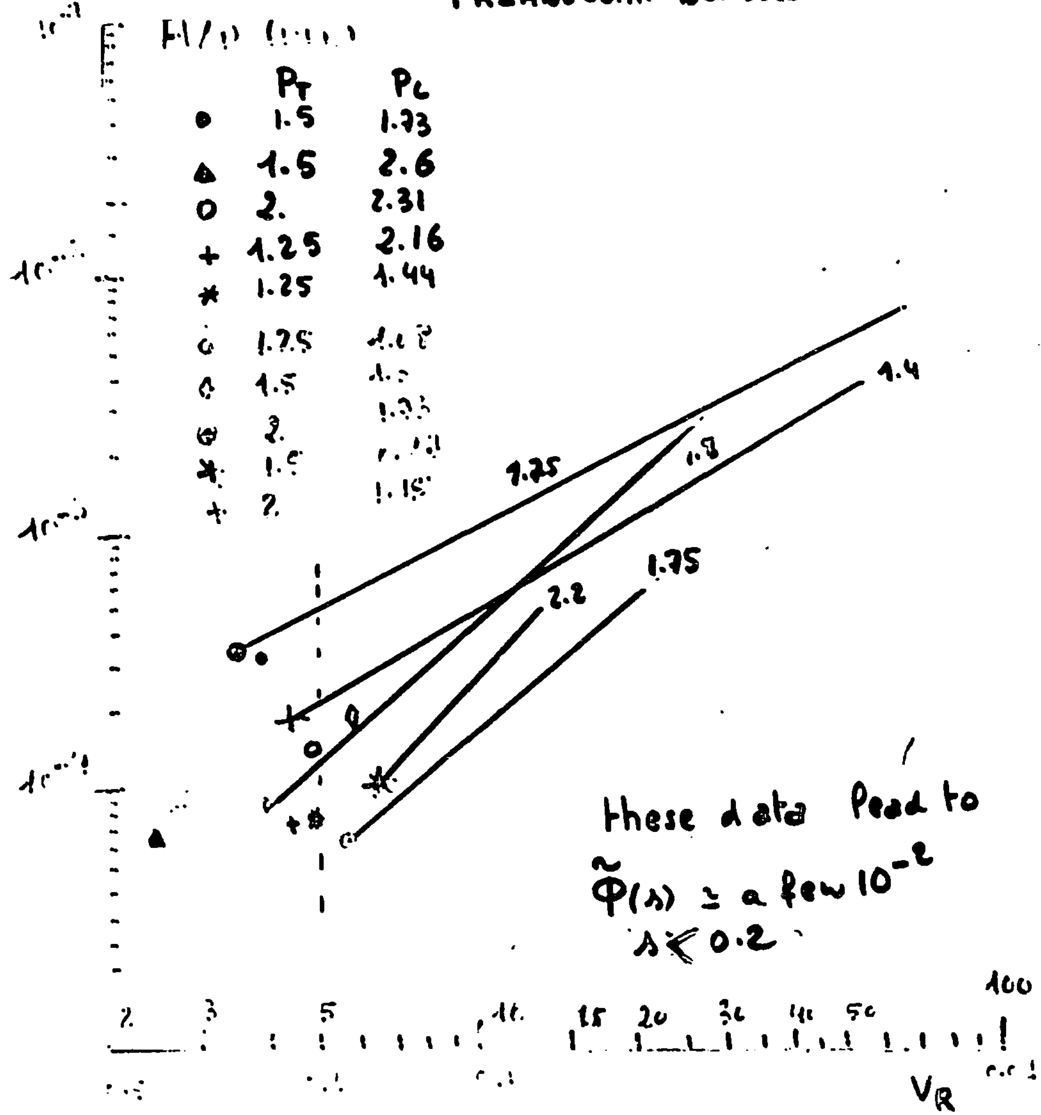
RECTANGULAR BUNDLES

TRIANGULAR BUNDLES



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Cross-Flow Induced Vibration of U-Bend Tubes of Steam-Generator Tubes

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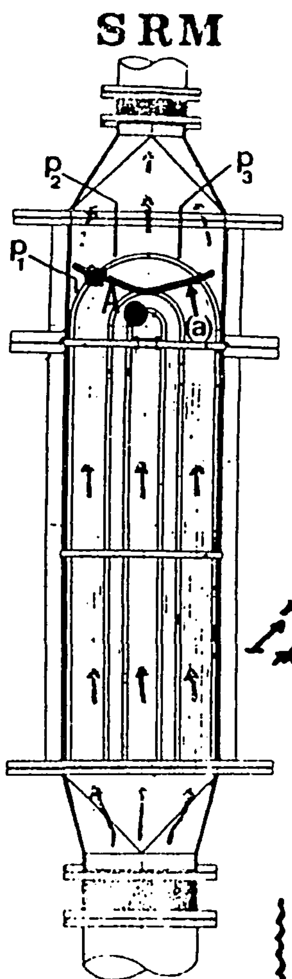
C.E.A. CEN Saclay DEMT, F-91191 Gif-sur-Yvette Cedex, France

SHORT RADIUS MODEL :

SRM

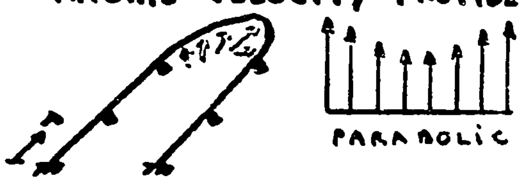


MODEL	SRM
Scale	1
Material	Inconel 600
Young Modulus	2×10^{11} Pa
Volumic mass	8200 kgm^{-3}
Diameter	19.05 mm
Thickness	1.09 mm
Radius of curvature ..	75 - 322 mm
Straight span length .	1038 mm
Square pitch	27.4 mm

40 LAYERS × 5 TUBES

REDUCED PITCH = 1.44

RADIAL VELOCITY PROFILE $u(s)$:



PARABOLIC

TESTS PERFORMED:

(a) AVG-IN

- $2.1 \le V_g \le 8.2\ m\,s^{-1}$; 3 INNER TUBES
- $\tilde{\Phi}_F(f_R)$ TURB. FORCE SPECTRUM

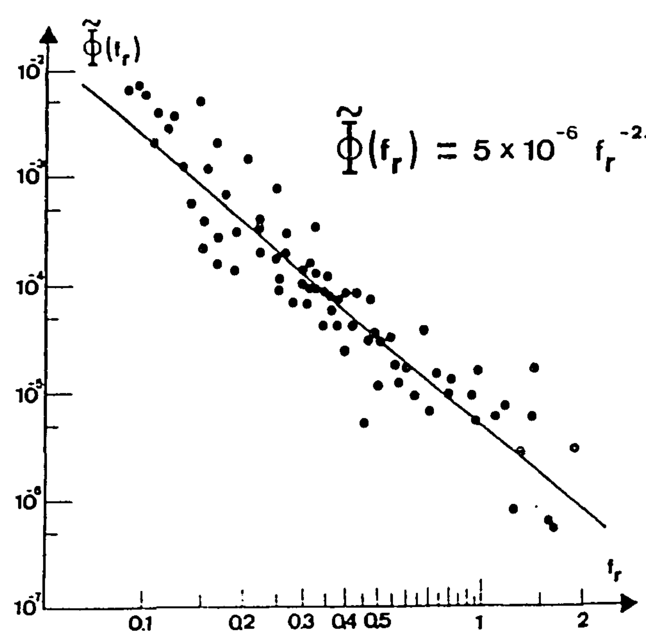
(b) AVG-OUT

- $0.3 \le V_g \le 2.2\ m\,s^{-1}$; 4 OUTER TUBES

{ P_i = PRESSURE PROBES
{ A_i : IN & OUT OF PLANE ACC.

$$\sigma_n^2(s) = \left(\frac{1}{2}\rho D V_g^2\right)^2 \frac{D}{V_g} \tilde{\Phi}_F\left(\frac{f_n D}{V_g}\right) \frac{\varphi_n^2(s)\, L_{cn}^2}{64\pi^3 \zeta_n M_n^2 f_n^3}$$

$$L_{cn}^2 = \int_0^L \int_0^L \varphi_n(s_1)\varphi_n(s_2)\left[u(s_1)\,u(s_2)\right]^2 \exp\left(-\frac{|s_2-s_1|}{\lambda_c}\right) ds_1 ds_2$$



$$C_L^2 = \int_0^\infty \tilde{\Phi}_F(f_R)\, df_R$$

$C_L = 0.03$

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CHARACTERISTICS OF A SUPERPHENIX I. H. X

BUNDLE

- Straight tube bundle of circular cross section
- Reduced pitch $P/D \simeq 1.4$
- Staggered or alined, depending on azimutal direction

SUPPORTS

- Tubes are clamped at their ends on stiff tube support plates (T.S.P)
- Intermediate supports are provided by anti-vibratory belts (A.V.B) acting roughly as pinned conditions

EXTERNAL FLOW (primary sodium)

Nominal cross flow :

Inlet (upper part of I.H.X) along a span of 0.75m
Outlet (lower part of I.H.X) " "

IT WAS ASSUMED THAT :

Inlet : Uniform cross flow $V_{gi} = 2.1$ m/s
Outlet : Uniform cross flow over partial span: $\ell = 0.39$m from T.S.P, $V_{ge} = 3.9$ m/s

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PREDICTIVE ANALYSIS OF F.I.V FOR THE SUPERPHENIX I.H.X

$F_0 \simeq 70$ Hz (L=0.75m, Clamped pinned)
$\zeta \simeq 10^{-2}$

INLET
$A_R = 0.23$ $\qquad V_{Rc} = 4\sqrt{A_R} = 1.9$
$V_R = 2.28$

OUTLET
$A_R = 0.42$ $\qquad V_{Rc} = 2.6$
$V_R = 4$

HENCE INSTABILITY WAS PREDICTED

IN ADDITION

$A_R < 1 \quad V_R \simeq 2 \Rightarrow S \simeq 0.5$

HENCE "LOCK IN" OR STRONG RESPONSE TO FLUCTATING FLOW PERIODICITY WAS TO BE FEARED AT THE INLET

[illegible]
[illegible] for fluctuating forces $C_L \simeq$ [illegible]

INLET $\sigma \simeq 10\ \mu m$
OUTLET $\sigma \simeq 18\ \mu m$

I.H.X. MODEL :

GENERAL VIEW

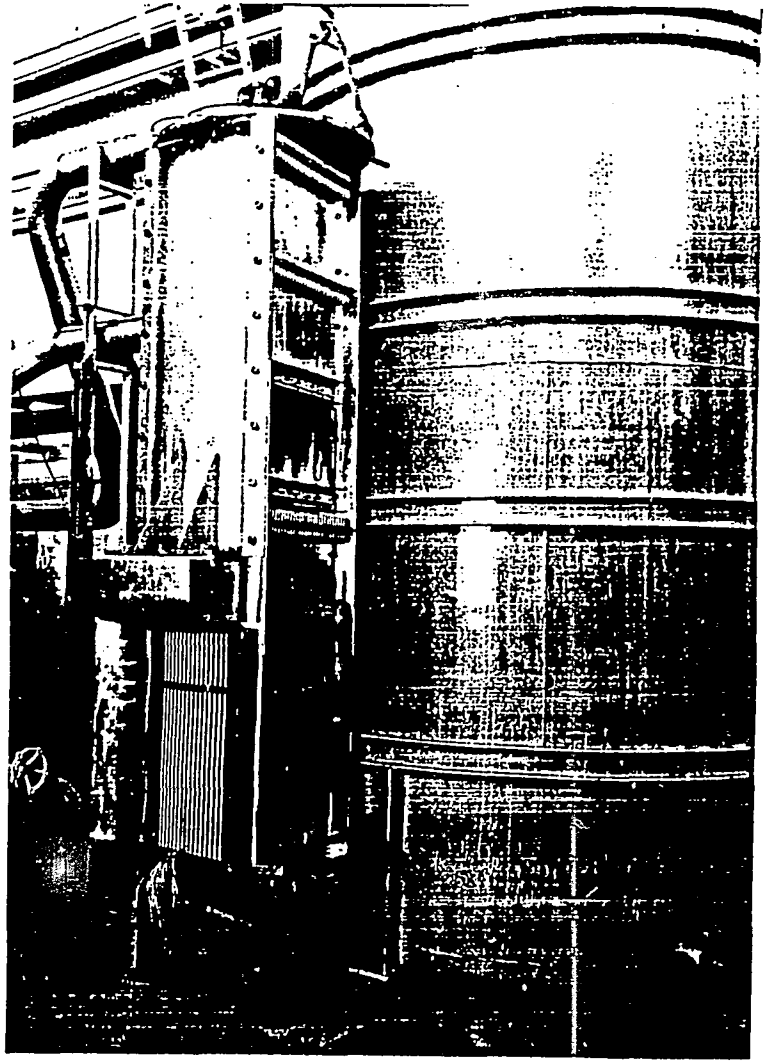
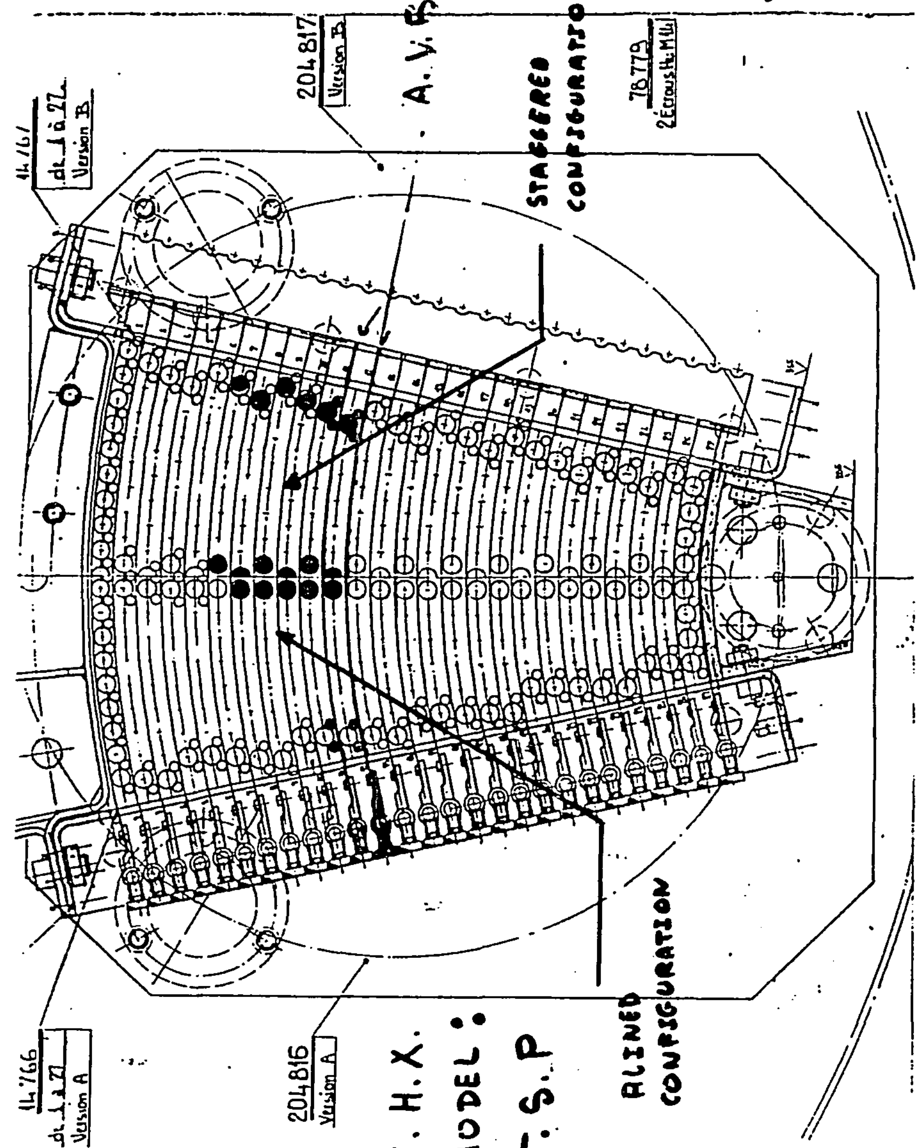


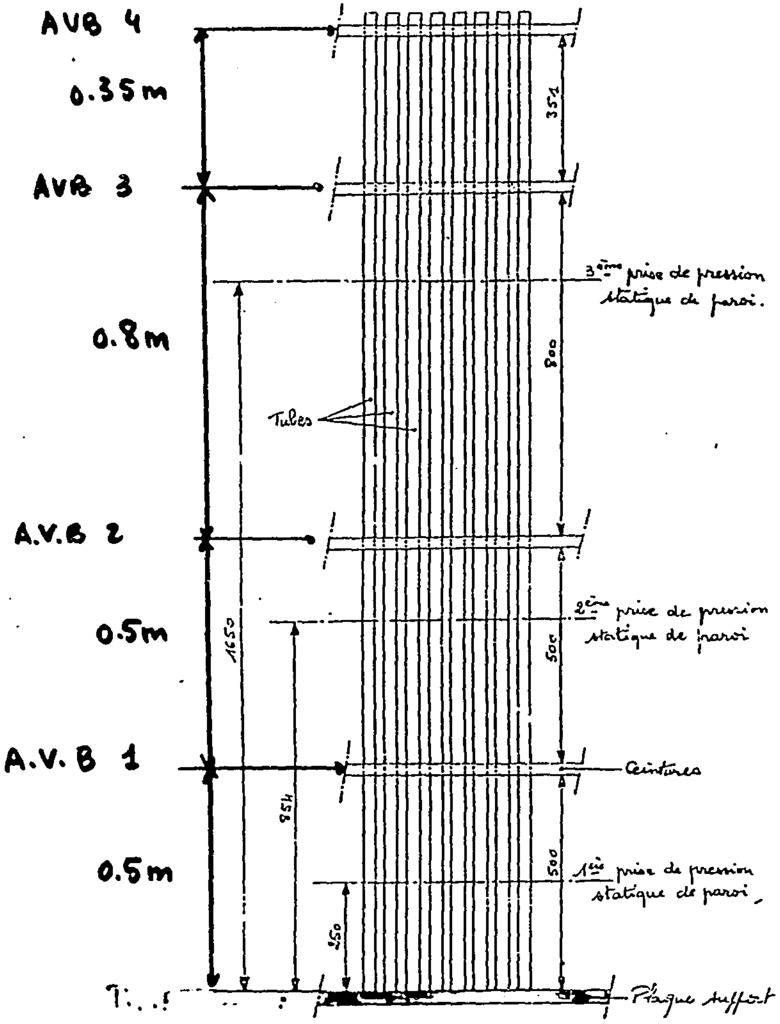
FIGURE 1 - VUE GENERALE DE LA MAQUETTE

Figure 2



I.H.X. MODEL : T.S.P

A.V.B : ANTI VIBRATORY BELT

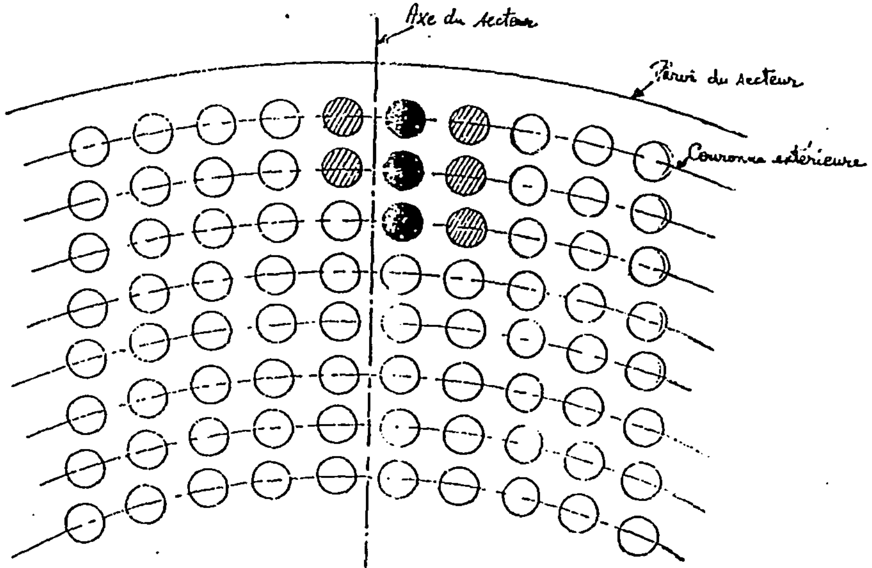


Vue de face du faisceau

Figure 3 : Implantation des prises de pression statique de paroi

SCHEMATIC VIEW OF THE
I.H.X MODEL : FRONT VIEW OF
THE BUNDLE

Vue de dessus du faisceau.



FAISCEAU E.I

CONFIGURATION ALIGNEE AU CENTRE

Tubes équipés d'accéléromètres uniaxiaux pour mesurer l'accélération transverse.

Tubes équipés d'accéléromètres biaxiaux

Figure 1 : Position dans le faisceau des tubes instrumentés d'accéléromètres.

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I.H.X MODEL : OBJECTIVES

MEASUREMENT OF

- CROSS-FLOW VELOCITY PROFILES
- AND CROSS-FLOW INDUCED VIBRATION,

IN

FIVE BUNDLE CONFIGURATIONS

1. Bundle "alined" at the center of the sector + First AVB at 512 mm of the TSP
2. Bundle "staggered"
3. Same as 1 but by pass flow at the walls of the mock-up is limited
4. Bundle "staggered" + First AVB at 762 mm of the TSP
5. Bundle "alined"

I.H.X MODEL

CROSS-FLOW VELOCITY PROFILE

AT THE OUTLET

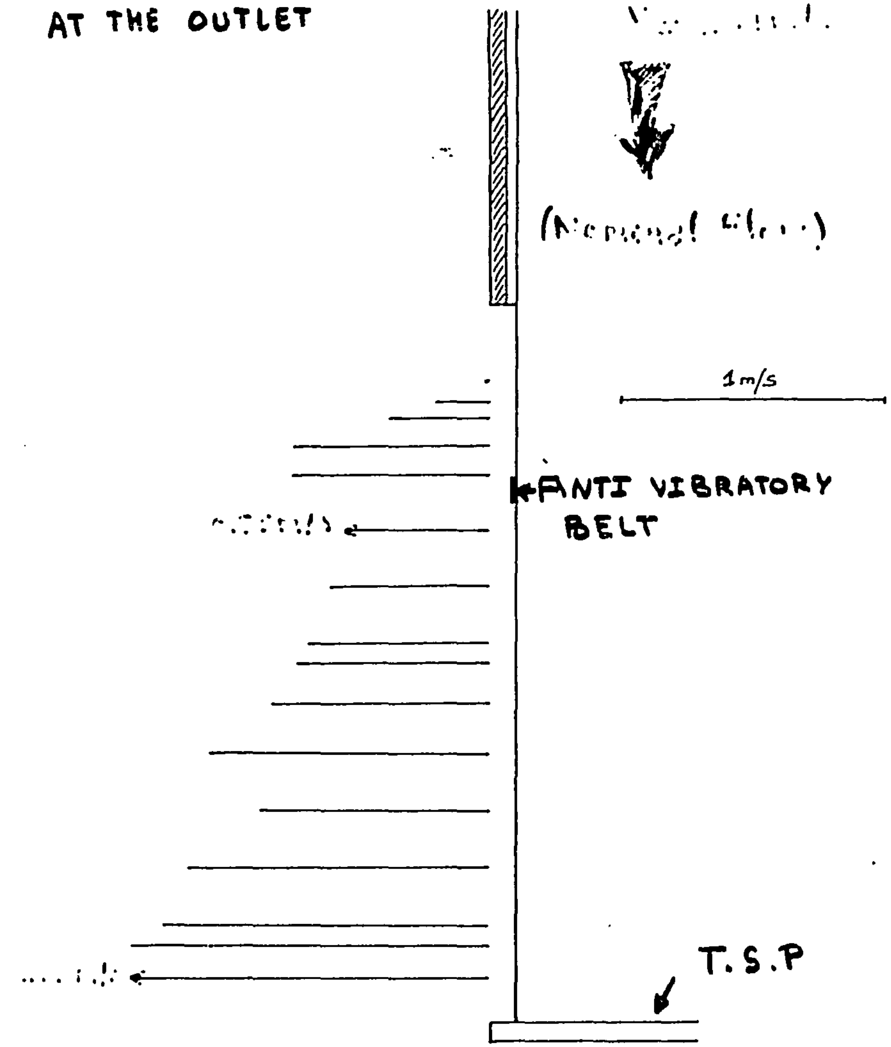

Figure 11: Evolution de la vitesse transverse - Génératrice A

V= 2,14 m/s

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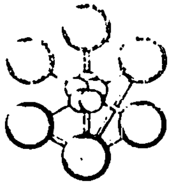
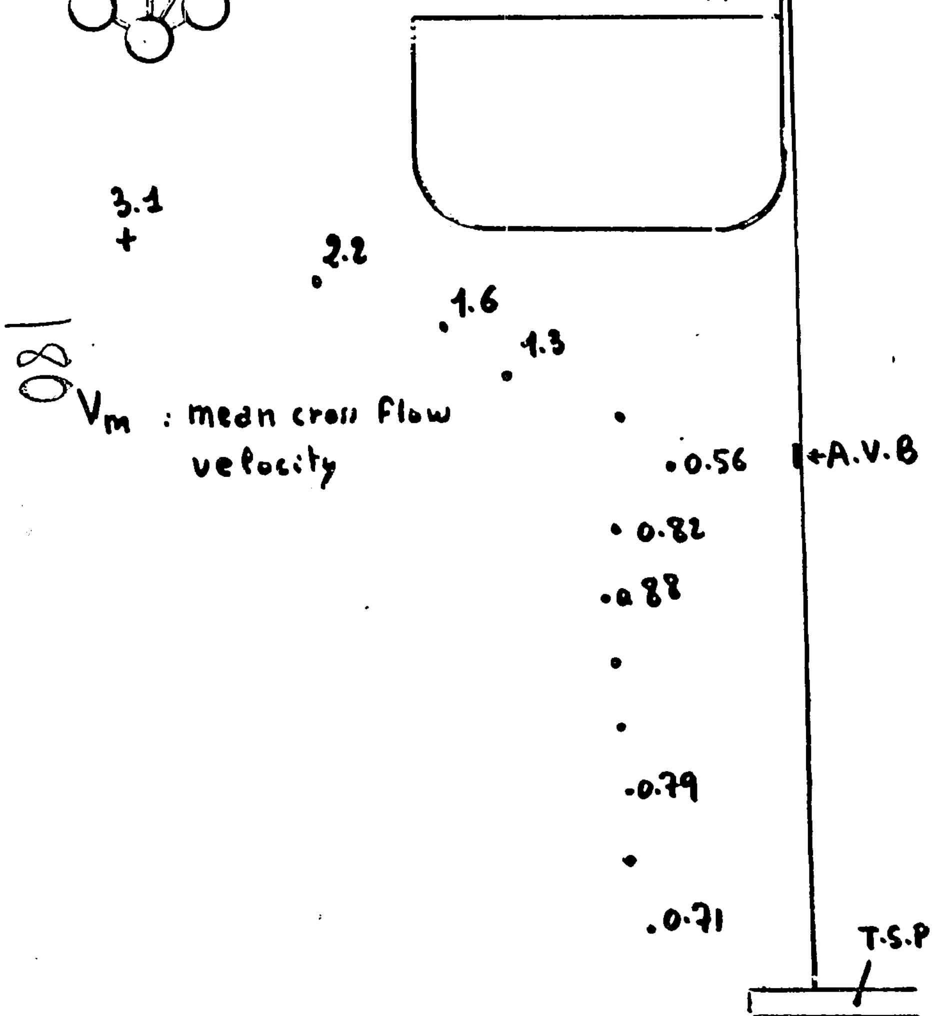
I. H. X. MODEL



CROSS FLOW VELOCITY PROFILE AT THE INLET : V/V_m



TUBE RESPONSE VS FLOW VELOCITY

FIGURE 7

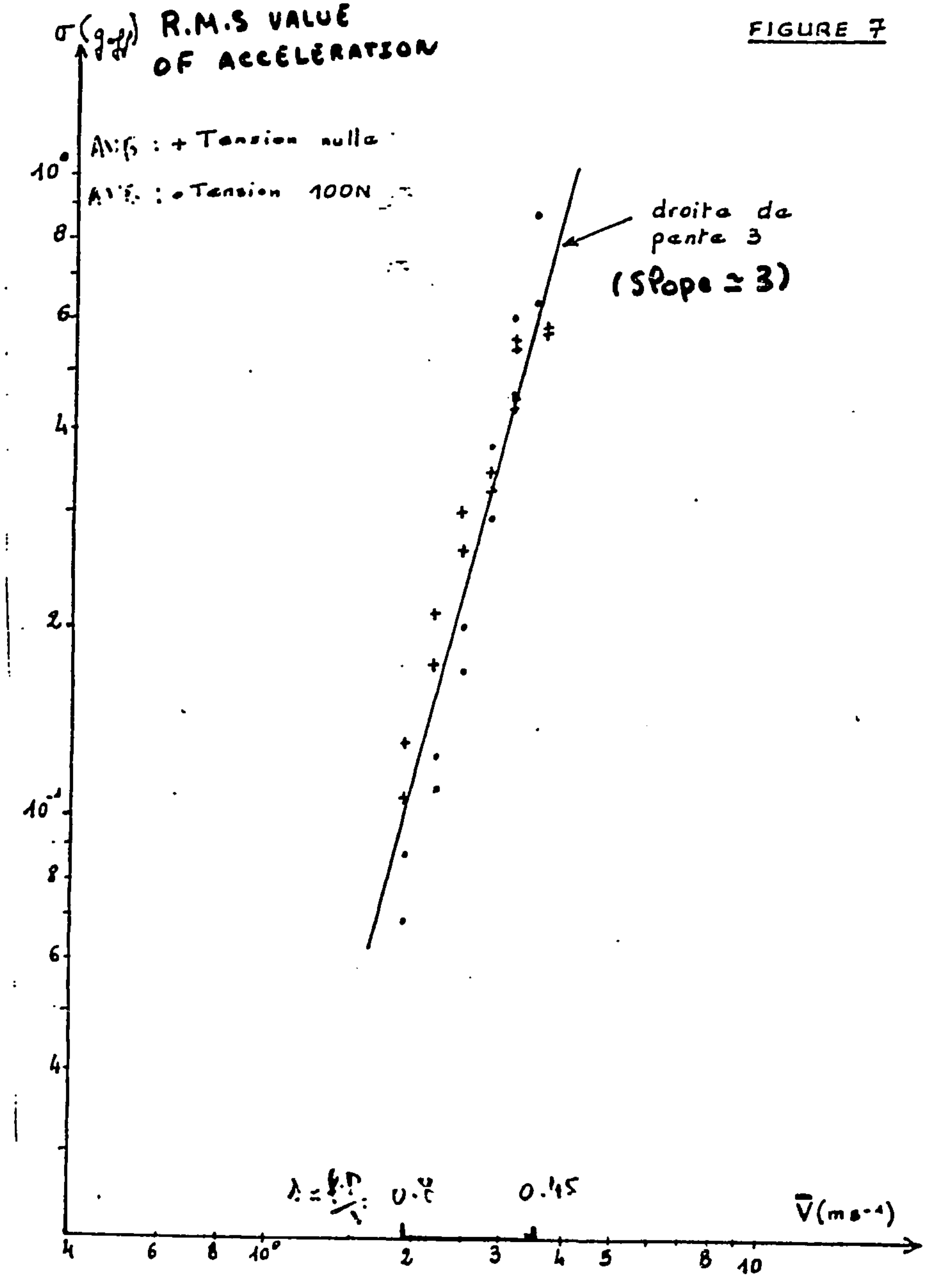
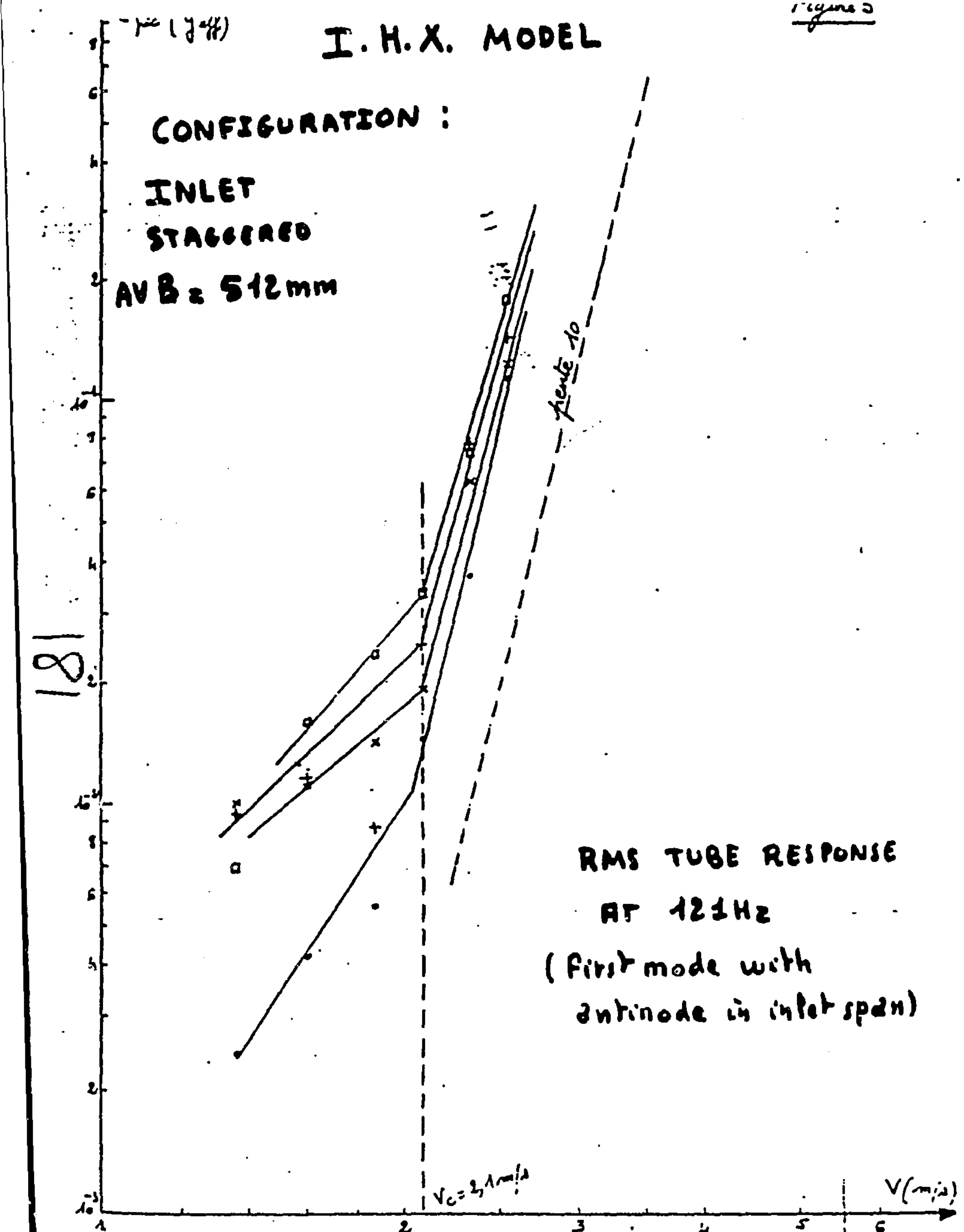


Figure 5

I.H.X. MODEL



Ecart-type du pic à 121 Hz
Accéléromètres de la 2e couronne de la 1re travée.

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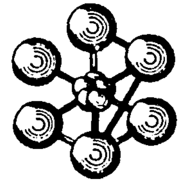
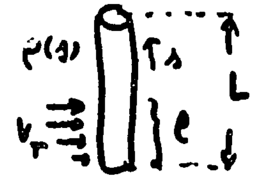
FLUIDELASTIC INSTABILITY :



NON UNIFORM CROSS FLOW
(F.B.E. Study)
STARTING FROM QUASI-STATIC MODEL
(Connors - Blevins)

$$m_e = \frac{M}{\mathcal{L}} = \frac{1}{\mathcal{L}}\int_0^L m(s)\,\varphi^2(s)\,ds$$



$$\mathcal{L} = \int_0^\ell \varphi^2(s)\,ds$$

$$V_e = \bar{V}\left[\frac{1}{\mathcal{L}}\int_0^\ell \frac{\rho(s)}{\rho}\left(\frac{V_T(s)}{\bar{V}}\right)^2 \varphi^2(s)\,ds\right]^{1/2}$$

$\bar{V}$ arbitrary reference velocity

$$V_{Rc} = \alpha K \sqrt{A_R} \qquad \alpha = \mathcal{L}\,\bar{V}/V_e$$

CONCLUSION : GENERAL GOOD AGREEMENT OBTAINED ON TUBES PARTIALLY SUBJECTED TO CROSS FLOW WITHIN LESS THAN 25% OF ERRORS

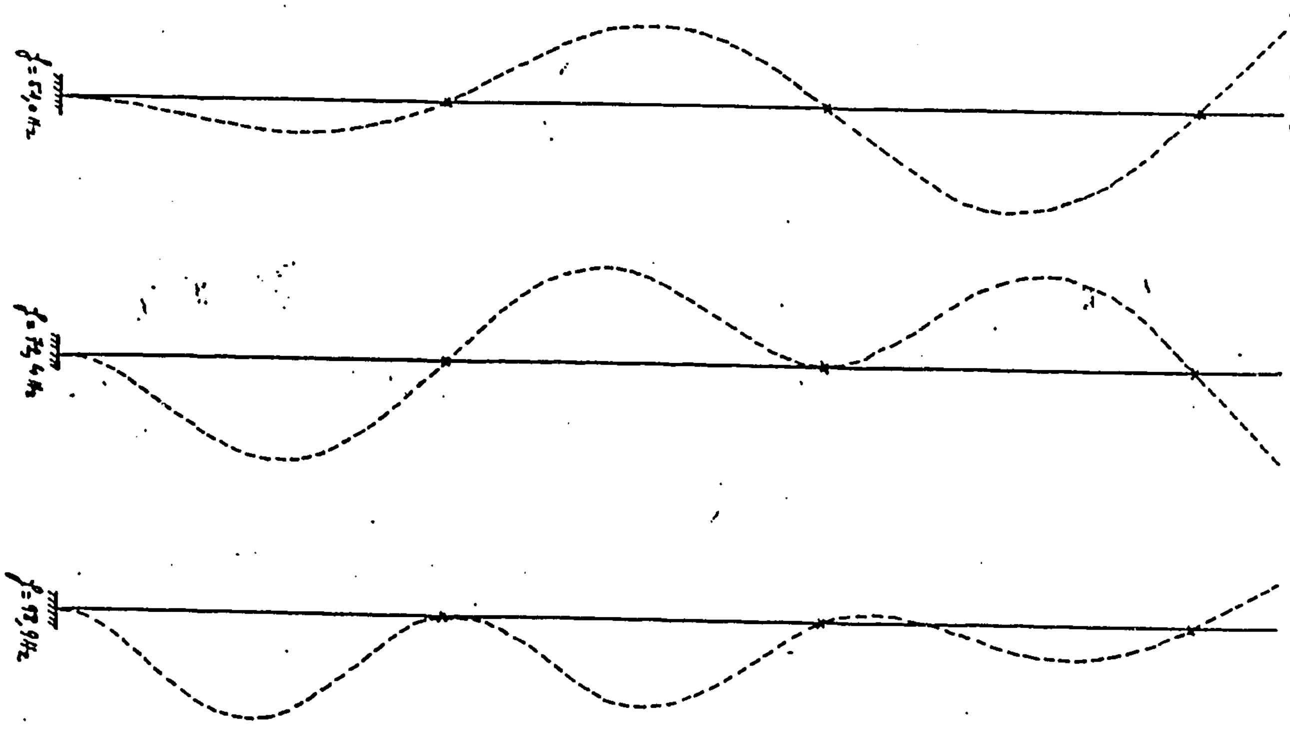


Figure 33

I.H.X FLUIDELASTIC INSTABILITY TEST VS PREDICTION

A.V.B	CONFIGURATION	INSTAB OBSERVED	Vmax Test m/s	Vc comp. m/s	Vc observed
512 mm	INLET ALINED SPAN 1	NO	2.8	5.7	
	INLET ALINED SPAN 2	NO	2.8	2.1	✗
	INLET STAGGERED SPAN 2	YES	2.7	2.2	2.1
	OUTLET ALINED SPAN 1	NO	3.2	7.3	
	OUTLET ALINED SPAN 2	NO	3.2	5.6	
	OUTLET STAGGERED SPAN 1	NO	2.4	6.8	
	OUTLET STAGGERED SPAN 2	NO	2.4	5.8	
762 mm	INLET ALINED SPAN 1	NO	2.6	3.3	
	INLET STAGGERED SPAN 1	NO	3.2	3.3	
	OUTLET ALINED SPAN 1	NO	2.9	3.2	
	OUTLET STAGGERED SPAN 1	NO	3.3	2.6	

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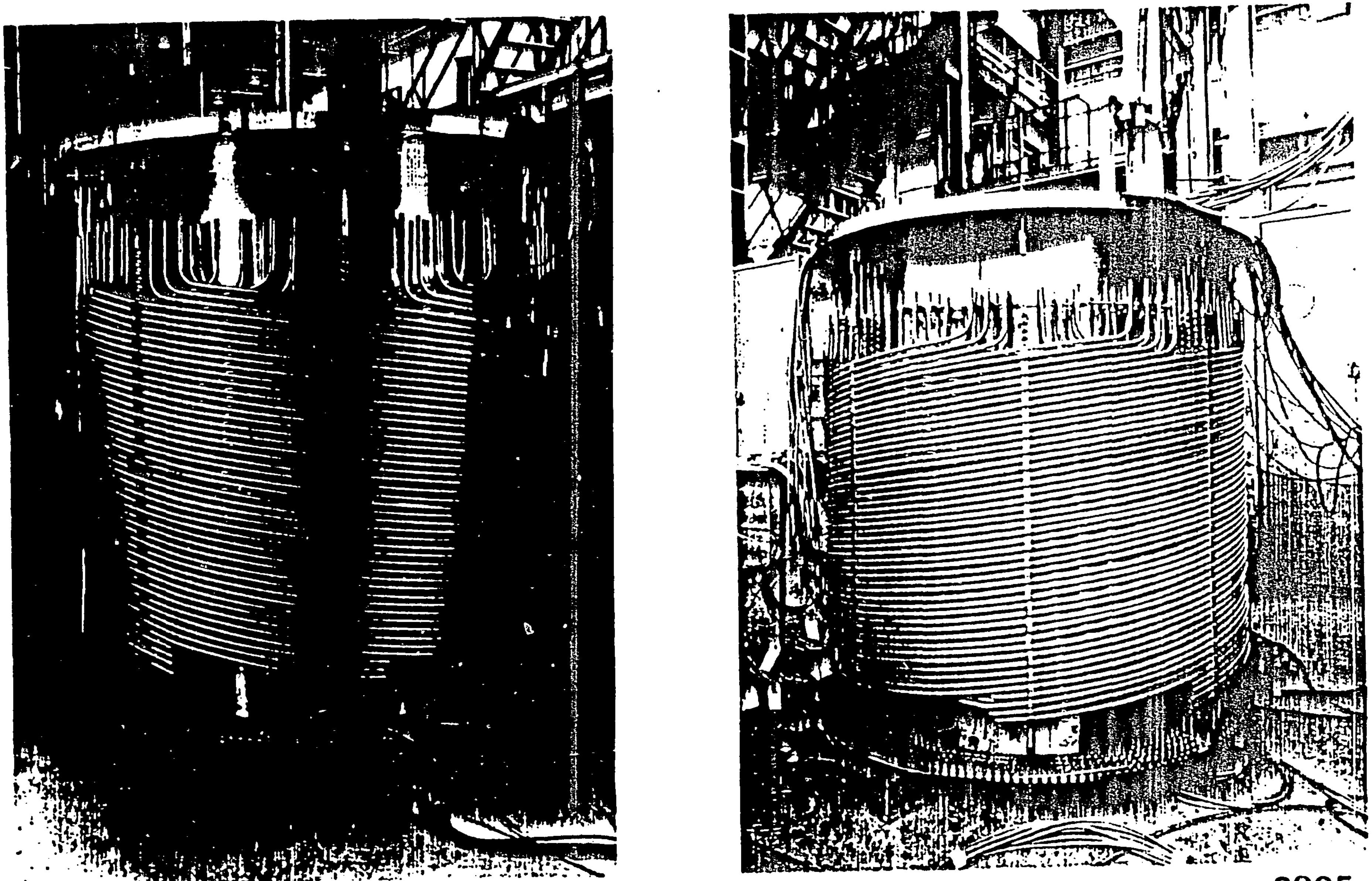

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FIGURE 1

MONTAGE de la MAQUETTE

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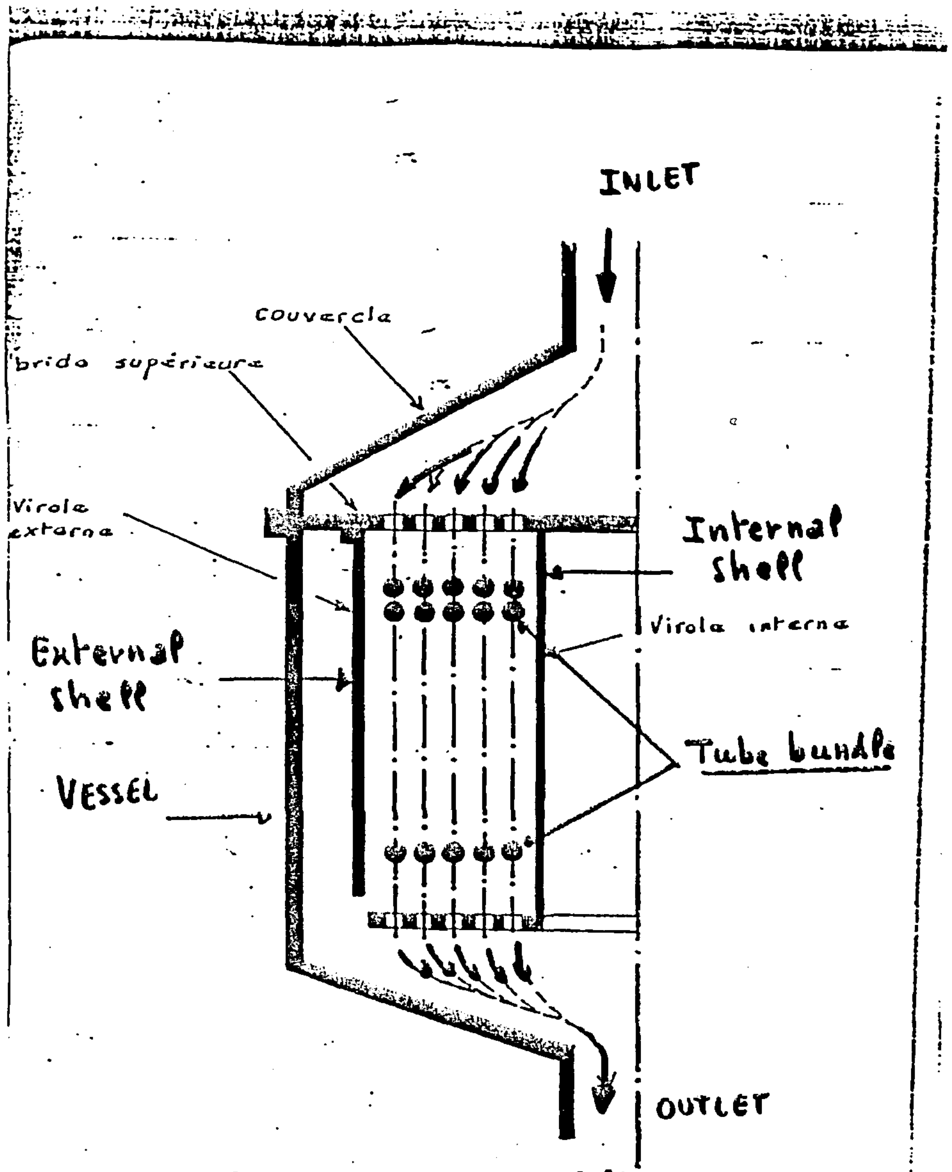
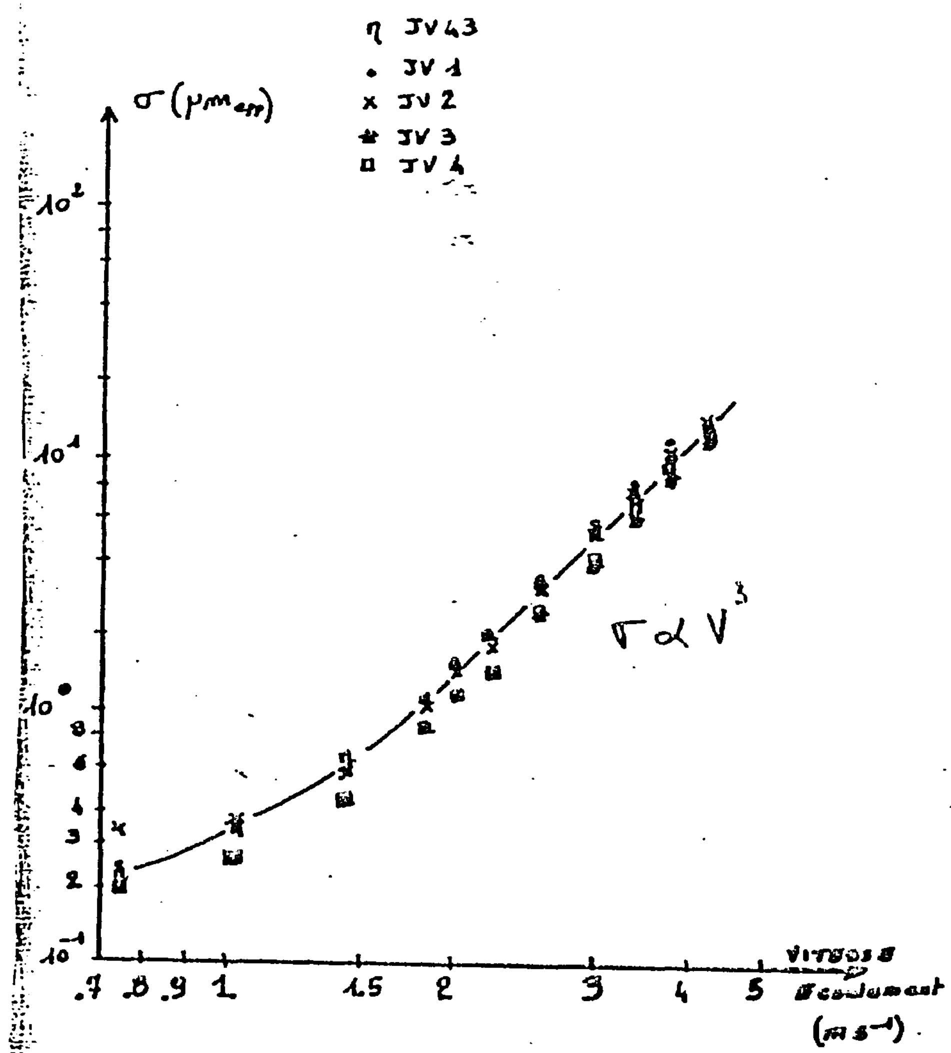


S.G. HALF SCALE MODEL



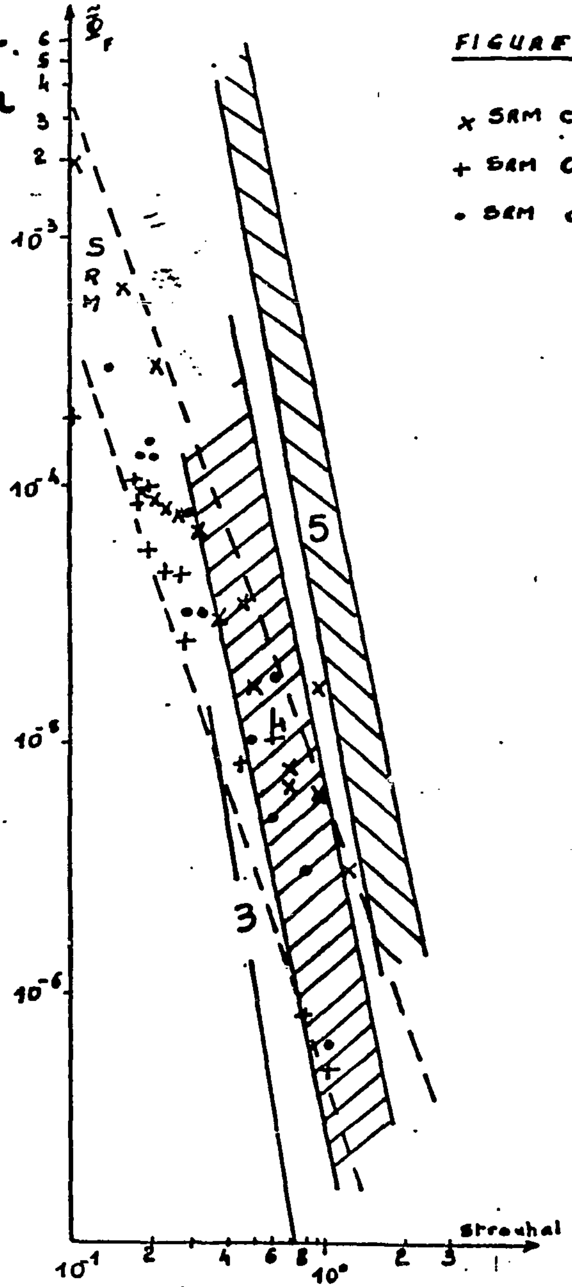
S.G 1/2 SCALE MODEL

TUBE RESPONSE VS FLOW VELOCITY

S.G. MODEL

NON DIMENSIONAL PSD OF FLUCTUATING FORCES

FIGURE 36



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STEAM GENERATOR 0.5 SCALED MODEL

INSTABILITY ANALYSIS

$F_0 = 148\ Hz$

$m \simeq 0.4\ Kg/m$

$\xi \simeq 10^{-2}$ $\quad 0.6\ 10^{-2} < \xi < 1.5\ 10^{-2}$

$A_R = 0.17$

$V_{RC} = 6\sqrt{A_R} \Rightarrow V_{RC} = 2.5$

MAXIMUM GAP VELOCITY REACHED DURING WATER TESTS

$V = 4.3\ m/s \Rightarrow V_{RC} = 2.3$

NO INSTABILITY WAS DETECTED