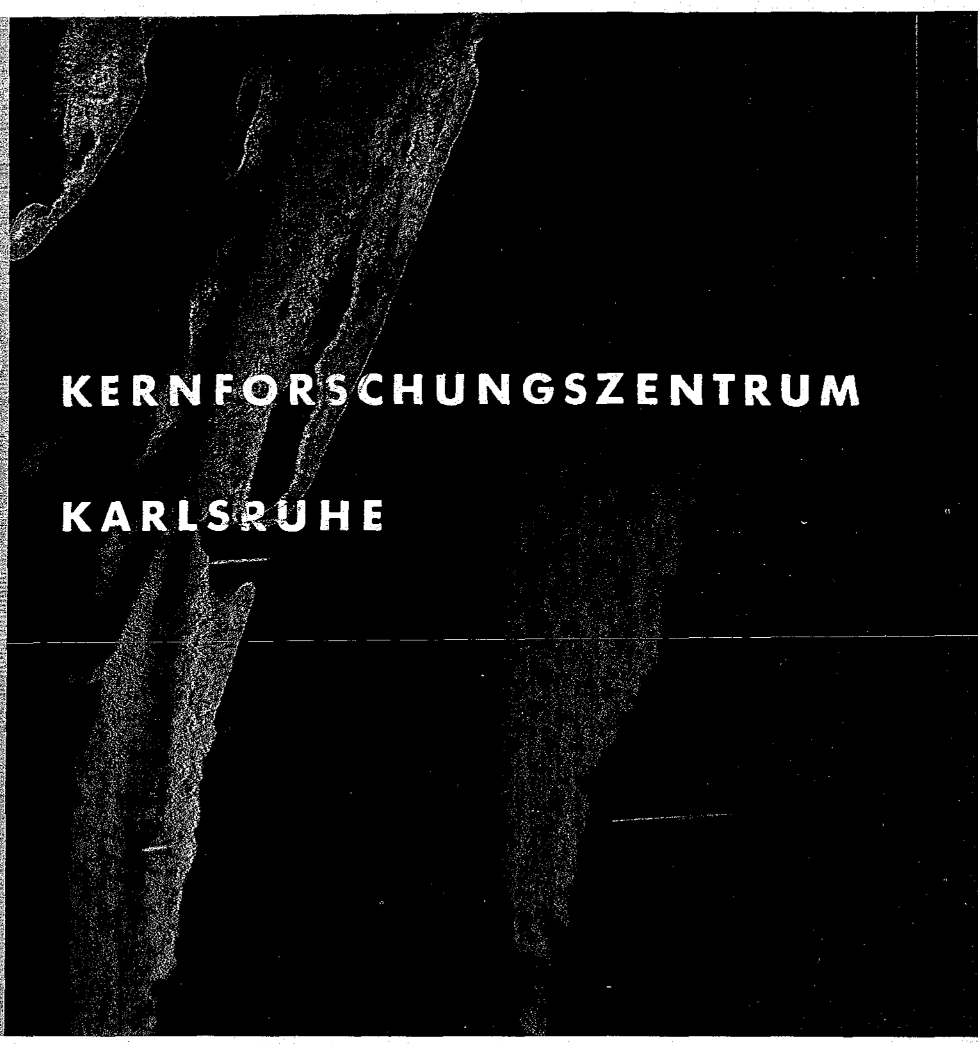

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Experimental Investigation of Loop Caused Influences on Parallel Flow-Induced Vibration of Fuel Pins

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Départment Engineering - Technologie

Abstract

The influence of the test loop on parallel flow-induced vibration of fuel pins of the Na-1 fast reactor design was investigated. The experiments were performed with the same subassembly mock-up, mounted in the test section of four different flow loops with several modifications. Experimental results are presented in the form of diagrams of noramlized rms-values of pressure fluctuations and vibration strains, plotted over the Reynolds number. The structure of pressure fluctuations and vibration strains is illustrated in several typical spectral density plots.

Zusammenfassung

Die vorliegende Arbeit befasst sich mit der Untersuchung des Einflusses des Versuchskreislaufes auf die hydrodynamisch induzierte Schwingung der parallel angeströmten Brennstäbe des schnellen Brutreaktors der Na 1 Studie. Die Experiemente wurden mit einem identischen Brennelementmodell an vier unterschiedlichen Versuchskreisläufen mit mehreren Anordnungsmodifikationen durchgeführt. Die gemessenen, normierten Effektivwerte der Druckpulsationen und der relativen Dehnungen der schwingenden Modellstäbe wurden über der Reynoldszahl aufgetragen.
Die Mikrostruktur der Druckpulsationen und der relativen Dehnungen ist in einigen typischen Diagrammen der Spektraldichtefunktion dargestellt.

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1. Introduction

Two types of predictions of hydrodynamically induced vibrating state of fuel pins in the reactor were made since the publication of the study of Burgreen et al. [1] in 1958. Both types are based on experimental investigations.

In the first group of investigations the vibration of fuel pins is directly measured on subassembly originals or mock-ups during the flow tests in hydrodynamic test loops. It is assumed that by maintaining the same values of hydrodynamic parameters (mean flow velocity, dynamic pressure, Reynolds number, etc.) as in the reactor, the results of such a measurement may be directly transferred to the working conditions of the subassembly in the reactor. In the second group of investigations attempts are made to generalize the results of measurements. In earlier investigations relating in most cases to one-span-fuel pins, various correlations were established between the amplitude of displacement of the vibrating pin (in the center of the span) and the hydrodynamic, elastic, damping and geometrical parameters These attempts were suggested by an almost periodic response of one-span-pins and by successful application of the similitude theory for prediction of hydrodynamic losses in straight channels, formed, for instance, by a bundle of fuel pins. An often duscussed feature of these correlations was the value of the exponent of the mean flow velocity. In most cases, values in the interval 1.5 to 2.0 were reported but different values were published also. A limited success of the mentioned simple correlations and the latest results of investigations of randomly responding multi-spanned fuel pins resulted in the attempt to predict the vibration state of fuel pins with the help of the theory of random processes. However, the necessary condition of possibly utilizing this theory is the knowledge of the cross-spectral density function of random pressure forces acting on fuel rods. At present, efforts to establish this function experimentally are taken simultaneously in several laboratories of the world. As in previous cases these investigations also are performed in hydrodynamic test loops.

It may be stated even inuitively that different loops with the mean values of hydrodynamic quantities remaining identical could have different levels and structures of pressure fluctuations in the flowing medium, and thus, may cause different dynamic response of the fuel pins. This assumption was confirmed experimentally, as stated for example by Basile et al. [2] or by Kadlec and

Appelt [3]. The question was raised about the degree of sensitivity of the pin vibration with respect to the level and structure of the pressure fluctuations in the test loop or in the reactor circuit. It is obvious that this phenomenon can be completely understood only as a result of a lot of experimental and theoretical work. To obtain at least the first necessary information, it was decided to utilize the presently available equipment in the laboratories of the Institute of Reactor Development of Karlsruhe Nuclear Research Center, and of Engineering Department-Technology, CCR-Euratom in Ispra, to approach in close cooperation the solution of the problem mentioned. The investigations were performed with the same "reference-subassembly", mounted in different loops in Karlsruhe and in Ispra. In this way it was possible to achieve a relatively broad variation (1:10) of the level of pressure fluctuations at the water inlet into the subassembly. Arrangements and results of these experiments are presented below.

2.o Experimental Arrangements

2.1 Subassembly Mock-up

A simplified drawing of the Na 1/2 subassembly mock-up used in our experiments is presented in Fig. 1. It refers to the sodium cooled fast breeder subassembly of the Karlsruhe Research Center Study Na 1, specified by Smidt and Müller [4], which was used for vibration investigations in support of the project. The bundle of this mock-ups has 37 pins of 6.7 mm OD and 2676 mm length, supported by spacer grids in 8 locations. A complete description of the mock-up and its instrumentation is given in the report of Krüger and Schwemmle [5]; the following brief description relates only to those transducer locations which are mentioned elsewhere in the article.

Pressure fluctuations at the inlet side of the subassembly (location I in Fig.1) were measured with a KULITE miniature pressure transducer type CPL-o7o-1oo S, mounted in the wall of the inlet tube. Another transducer of the same type was mounted on location L in the wall of the hexagonal subassembly sheath. For measurements of boundary layer pressure fluctuations in the fuel pin bundle one similar pressure transducer type XFL-o7o-1oo was mounted on one of the pins. This transducer was situated in location A, 255 mm in front of the first spacer grid. The membrane diameter of all pressure transducers is 1.8 mm.

Pin vibration was detected by means of strain-gauges mounted in the gas plenum inside the pin, as indicated in the lower part of Fig. 1. Strain gauge-half-bridges III/1 and III/2, mentioned further below in this article, are situated in the second span of pin Nr. III, 163 mm behind the first spacer grid. The location of transducers in the cross section of the bundle is indicated in Fig. 2.

2.2 Water Flow Loops

Four loop arrangements with some alternative subarrangements, used in our experiments, were achieved in Karlsruhe and Ispra through component rearrangements and different adjustments of control valves in water test loops (Fig.3). The experimental results, discussed in chapter 3, relate to 11 subarrangements with the follwong specifications:

Arr. 1 a: Karlsruhe flow loop (1oo mm ID duct) with circulating water pump, one flow control valve in series with the subassembly, additional orifice plate with 6o mm hole diameter.

Arr. 1 b: Karlsruhe flow loop as in Arr. 1 a, hole diameter of the orifice plate 4o mm.

Arr. 2: Ispra flow loop with opened circuit-flow, water discharge from the central storage tank (approx. 6o m height), one control valve in series with the subassembly.

Arr. 3 a: Ispra flow loop with closed ciruit-flow, circulating-water pump Nr. 2, by-pass.

Arr. 3 b: Ispra flow loop as in Arr. 3 a, by-pass closed, flow control valve V 3 (V 1 and V 2 completely opened).

Arr. 3 c: Ispra flow loop as in Arr. 3 b, V 1 partially closed (1o turns of the valve-spindle from "closed" to "opened" direction), V 2 completely opened.

Arr. 4 a: Ispra flow loop with opened circuit-flow, water discharged from central storage tank is pumped by pump Nr. 2, control valve V 3, valves V 4 and V 5 opened, V 1 partially closed (1o 1/8 turns of the valve-spindle from "opened" to "closed" direction).

Arr. 4 b: Ispra flow loop with opened ciruit-flow and cirulating water pump as in Arr. 4 a, V 1 and V 4 opened, V 5 partially closed (1o turns of the valve-spindle from "opened" to "closed" direction). Four additional angle struts on subassembly mock-up. The lower part of the subassembly was damped with sand bags.

Arr. 4 c: Ispra test loop with opened circuit-flow and circulating water pump as in Arr. 4 b; subassembly mock-up closed in a special box, filled with sand.

2.3 Data Acquisition and Processing

The strain gauges of pins and pressure transducers were connected to strain gauge units of Hottinger Baldwin Messtechnik, type KWS/II-5, with a carrier frequency of 5 kc/s. The amplified output signals were recorded on an AMPEX FR 13oo magnetic tape recorder. Root-mean-square voltages of signals were measured with Hewlett-Packard rms-voltmeter type 34oo a. From these values the rms-values of pressure fluctuations $\sqrt{\overline{p^2}}$ and strain $\sqrt{\overline{\varepsilon^2}}$ were calculated. Estimates of the spectral density functions of the signals $\overline{V^2}/\Delta f$ were made with the HSA/RSA Analyser of International Instruments Incorporated. The analyses was performed with a constant filter band-width $\Delta f = 2{\cdot}2$ cps, the integration time was 1o seconds. Therefore, magnetic tape loops with a turn-round time of 1o seconds were used. The adequacy of the above mentioned integration time was tested in additional investigations. A partial view on the experimental arrangement with the flow loop in Ispra is given in Fig. 4.

For measurements of the water-flow rate Q, standard orifice gauges were used. The values of the mean Reynolds number Re and of the mean dynamic pressure q, calculated from Q, relate to the free water passage cross-section in the pin bundle in all cases throughout this report.

Measurements of rms-values of pressure fluctuations and of vibrating strains were performed for several values of water-flow rate and every experimental arrangement. Measured rms-values, divided by the corresponding value of dynamic pressure, were plotted over the Reynolds number. Spectral density functions of pressure fluctuations and vibrating strains were determined only for a few typical flow regimes in every arrangement.

3.o Experimental Results

Measurements of rms-values and of spectral densities of pressure fluctuations and vibrating strains were performed in intervals of Reynolds numbers from 5ooo to 45ooo. Values of dynamic pressure up to 3ooo kp/m^2 were achieved.

3.1 Root Mean Square Values

The normalized values of pressure fluctuations $\sqrt{\overline{p^2}}/q$ at water inlet (location I) are plotted over the Reynolds number in Fig. 5. The exponential form of the curves is typical for all measurements. It appears from the diagram that for high values of the Reynolds number the rms-values of pressure fluctuations are linearly proportional to the dynamic pressure. For smaller values of the Reynolds number this dependence is not as strong as for greater values. It should be noted that this general tendency holds also for rms-values of vibrating strains. With respect to the above mentioned correlation our results indicate that the exponent at the mean flow velocity is equal to 2 for high values of the Reynolds number, and approx. 1.5 for lower Reynolds numbers.

In case of curve 1 a in Fig. 5, the rms-value of pressure fluctuations of approx. 3.5 °/o of the value of dynamic pressure in the pin bundle is obtained for Re = 20ooo. The tendency to converge to even smaller values at high Reynolds numbers is shown only by the pressure fluctuations of the experimental arrangements 2 without circulating water pump (symbol ▲). Because of the low value of the static delivery head of this arrangement it was not possible to reach higher values than 13ooo for the Reynolds number. In the range of low Reynolds numbers, however, an interesting phenomenon was observed. As appears from Fig. 5, the exponential form of the curve is interrupted at Re = 77oo and a multiple increase of pressure fluctuations takes place. The generation of this flow instability was found to be fully reproducible. The phenomenon is obviously a constant property of that particular experimental arrangement.

The pressure fluctuations of the experimental arrangement 4 with storage tank and pump in series (symbols ▼) show also the tendency to decrease towards relatively slow values. Differences in values from different sub-arrangements take place only at low Reynolds numbers. High values of pressure fluctuations were observed for all alternatives of arrangement 3.

From Fig. 5 follows that the highest values of pressure flutuations occur in the case of flow control by the by-pass (curve 3 a). Also the use of only one control valve in series with the subassembly yields relatively high-level pressure fluctuations (curve 3 b). More favourable results may be achieved by use of two control valves in series (curve 3 c). Substantial reduction of pressure fluctuations was reached by an optimal adjustment of these two control valves (curve 3 d). The ratio between maximum and minimum values of pressure fluctuations for different arrangements and identical Reynolds numbers in Fig. 5 is greater than 1o.

The normalized rms-values of pressure fluctuations on the wall of the subassembly sheath (location L) are plotted over the Reynolds numbers in Fig.6. The course of the curves is similar to that in Fig. 5. For low Reynolds numbers the pressure fluctuations at the inlet (location I) are slightly higher. For high-level inlet pressure fluctuations the fuel pin bundle obviously acts as a filter. For high Reynolds numbers the pressure fluctuations generated in the subassembly prevail so that the resulting level in the bundle is higher than at the subassembly inlet. Because of this phenomenon the maximum and minimum values of pressure fluctuations are less scattered than in Fig. 5. The smallest rms-values of pressure fluctuations (arrangements 2 and 4 with opened water-circulation) are equal to approx. 7 $^{o}/_{o}$ of dynamic pressure in the bundle. It should be noted that this value exceeds at least seven times the value obtained by measurements of pressure fluctuations in "ideal" channels. The highest values equal approx. 3o $^{o}/_{o}$ of dynamic pressure. From this situation follows that the values $\sqrt{\overline{p^2}}/q$ in the pin bundle may be used as a criterion for judging the "quality" of the flow loop and should therefore accompany every investigation of hydrodynamically induced vibrations of fuel pins.

Normalized rms-values of bending strain of the vibrating pin Nr. III are plotted over the Reynolds number in Figs. 7 and 8. The profile of the curves is similar to that for pressure fluctuations. Highest rms-values of vibrating strain occur in the experimental arrangements 3 b, c, d and 1 b. More favourable results were achieved by arrangement 1 a with smaller throttling after the test section and by arrangements 4 a, b and c with the water supply tank and the circulating pump in series. A reduction of vibrating level of about 3o $^{o}/_{o}$ was achieved in plane x - y by additional damping of the test section with sand (curve 4 c in Fig. 8). This gives evidence that the pin vibration in plane x - y was partially excited by the vibrating conduit of the water loop. The smallest rms-values of vibrating strain were obtained in case of experimental arrangement 2 without water circulating pump. The ratio of maximum and minimum values of vibrating strain for the same Reynolds numbers and different experimental arrangements is approx. 3.

The comparison of Figs. 7 and 8 with Figs. 5 and 6 reveals the active role of pressure fluctuations in coolant flow before the subassembly by the generation of fluctuating pressure field in the subassembly and the excitation of fuel pin vibrations. On the other hand, the rate of change of the vibration amplitude does not equal the rate of change of the level of pressure fluctuations. The reason for this apparent discrepancy is the fact that only the pressure differences, acting on opposite sides of the pin, may contribute to the increase of amplitude of pin vibrations. The second important condition is the necessity of coincidence of these pressure differences with vibration modes of the pin.

Because of technological difficulties it was not possible to measure the mentioned pressure differences in our experiments. To check the influence of the level of pressure fluctuations in the flow on the level of fluctuating pressure differences, an additional experiment with only one instrumented rod (18 mm OD), located in the center of the circular flow channel(5o mm ID), was carried out. The test rod (1ooo mm length) was at three axial locations (with coordiantes 1oo, 3oo and 5oo mm) provided with pressure transducer pairs, which facilitated the measurement of pressure fluctuations p and p' on opposite sides of the test rod diameter. The entire channel was mounted in a test section of experimental arrangement 2 with opened water circuit; an additional reduction of the pressure fluctuation level at the channel inlet was achieved by applying a long settling chamber (circular duct of 1oo mm ID and 6 m length) before the working section. The rms-values of the pressure fluctuations p and p' from each transducer pair, as well as of pressure differences p-p', were measured similary to previous cases. Complete results from these experiments will be published later; some informative results for the transducer pair with coordinate 3oo mm are given in the following table (q = 49oo kp/m^2 in both cases):

	$\sqrt{\overline{p^2}}$	$\sqrt{\overline{p'^2}}$	$\sqrt{\overline{(p-p')^2}}$
	[kp/cm^2]		
variant 1 (with settling chamber)	0.0064	0.00656	0.00496
variant 2 (without s.ch.)	0.034	0.036	0.0079

From the table follows the causality between the levels of pressure fluctuations $\sqrt{\overline{p^2}}$ and $\sqrt{\overline{p'^2}}$ and of fluctuating pressure differences $\sqrt{\overline{(p-p')^2}}$. The rates of change of both of these quantities are different, as could be expeeted from the results of previous experiments.

On the basis of the results presented it can be concluded that in general the pressure fluctuations in the subassembly as well as the vibration of fuel pins follow the changes of level of pressure fluctuations in coolant flow in the inlet zone of the coolant into the subassembly. The resulting change of state of vibration of the fuel pins depends on the modification of pressure fluctuations on their way through the subassembly and on the grade of correlation of the resulting pressure forces, acting on vibrating pins, with their normal modes. The rate of variation between minimum and maximum values of at least 1 : 3 should be taken into account by interpreting the results of vibration experiments performed in conventional flow loops. In order to find out on which side of possible scattering the measured values lie, the previously mentioned criterion $\sqrt{\overline{p^2}}/q$ for the level of pressure fluctuations in the fuel pin bundle may be used. Depending on the quality of the flow loop it is to be expected that with high Reynolds numbers these values fall in the range of 0.05 to 0.4.

3.2 Spectral Density Functions

Additional information about the influence of loop arrangement on pressure fluctuation and on pin vibration are supplied by the spectral density functions. Quantity $\overline{V^2}/\Delta f$, linearly proportional to the spectral density function of the amalysed random process, is plotted over the frequency for different transducer locations and different experimental arrangements in Figs. 9 to 13.

Typical spectral densities of pressure fluctuations at channel entrance of different test loops are presented in Fig. 9. It appears from these plots that the level and structure of pressure fluctuations differs from arrangement to arrangement and that the knowledge of mean values, such as flow rate or Reynolds number is evidently insufficient for their prediction. The way in which the different conditions at the channel entrance are reflected by vibrating response of pins, is illustrated in the following figures.

Spectral densities of pressure fluctuations at subassembly inlet and in the pin bundle, as well as of vibrating strain at location III/1, are plotted in Fig. 1o for experimental arrangement 2b. Plots in the first line relate to the case of the previously mentioned flow instability in the vicinity of Re = 8ooo. Pressure fluctuations of this instability are concentrated in the frequency band below 1o c/s and induce the bending vibration of the entire test section, which has its first natural frequency at 6 c/s (first peak in plot of strain gauges III/1). The second peak, which lies in the vicinity of 7o c/s, corresponds to the vibrating response of the pin in the first mode (calculatied natural frequencies of pin form the sequence 7o.27; 82.97; 91.17; 1o3.8; 119.7; ... cps /3/). Plots in the center of Fig. 1o illustrate the production of pressure fluctuations in the subassembly. Pressure fluctuations generated in the boundary layer and on spacer grids superimpose on those which pass through the subassembly inlet, and cause the previously mentioned difference in pressure fluctuation levels of Figs. 5 and 6.

Typical spectral densities from experi mental arrangement 4d (which had been developed from arr. 2 by coupling of one water-circulating pump in series with the water supply tank) are plotted in Fig. 11. In spite of the relatively small change in the loop design, differences in spectral densities are considerable. Instead of the lowfrequency peak another peak appears in the band 15 to 25 c/s. In addition, further sharp peaks at the frequencies 49 and 98 c/s may be observed (pressure transducer I), which are most probably caused by impeller-unbalance of the water-circulation pump. These phenomena are reflected in the spectral density plot of pin response with peaks at 11, 25, 37, 49 and 98 c/s. As in the case of the previously mentioned peak at the frequency of 6 c/s, also these new peaks my be explained by bending vibrations of the entire test section.

Spectral density plots relating to the experimental arrangement 1b with water-circulation pump and closed water circulation are presented in Fig. 12. The diagrams on the left side of the figure illustrate the spectral densities of location DA V with the pressure transducer mounted directly on the pin; the corresponding plot of pressure flucuations at the channel entrance is presented for Re = 135oo in Fig. 9. In the case of test loop 1 the spectral density function in frequency band 15 to 25 c/s has very low values. The vibration of the entire test section at the frequency of 6 cps is evident for Q = 29,5 m^3/h (location III/1). In that portion of plots which relate to pin vibrations at their natural frequencies slightly higher response in the second and third vibration modes can be noted. The relatively good agreement betweeen plots relating to pressure transducer on the pin (location DA V) and in the wall of the subassembly sheath (location L) is another point of interest.

Spectral density plots obtained by checking the influence of fixing and damping of the test section on pressure fluctuations and pin vibrations is illustrated in Fig. 13. The way of fixation is indicated in schemes on the left side of the figure. Plots in the first and second line relate to experimental arrangement 4 b, plots in the third line relate to experimental arrangement 4 c. The energy of excitation of vibration of the pin bundle at 49, 98 and 147 cps, which has no adequate correlation in spectral density plots of pressure fluctuations, in obviously transferred from the water-circulation pump via conduit of the loop. Additional damping of the test channel with sand has reduced remarkably the bending vibration of the test section. Reduction of vibration of pins in their natural modes as well as reduction of pressure fluctuations are also evident.

4.o Conclusions

Four different experimental arrangements with several additional modifications were used to investigate the influence of the test loop on bending vibrations of fuel pins in the reactor subassembly. The same "reference subassembly" was used in all experiments. It was noted that different experimental arrangements differ considerably in rms-values and spectral densities of pressure fluctuations at the channel entry. Pressure fluctuations pass through the subassembly and modify the fluctuating pressure field in the pin bundle. By different experimental arrangements and identical mean values of hydrodynamic quantities in our experiments the rms-values of pressure fluctuations in the pin bundle reached 7 to 3o % of the value of dynamic pressure of the flowing coolant. This values are at least 7 to 3o times higher than the corresponding values measured in "ideal" channels. In accordance with the grade of correlation of fluctuating pressure forces with vibration modes of pins, different response is to be expected by otherwise identical mean values of hydrodynamic parameters. In our experiments the variation of rms-values of vibrating strain was found to be 1 : 3.

It follows from the results presented that one possible way to reduce the vibration of fuel pins is to minimize the level of pressure fluctuations at the entry of coolant in the reactor core. Unfortunately, no reliable method of prediction of fluctuating pressure field in the primary circuit has been abailable until now for the design of primary circuit. The development of such a method should therefore be pursued among other activities conducted in the field of flow induced vibration of fuel pins. In the immediate future, however, deviations from real values must be taken into account by attempts to predict the state of vibration of fuel pins in the reactor, if such attempts would be based on the generalization of results of vibration investigations, performed in conventional flow loops. To facilitate the correct interpretation of results of such experiments, the performance of complementary measurements of pressure fluctuations in pin bundle is recommended.

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List of Figures

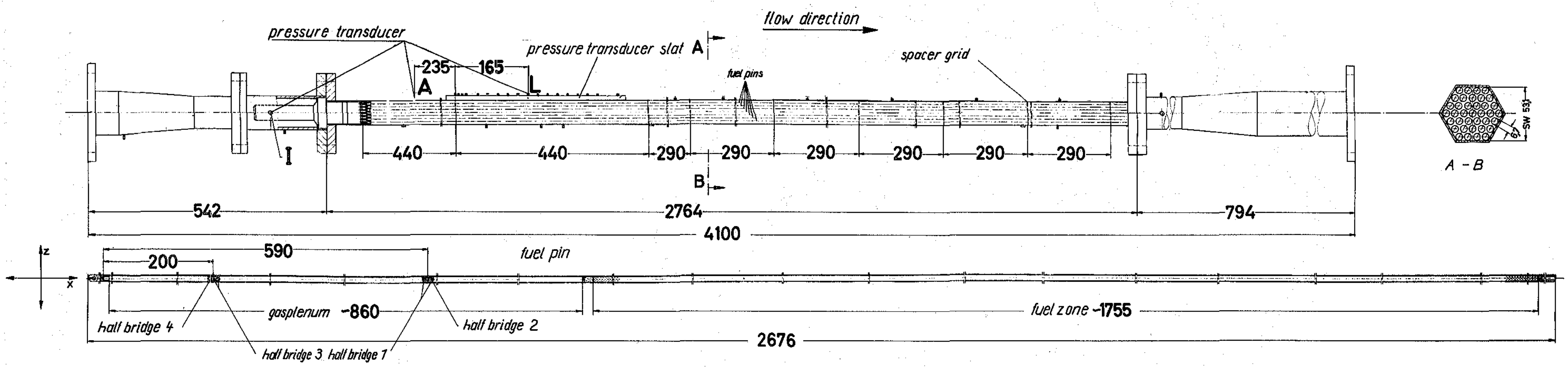

Fig.1. Subassembly mock-up Na 1/2

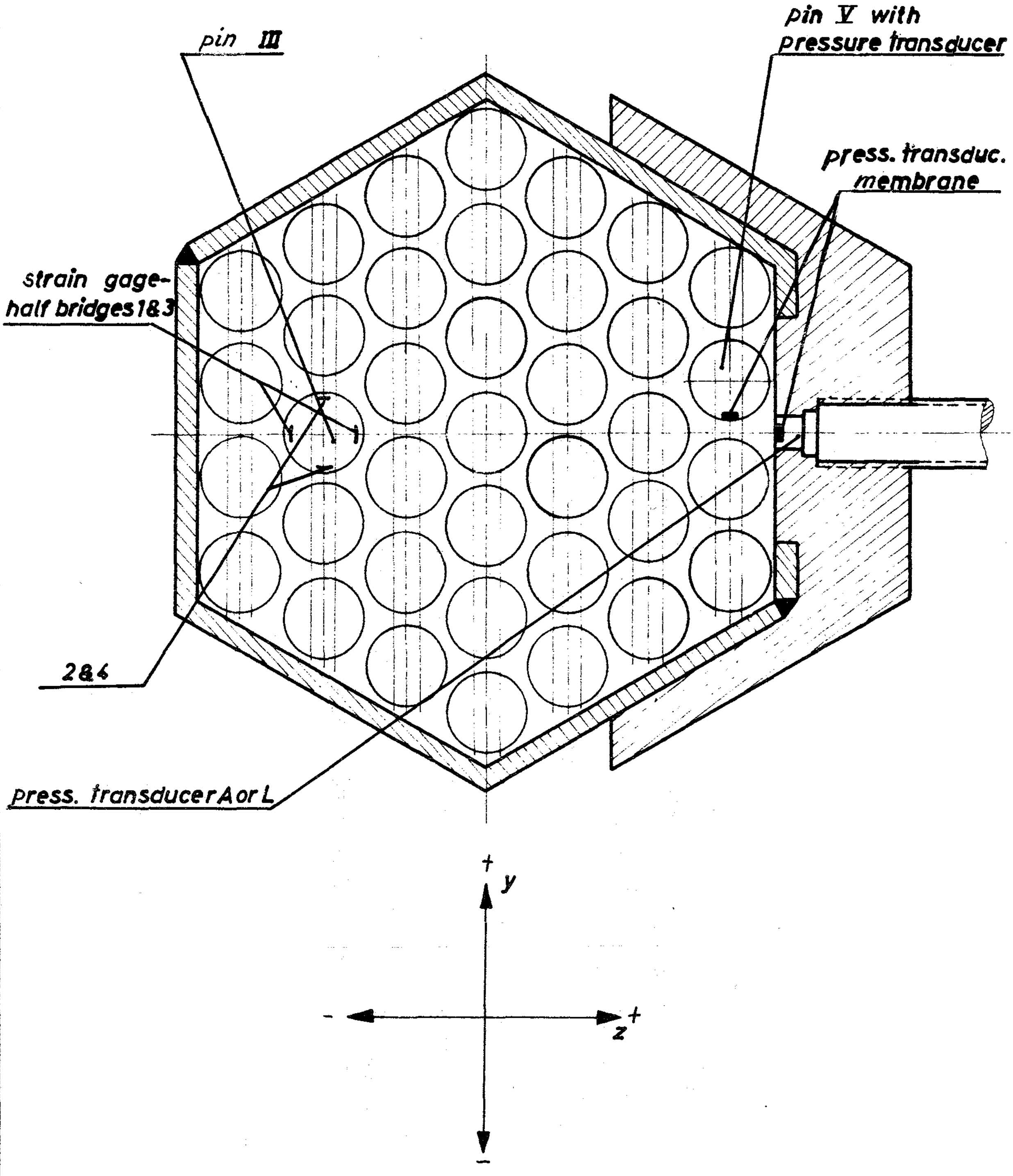

Fig. 2. Location of transducers

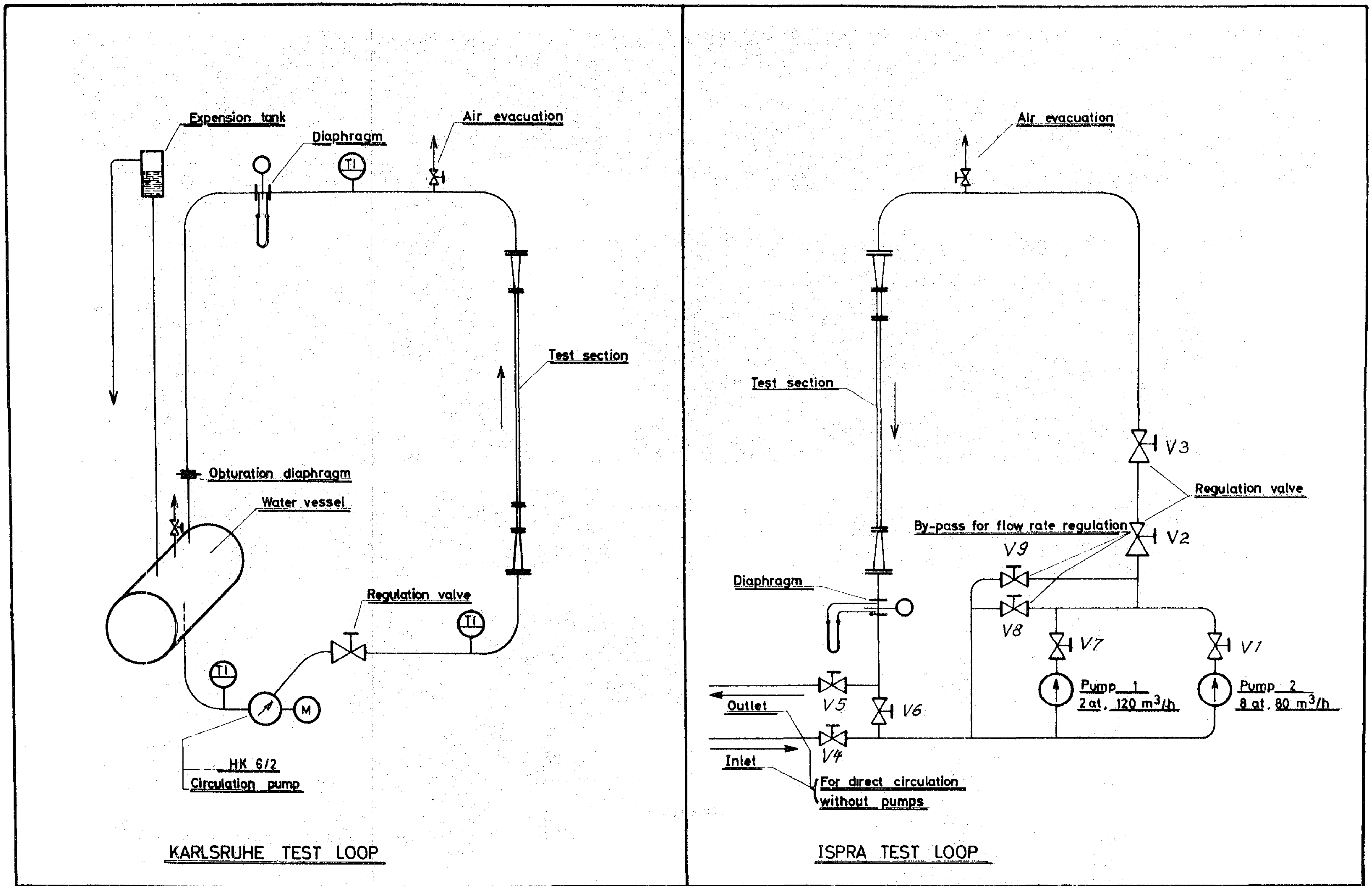

FIG. 3 SCHEMA OF TEST LOOPS

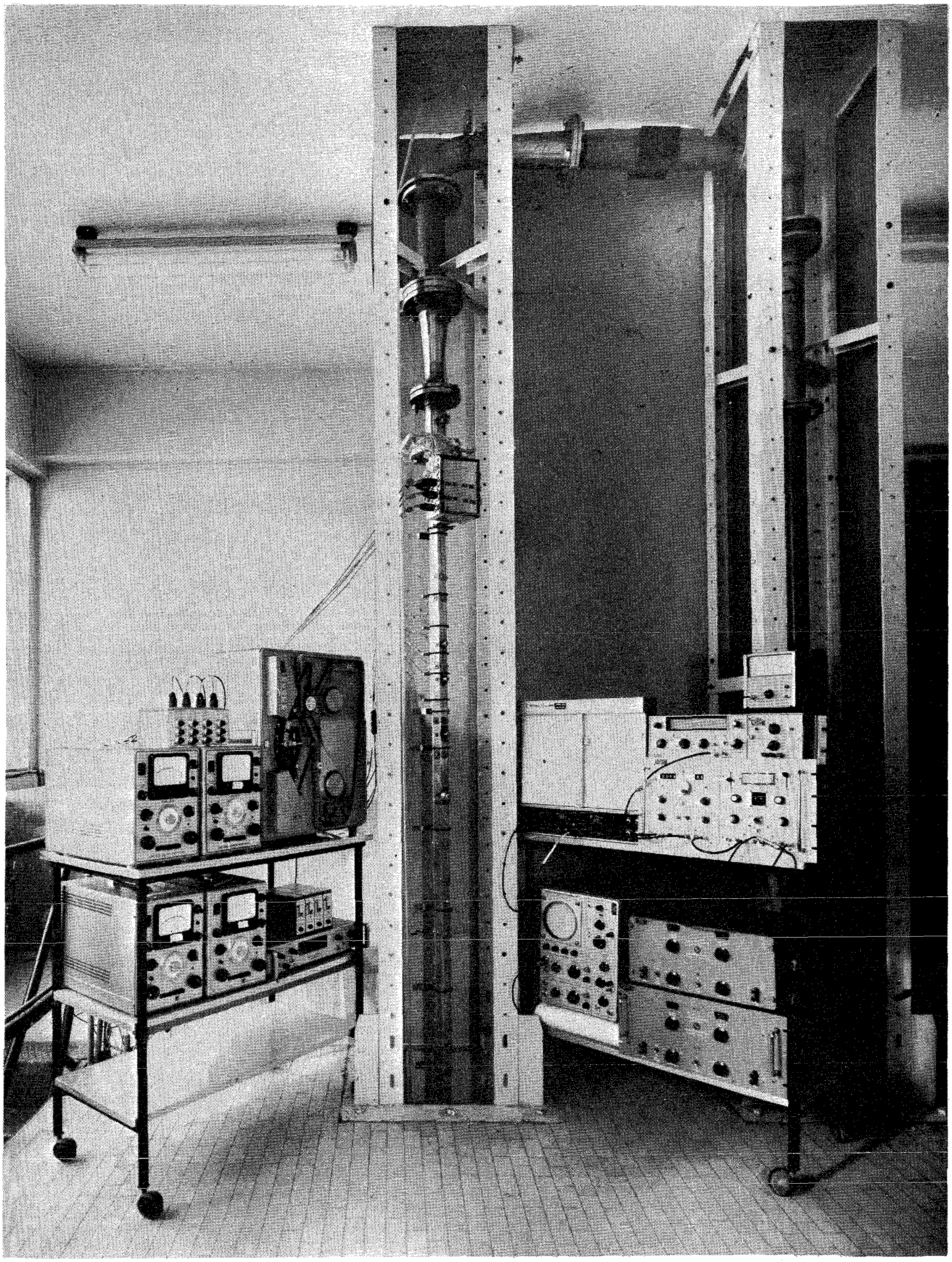

Fig.4: Partial view of experimental arrangement

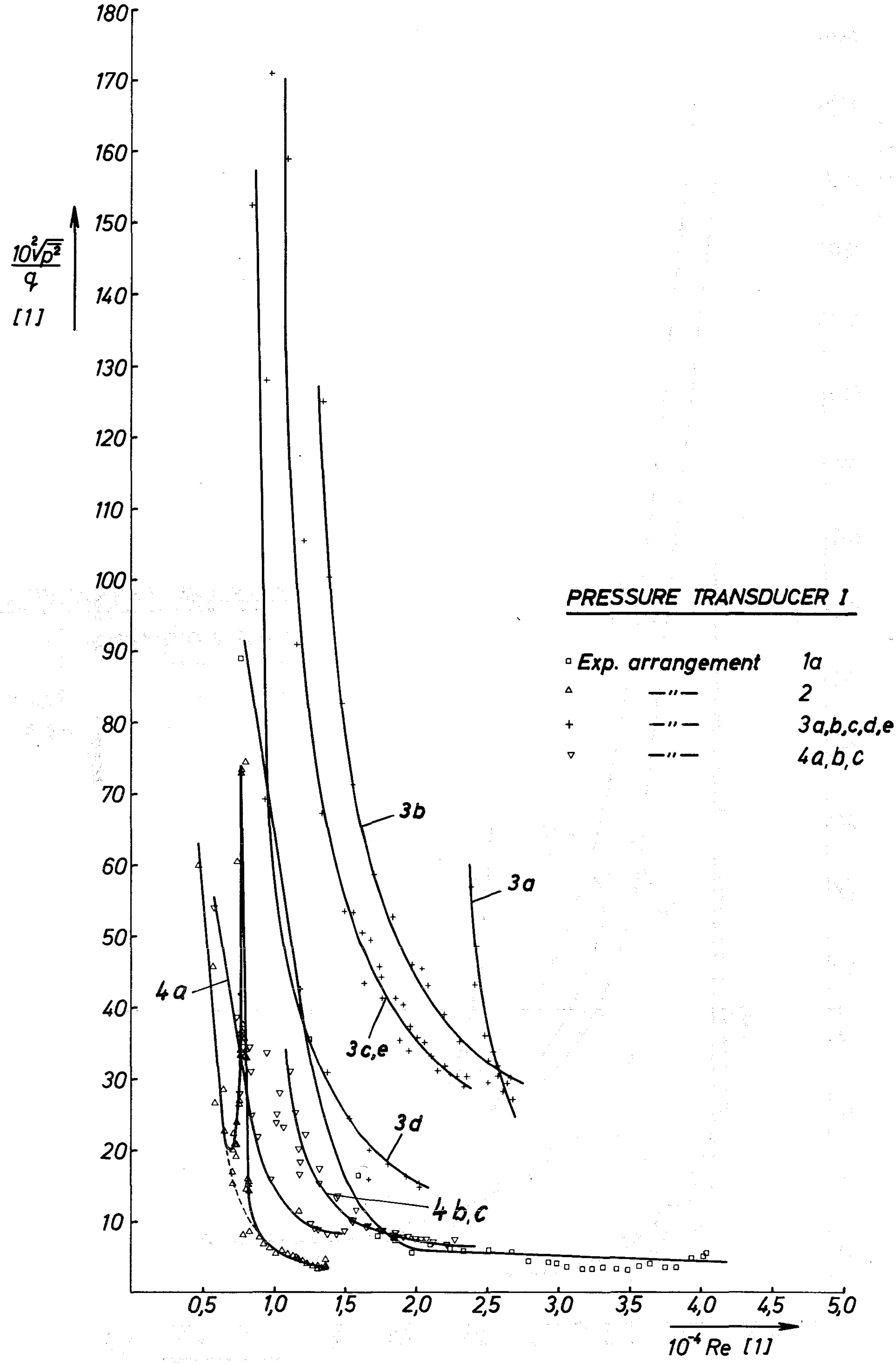

Fig.5 RMS-values of pressure fluctuations at water inlet in subassembly

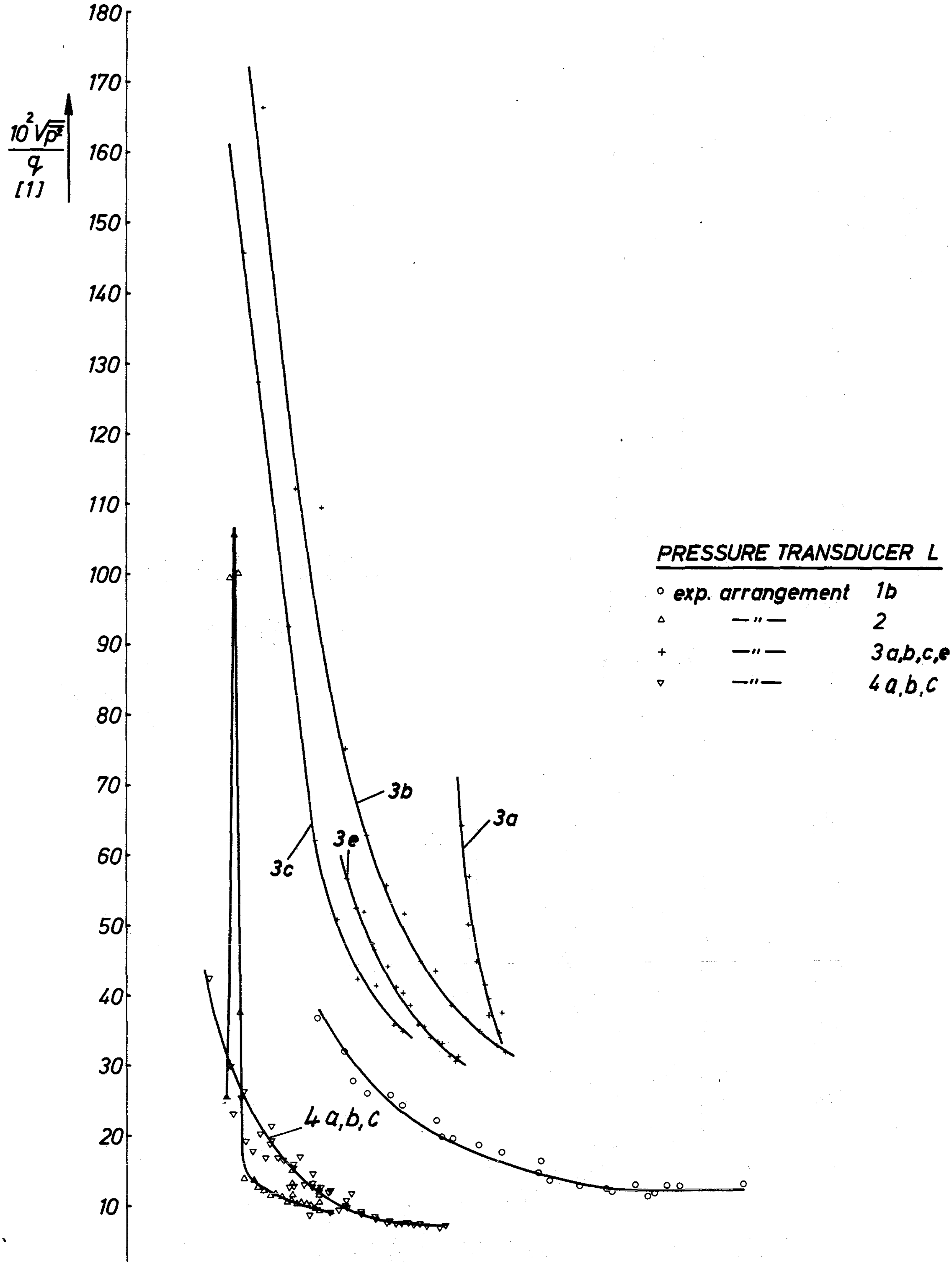

Fig. 6 RMS-values of pressure fluctuations in pin bundle

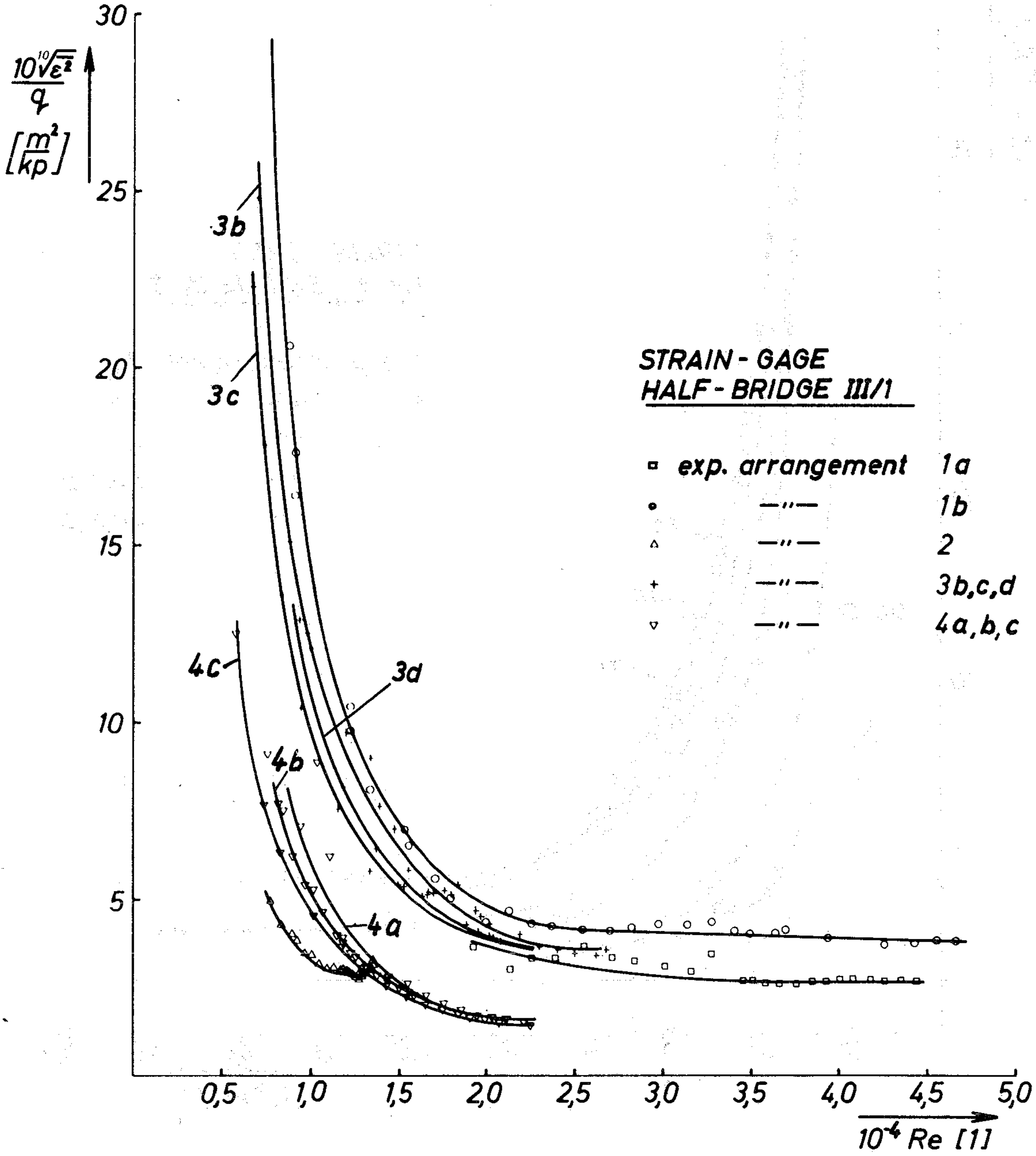

Fig.7 RMS-values of bending strain of vibrating pin No. III. Plane of vibration x - z.

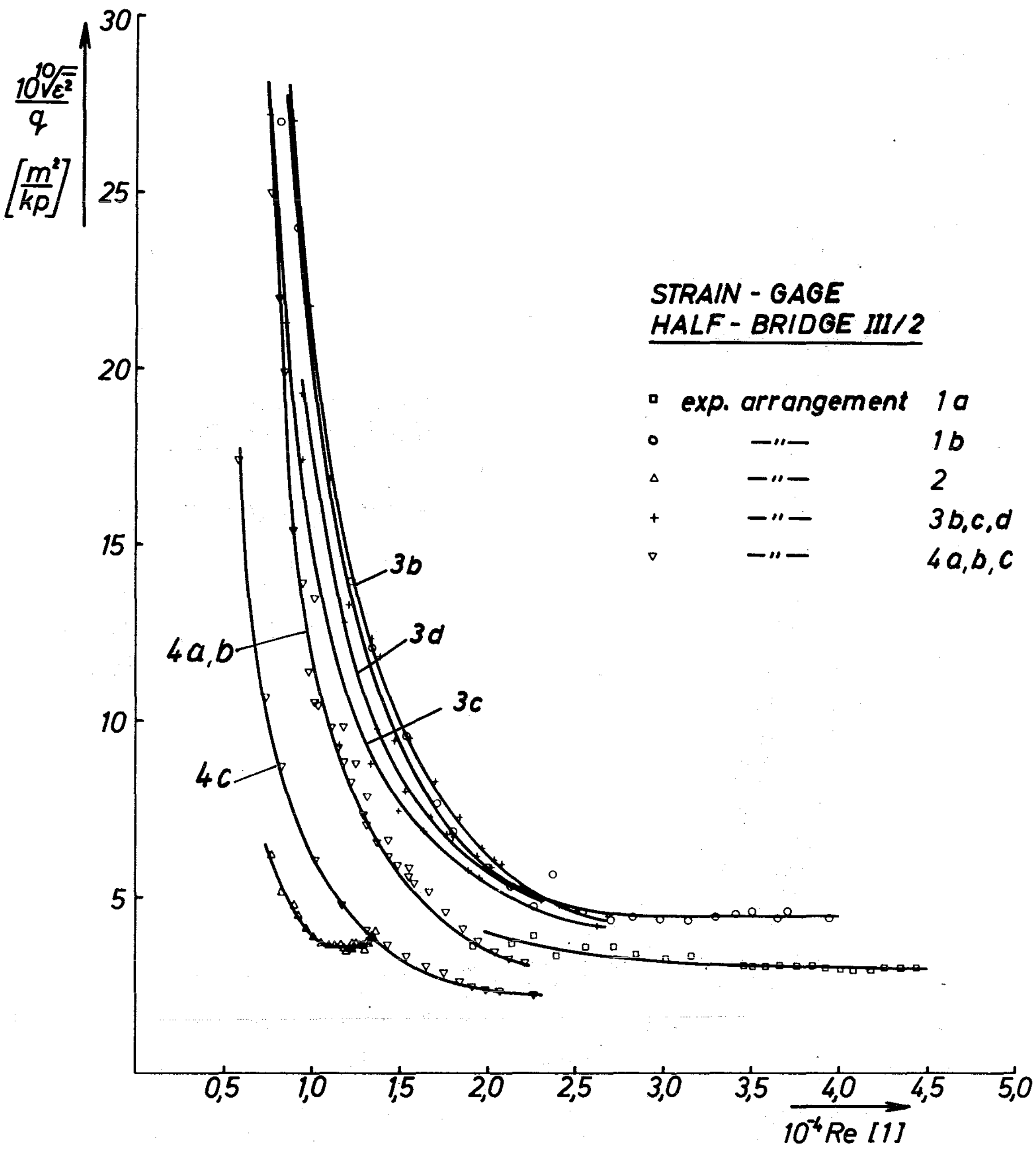

Fig.8 RMS-values of bending strain of vibrating pin No.III. Plane of vibration x - y

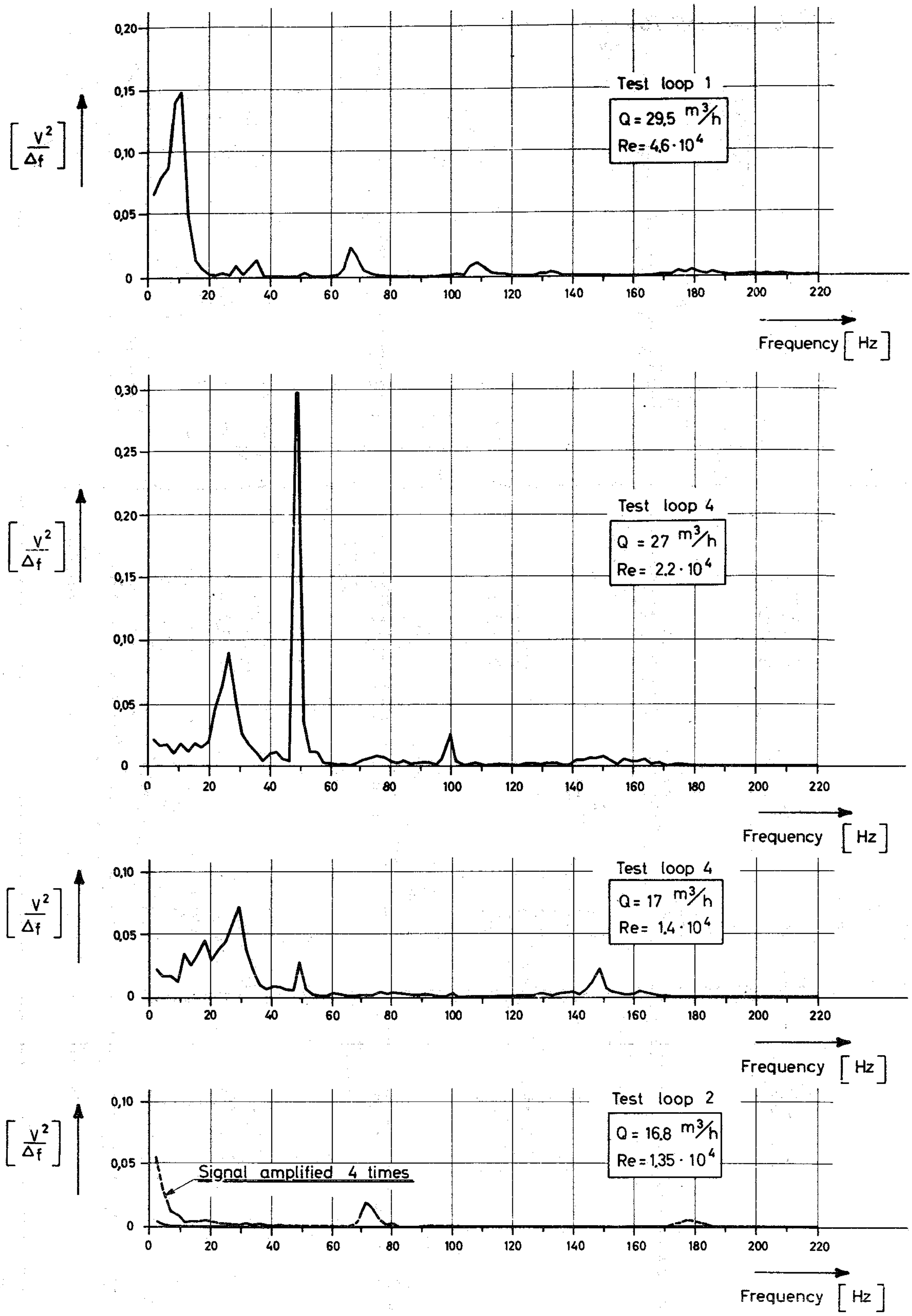

FIG. 9	PRESSURE FLUCTUATIONS (DA I) at channel entrance

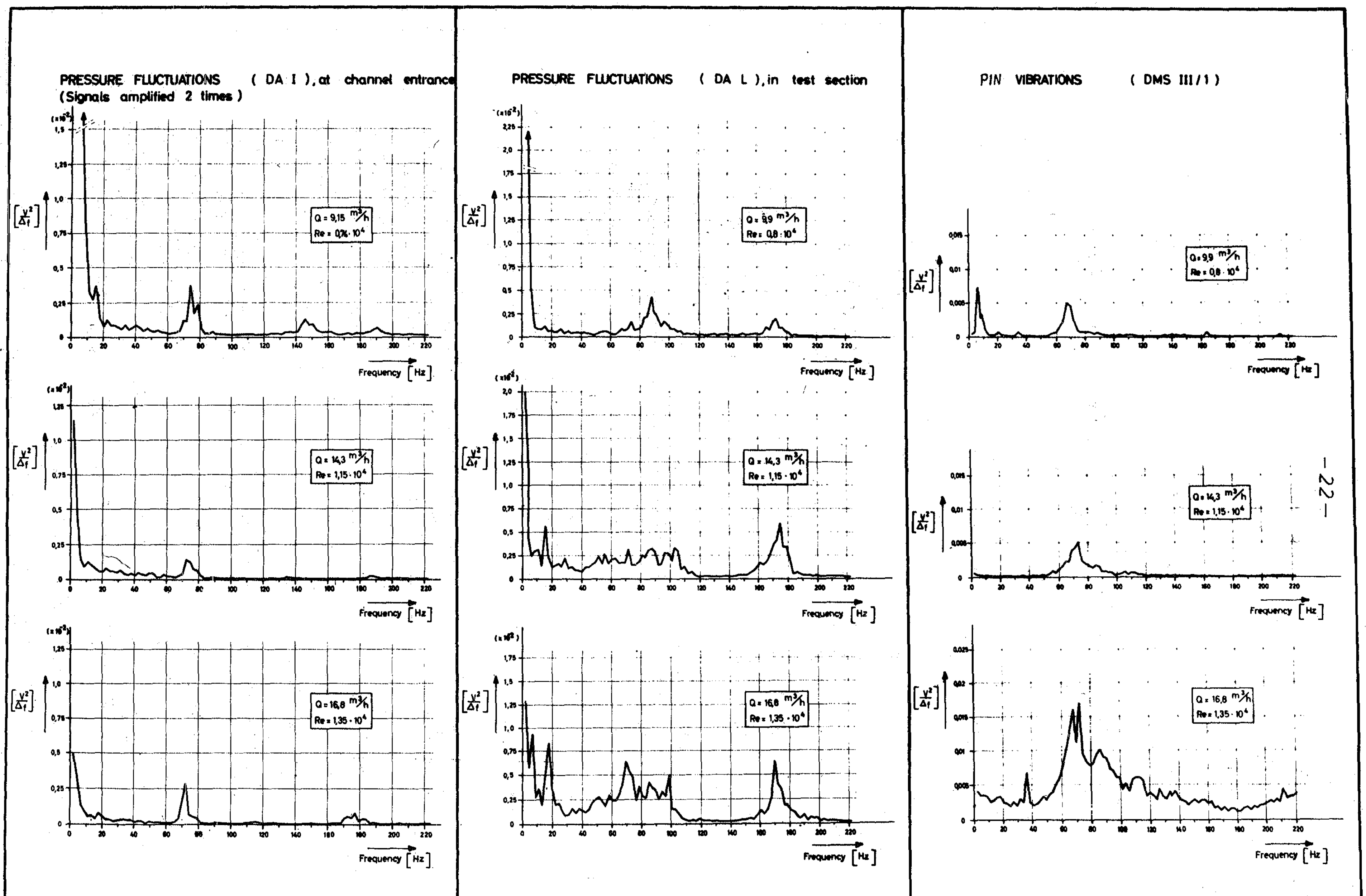

FIG. 10 PSD - DIAGRAMS FOR TEST LOOP 2

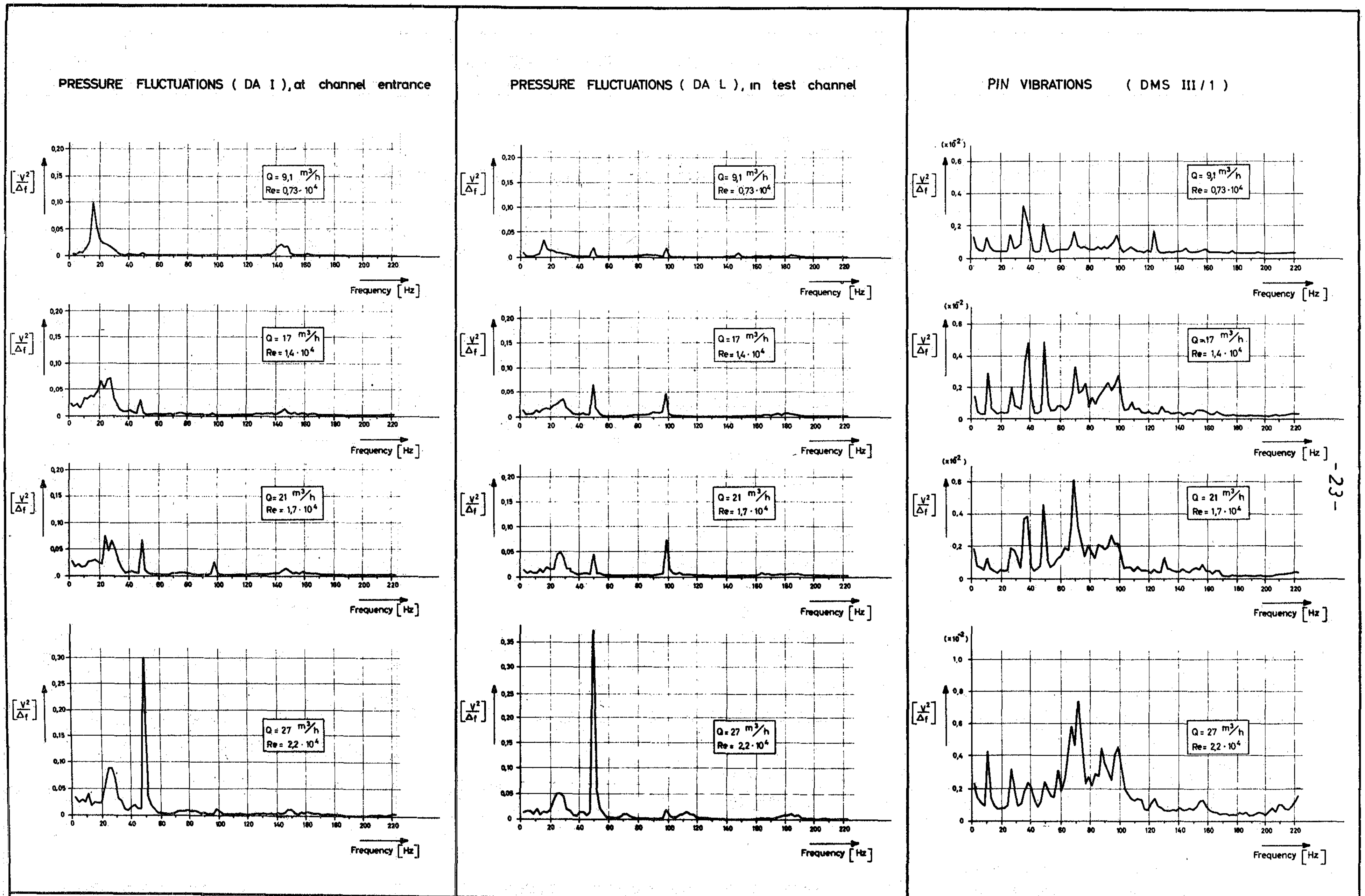

FIG. 11 PSD - DIAGRAMS FOR TEST LOOP 4

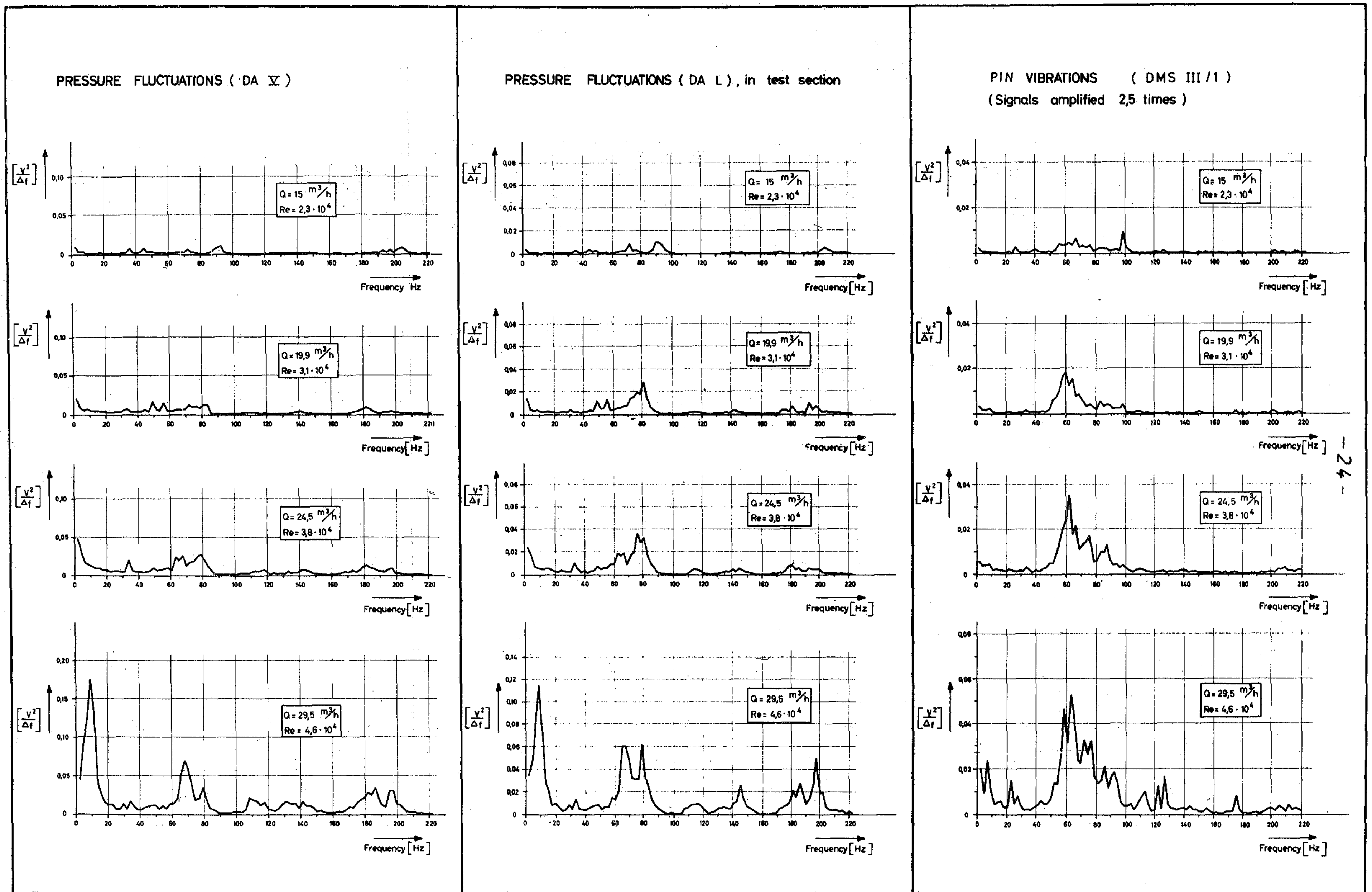

FIG. 12 PSD - DIAGRAMS FOR TEST LOOP 1

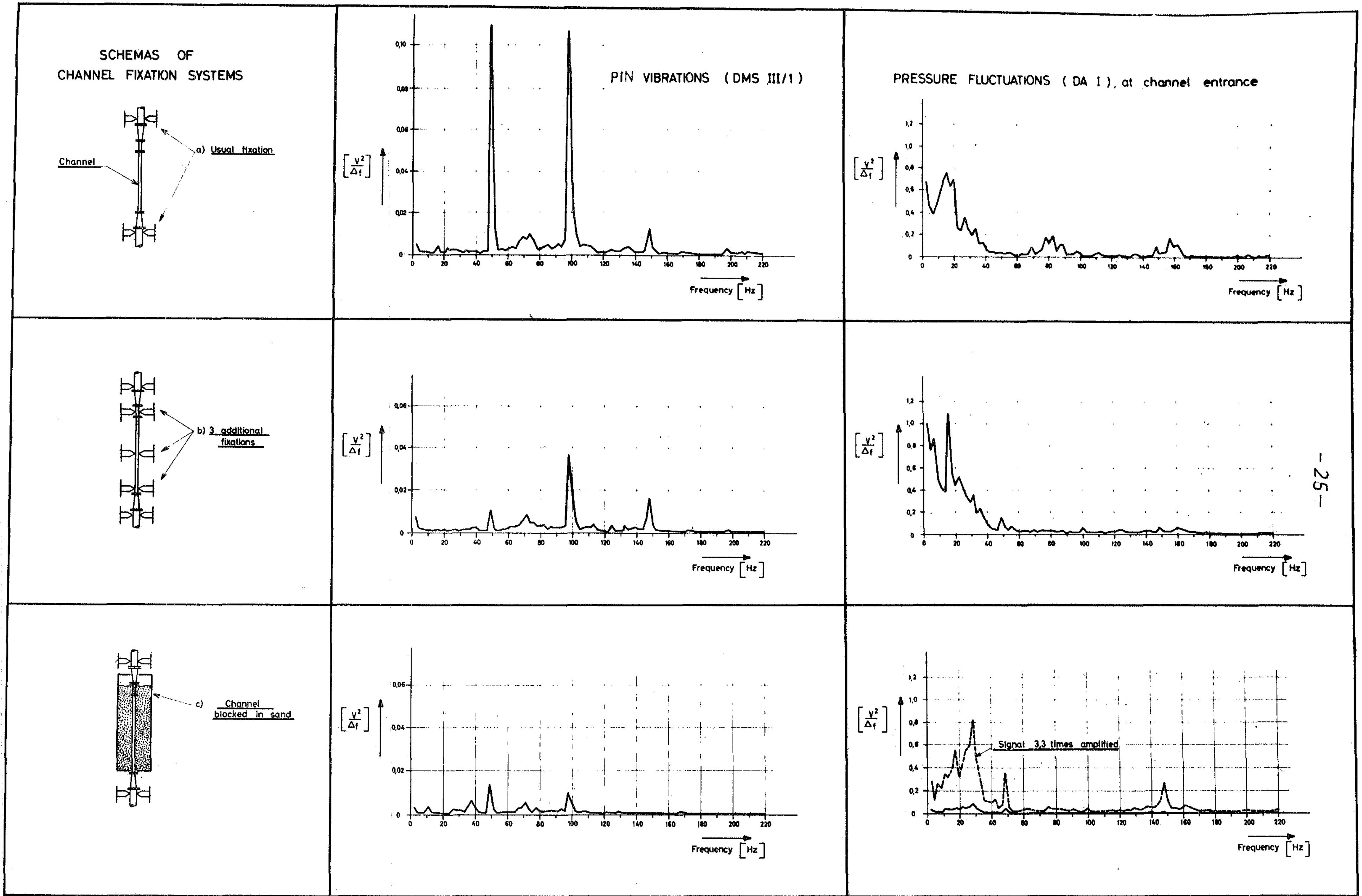

FIG. 13 INFLUENCE OF CHANNEL FIXATION SYSTEMS, Flow rate: Q = 16,8 (m^3/h)