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SCALE EFFECT CONCERNING HYDRAULIC QUASI-STATIONARY OSCILLATIONS ON A TURBINE MODEL AND TEST CIRCUIT

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# SCALE EFFECT CONCERNING HYDRAULIC QUASI-STATIONARY

# OSCILLATIONS ON A TURBINE MODEL AND TEST CIRCUIT


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## SYNOPSIS


For the continuation of the study undertaken during the Amsterdam Symposium and within the framework of the "Work Group on the Behaviour of Hydraulic Machinery under steady oscillatory conditions" the authors have the following objectives :

. comparison between the experimental responses of the circuit to a piston machine excitation and the calculated responses by the impedance method,

. comparison between the experimental responses of the circuit to a piston machine excitation and the responses to excitation produced by the flow at partial load,

. conditions under which a pulsation phenomenon occurs at high loads.

The first aim is achieved but yet under restrictive conditions.

The second investigation shows that the scale effects of fluctuations versus/test head have the same tendencies as the frequency responses of the circuit but that the occurrence of cavitation deeply changes such responses.

Finally, the occurrence of pulsations at high loads is closely related to the axisymmetric vapour amount in the draft tube and the pulsation frequency also varies with the characteristics of this vapour amount.

# SCALE EFFECT CONCERNING HYDRAULIC QUASI-STATIONARY OSCILLATIONS ON A TURBINE MODEL AND TEST CIRCUIT

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## PURPOSES

During the latest AIRH symposium in Amsterdam, the authors presented a paper on the analysis of pressure signals and motor torque at partial loads with variable test head. Significant scale effects were noted, in particular for a given value of the cavitation parameter $\sigma$ and for the second harmonic of the fundamental rotational frequency of the dead water core. An influence of the test circuit and/or a similarity problem of the cavitation phenomenon developing in the draft tube may be derived from this result.

On the other hand, the behaviour of amplitudes and signal phases versus $\sigma$ shows that for the same value of $\sigma$ already mentioned, there is a self-amplification of the net head on the runner which is obviously associated with a dynamic amplified torque on the shaft.

Finally, the authors have been able to check that at least one of the pressure signals followed the evolution of the torque signal, namely the pressure measured at the draft tube elbow outlet.

The "Work group on the behaviour of hydraulic machinery under steady oscillatory conditions" was formed soon after the symposium. During the first meeting held in September 1983, our attention was drawn to two types of investigations :

- experiments proving the decisive influence of the draft tube elbow on dynamic amplitudes of discharges/head/torque (1), with a view to confirming our analysis whereby the unit discharge variation is induced by the complex movement of the helicoidal vortex in this elbow.

- theoretical and experimental study of the impedances of the test circuit/turbine assembly showing that it is interesting to know the dynamic characteristic of the test circuit in order to determine whether acceptable test conditions exist without resonance and to make use of model results to carry out predictions regarding the prototype behaviour (2) (3) (4) (5) (6) (7).

The scale effect at partial loads has therefore been investigated in greater detail by "correlating" this scale effect with the dynamic response of the test circuit for a given excitation produced by the movement of a piston delivering a periodic discharge into the draft tube. In addition, a mathematical modelization has been carried out using the impedance method and the first results have been compared to the experiments. On the other hand, considering the self-amplification phenomenon at partial loads, in terms of $\sigma$ , we have immediately experimented another self-amplification case occurring at high load. This phenomenon may be of some importance at the prototype scale if the project includes appreciable head variations.

## 1. MEASUREMENT OF THE CIRCUIT RESPONSE TO A GIVEN EXCITATION

A piston machine with adjustable stroke and diameter is delivering a periodic discharge on the draft tube wall. The applicable frequencies range from 0.3 Hz to 12 Hz and the maximum discharge at 12 Hz is 26 litres per second. The response is measured by means of quartz transducers installed at locations 1, 2 and 7 in the spiral case inlet and draft tube (Fig. 1).

The circuit is tested under various conditions namely :

A - No flow - pressurized downstream water tank

B - Flow under turbine optimum conditions

C - No flow - downstream water tank at the atmospheric pressure

The experimental responses are presented in $20 \log \frac{\Delta H_C}{\Delta H_e}$ (C = 1, 2, 7)

where $\Delta H_e = 0.013 f^2$ is the

pressure fluctuation at the piston outlet in RMS (Fig. 2).

This reference fluctuation has been measured and calculated.

According to fig.2, particular note should be given to

- For conditions A (no flow and pressurized circuit) :

  . A very close fluctuations behaviour between the transducers 2 and 7,

  . A very clear agreement between the peak frequencies measured at transducers 2 and 1. Up to 7 Hz, signal 1 is amplified in relation to signal 2 and beyond 7 Hz, an appreciable attenuation is observed.

- For conditions B (flow under turbine optimum conditions) :

  . A virtually similar fluctuations measured at 2 and 7 (this is not applicable to a flow with vorticity at partial loads),

  . A damped behaviour of 2 and 7 pressures versus frequency compared to the no-flow behaviour,

  . A good agreement between the measurement results at 1 and 2 with an appreciable attenuation for signal 1 beyond 6 Hz, thereby confirming the influence of the turbine as a filter.

Fig. 3 shows a comparison between the experimental and calculated response of circuit in conditions C and B. The sound velocity adopted for calculations is that one measured in the circuit using several methods. The fair agreement between the calculation and measurement results confirms the very low value of about 200 m/sec under our experimental conditions.

## 2. MEASUREMENTS AT PARTIAL LOADS WITH VARYING TEST HEADS AND SIGMA VALUES

With a Francis model of $n_q$ = 48 and for :

$A/A_{\wedge}$ = 0.8 and $H/H_{\wedge}$ = 0.74, the measurements are carried out by varying :

H = 7 m, 9 m, 12 m, 18 m, 25 m, 35 m

$\sigma$ = 0.35 - 0.21 - 0.16 - 0.11 - 0.077

The recorded signals are the torque fluctuations $\Delta T$ and the pressure fluctuations $\Delta H_C$ (C = 1, 2, 3, 7) (Fig. 1).

The results give the following indications :

- amplitudes and phases versus sigma (Fig. 4),

- amplitudes versus test head (Fig. 5),

- comparison, in terms of frequency, between the signals measured at partial loads and those measured during excitation by the piston machine (Fig. 6).

The excitation is shown :

. with and without flow under single phase conditions (upper curves),

. without flow with a flexible bag below the runner containing 10 litres of air (lower curve).

A first analysis can be made :

- Harmonics 1 and 2 are very small (fig. 4 and 5) (this was not the case with a turbine of $n_q$ 75 [8] ),

- A relative amplification for $0.11 < \sigma < 0.16$ occurs far beyond the $\sigma$ standard and $\sigma$ plant values, (fig. 4).

- Low test heads produce an increase in fluctuations for $\sigma$ values (0,16 and 0,21) in this special case of turbine and circuit, thereby confirming that there is no general relation between fluctuations and test head (fig. 5),

- Amplitude variations measured between transducers 2 and 3 confirm previous observations (fig. 4),

- With a high sigma value (0.35), fluctuations amplitudes are almost constant with the test head or corresponding frequencies. A fair agreement between the responses of the system excited either by the downstream flow or the piston (conditions B) is therefore checked provided there is no significant vapour amount. In fact, when the value of $\sigma$ decreases (0.21) and a visual dead water core appears with $H < 12$ m ($f = 3$ Hz) an important head scale effect occurs. With $\sigma = 0.16$, the influence of the frequency/head becomes very important, as it could be expected by the dead water piston test including a certain amount of air in the flexible bag (fig. 6),

- Strong variations occur in the responses of the system to piston excitation depending on whether the test is carried out with or without flow conditions.

It is therefore interesting to check the modelization process with the test results in both conditions.

## 3. MEASUREMENTS AT HIGH LOADS

For a hydroelectric scheme including appreciable water head variations, the manufacturer shall generally guarantee the highest possible output under the lowest head (Fig. 8), which involves the necessity of applying comparatively high values of $\Psi/\Psi_{\Lambda}$ to high head outputs. From our past experience on prototypes and scale models, it is known that self-pulsations of varying frequency may then occur although the flow downstream of the runner remains a quasi-rectilinear axis vortex.

The influence of the following parameters on the occurrence of such pulsations has been investigated :

- distributor opening,
- sigma value (0.07, 0.10 and 0.15),

How is the phenomenon occurrence determined ?

a) Speed is slowed down at a constant opening up to an area where the dead water vapour core can be seen with a radial pulsation,

b) In this area, the pressure signals are then analyzed "on line". When the phenomenon is installed, a peak occurs at a much lower frequency than the rotational frequency $f_N$ and it seems to be very well correlated (coherence index > 0.95) between the upstream and downstream sides of the runner (Fig. 7),

c) The appearance limit corresponds to the first occurrence of these peaks on the various signals (these limits are shown in Fig. 8)

Two comments can be made :

. The limit at which there is pulsation occurrence strongly depends on the sigma value and appears for a given sigma value at a comparatively constant discharge. Consequently, it may be concluded that the average pressure below the runner controls this occurrence or the axisymmetrical cavitating volume is decisive. In fact, this conclusion involves the necessity of also considering velocity distribution at the runner outlet as it modifies this cavitating volume.

. The pulsation frequency decreases when observations are made at a constant opening and for a decreasing sigma value. This decrease is qualitatively in agreement with the theoretical result of a two-phase monodimensional modelization (9) in which the natural frequency of the system varies as

$$f/f_N \approx \frac{k}{\sqrt{\partial Vc/\partial\sigma}}$$

where $\frac{\partial Vc}{\partial\sigma}$ is "the cavitation compliance" which increases when $\sigma$ decreases.

The modified velocity distribution at the runner outlet is also probably contributing to decreasing frequencies at a constant opening and for a decreasing $\Psi$ value.

CONCLUSIONS

The manufacturer's desire is, of course, to predict the behaviour of the turbine prototype with its conduits. For this purpose, he needs to know the excitation produced by the active parts of the turbine as well as the response given by the conduits and the turbine itself.

The usual model tests do not directly solve this problem. However, the model may have several useful functions :

. turbine optimization as an exciting source provided the test circuit impedances are known and they do not vary too much within the frequency range concerned,

. experimental knowledge of turbine impedances to introduce them in the mathematical modelization,

. experimental checking of the validity of the test circuit impedance calculation.

The mathematical modelization can then be carried out on reliable bases and allow prototype predictions by replacing the model test circuit by the prototype conduits in calculations.

Considering the general purpose mentioned above, we have firstly tried to estimate the following results :

1 - Responses of the circuit to a given excitation and calculations of these responses by the impedance method,

2 - Responses of the circuit to a given excitation (piston machine) and fluctuations at partial load with respect to the head,

3 - Conditions under which a pulsation phenomenon occurs at high loads for a varying discharge and/or sigma value.

Regarding the first point above, it is noted that there is a fair agreement between calculation and experimental results. However, this agreement is only existing in the absence of cavitation. It is also to be noted that the experimental responses are much smoother in terms of the frequency for $\hat{V} \neq 0$ than for $\hat{V} = 0$ (fig. 2 and 3).

As regards the second point, it must be said that at partial loads, the behaviour of the turbine $n_q = 48$ is rather different from that of the turbine $n_q = 75$ which has been tested in the same circuit and with the same heads (8) but with a different operating point. The harmonic frequencies virtually become negligible while they played an important part in the previous experiments.

It is then confirmed that there is no general tendency towards a relation between the test head and the relative fluctuations

$$\frac{\Delta H}{H} \quad \text{and} \quad \frac{\Delta T}{T}$$

and in particular, the low heads do not lead to low fluctuations. Finally, the pressure and torque fluctuations vary very much with the head depending on the sigma value. For a high sigma value at partial loads, the scale effect can virtually be disregarded and the responses of the system versus frequency can be compared to those resulting from an excitation caused by the piston machine.

On the contrary, when the sigma value decreases and a vapour amount appears, the influence of the head (and of the frequency) becomes important and qualitatively confirms the tests which have been conducted with a piston machine by introducing a quantity of air below the runner in a flexible bag.

The reliable calculation of the responses of the system can be effected only by including the gaseous element laws in the future.

As far as pulsation investigation at high loads is concerned, it appears that the vapour amount below the runner has a decisive effect on the occurrence of the phenomenon. This amount of vapour depends on the discharge, sigma value and also, to a lesser extent, on velocity distribution of axisymmetric vortices. The pulsation frequency decreases with the sigma values if a constant opening is held, which gives a fair qualitative agreement with a simplified type of modelization.

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## NOTATIONS

| Symbol | Unit | Quantity |
|---|---|---|
| $H$ | m | net water head on the turbine |
| $\Delta H/H$ | - | dynamic relative variation of local pressure - peak to peak value |
| $\dot{V}$ | m3/sec | discharge |
| $f$ | Hz | frequency |
| $f_N$ | Hz | frequency corresponding to rotational speed N : $f_N = N/60$ |
| $f/f_N$ | - | relative frequency |
| $f_o$ | - | fundamental rotational frequency of dead water core |
| $T$ | mN | torque |
| $\Delta T/T$ | - | relative dynamic variation of torque-peak to peak value |
| $\sigma$ | - | Thoma's cavitation number with reference to runner blade outlet |
| $A/A_{\wedge}$ | - | relative distributor opening |
| $\omega$ | rad/sec | $2 \pi f_N$ |
| $R$ | m | outlet radius of the runner |
| $\varphi$ | - | $\varphi = \dot{V}/_{\pi R^3 \omega}$ |
| $\Psi$ | - | $\Psi = 2\, gH/_{R^2 \omega^2}$ |

Schematic represention of the IMH-EPFL test circuit

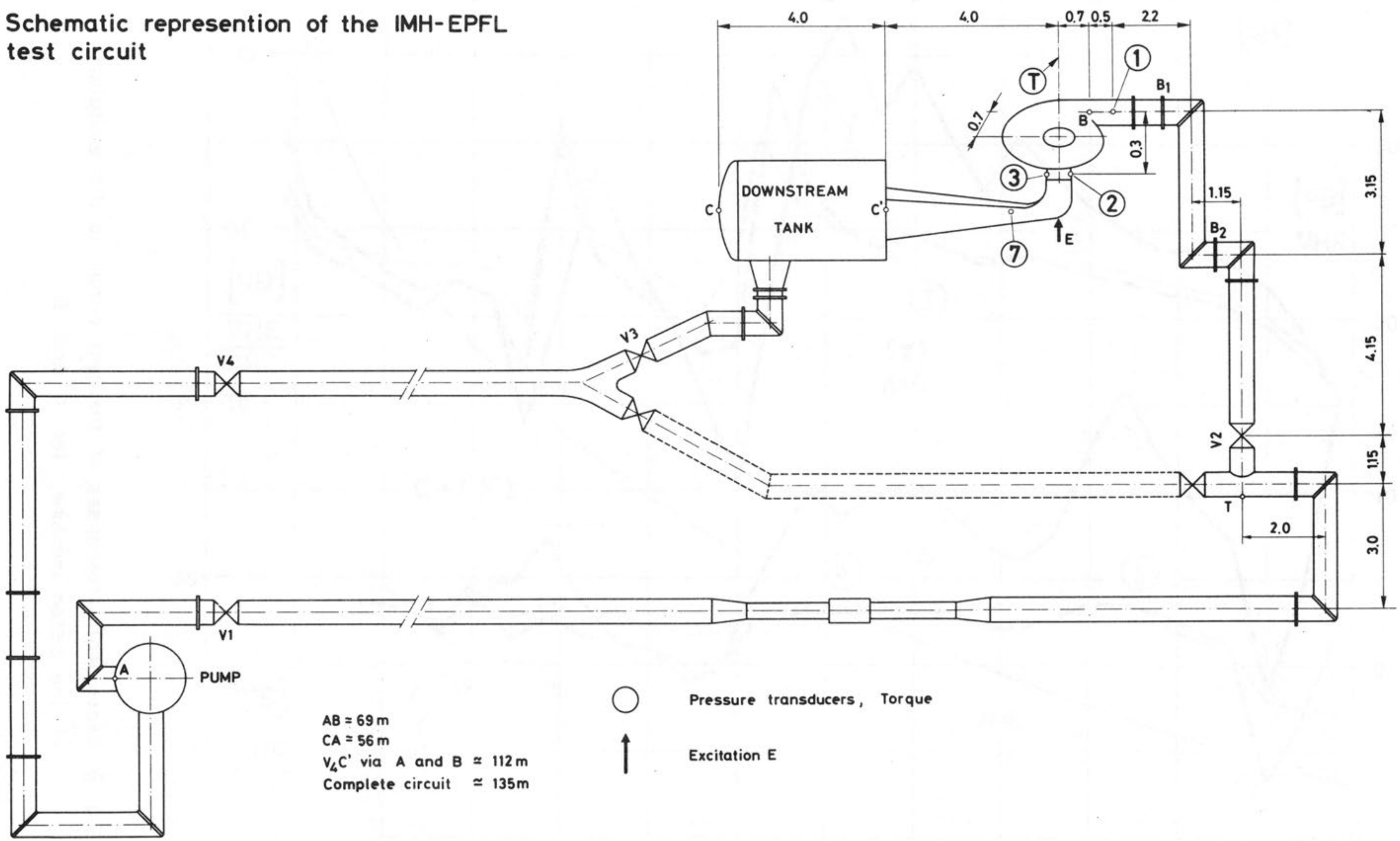



Fig. 1 Schematic representation of the EPFL test circuit and location of torque and pressure transducers.

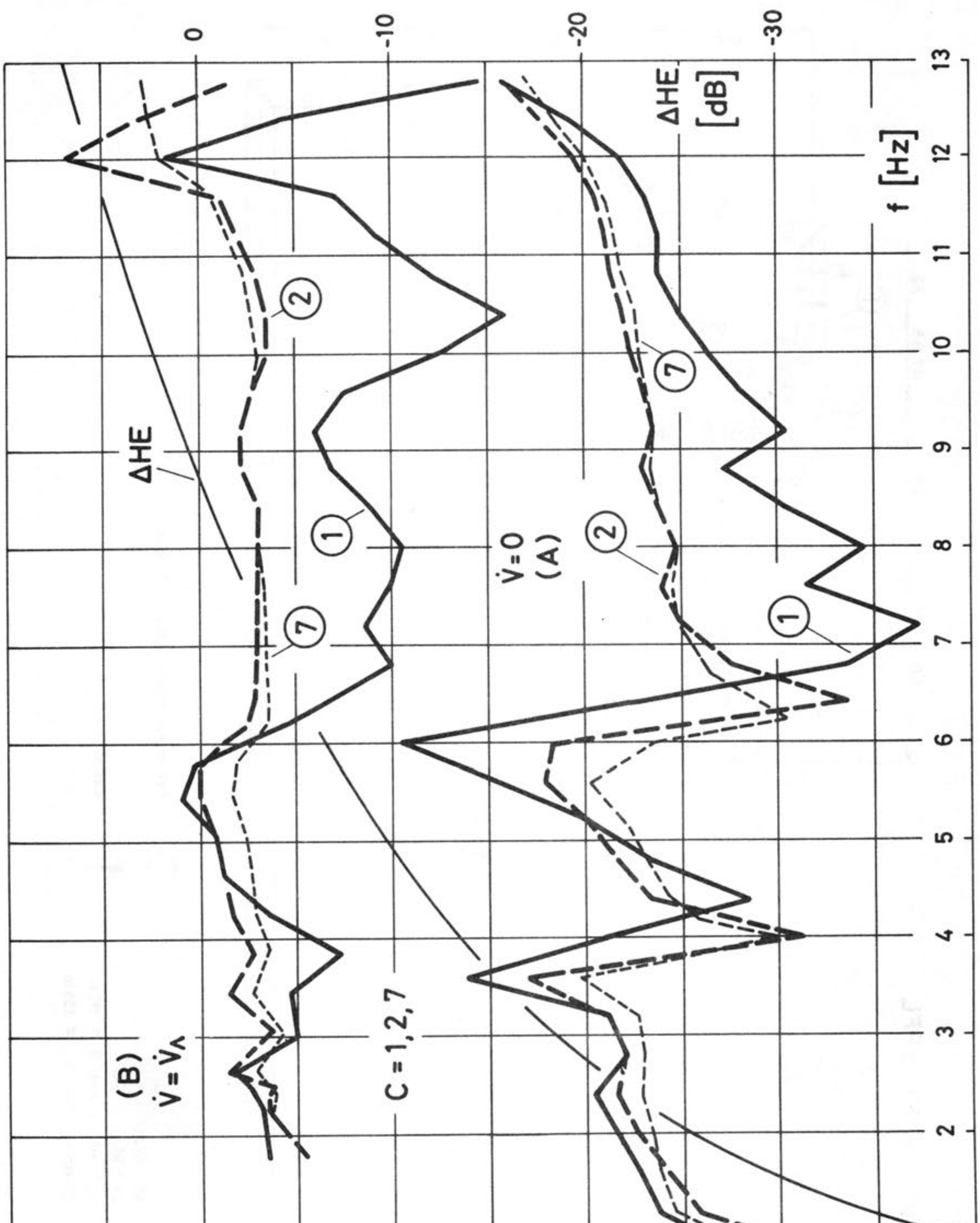



Fig. 2 Experimental responses of the test circuit to the excitation of the piston machine, for A and B

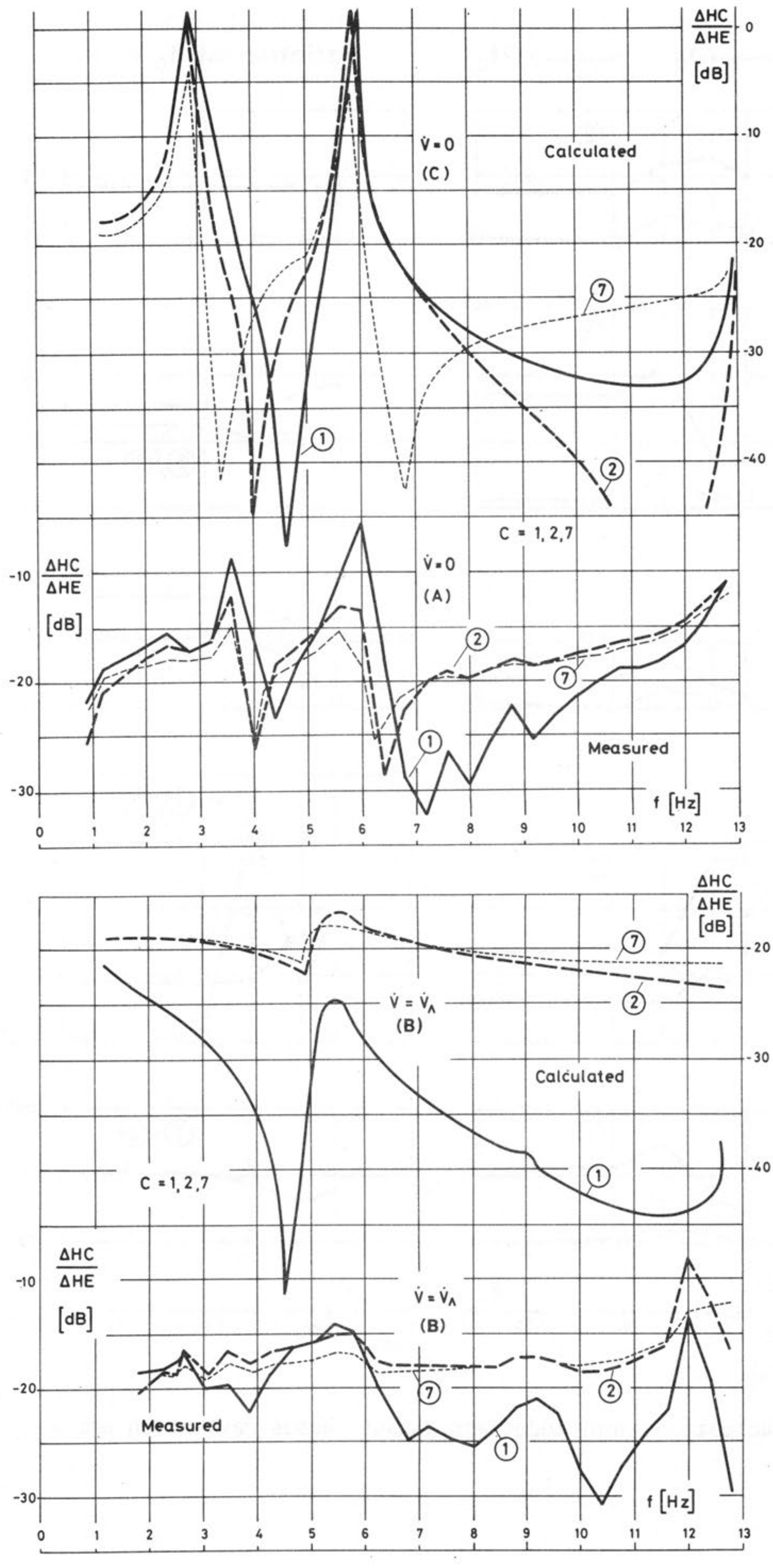



Fig. 3 Comparison of calculated and measured results of pressure fluctuations.

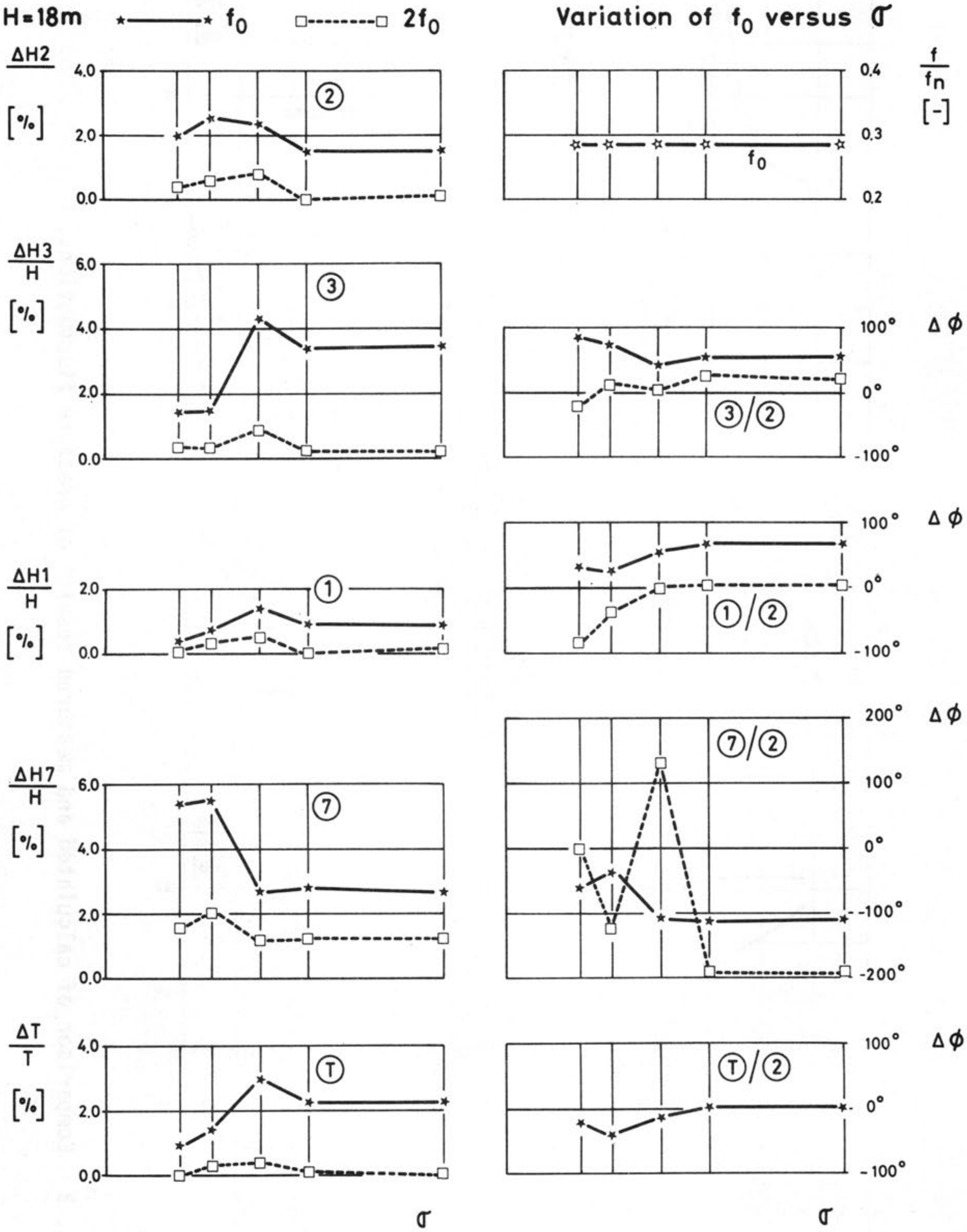



Fig. 4 Fluctuations amplitudes and phases versus cavitation number.

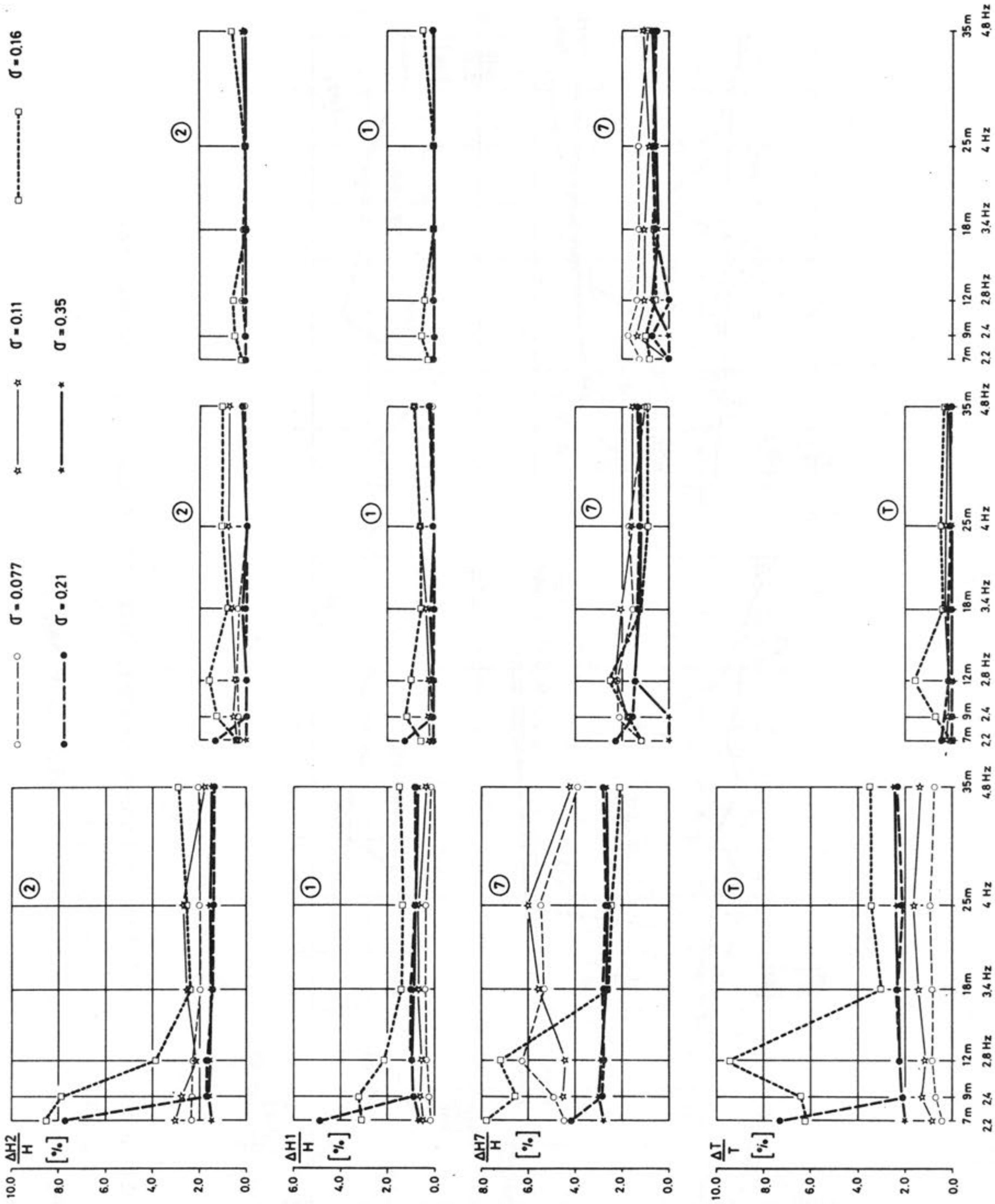



Fig. 5 Fluctuations amplitudes versus test-head.

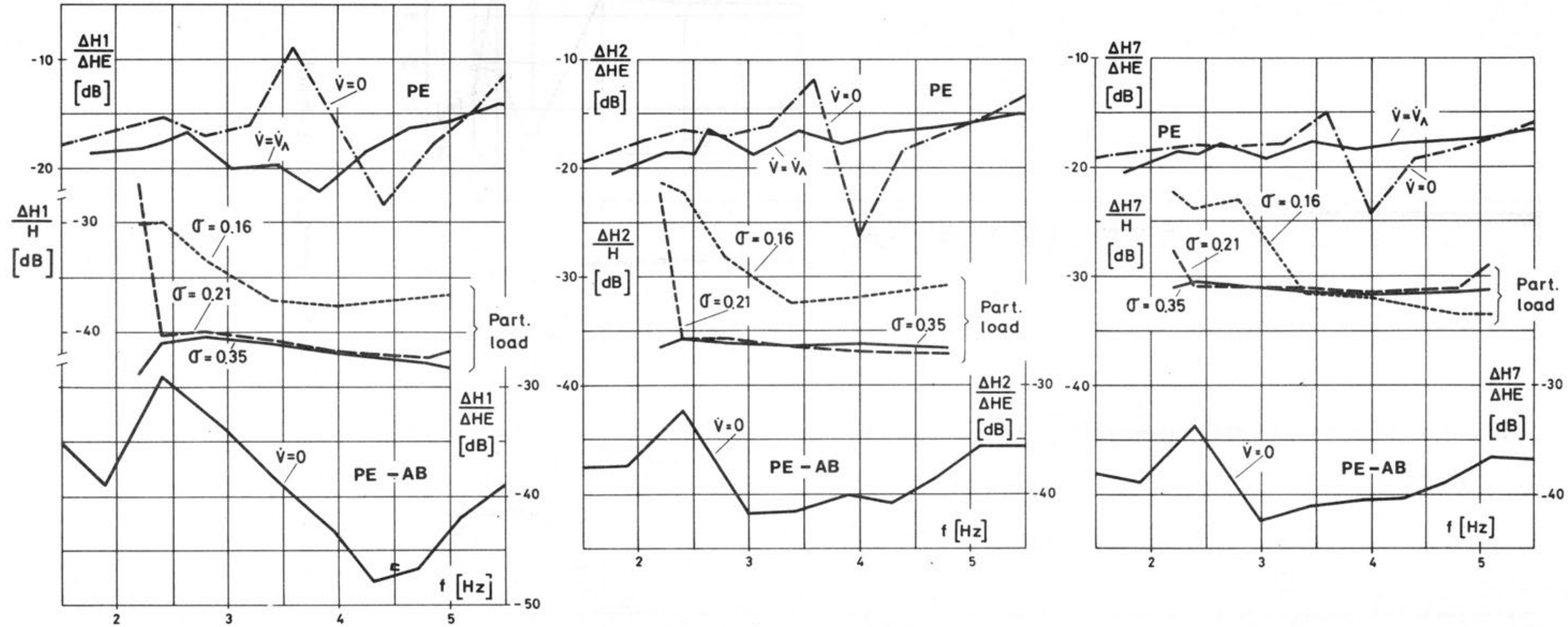
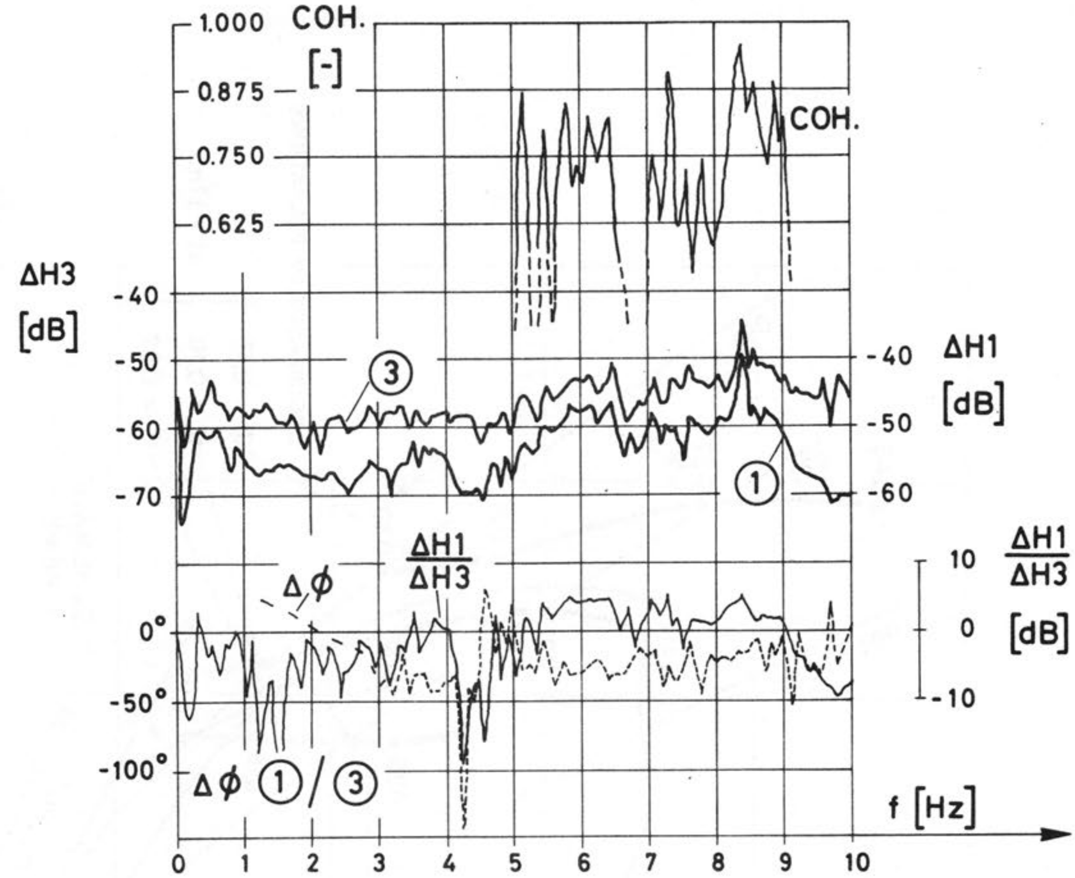



Fig. 6 Comparison of partial load pressure signals and responses at piston excitation.

PE: excitation by the piston
PE-AB: excitation by the piston, with "air bag".



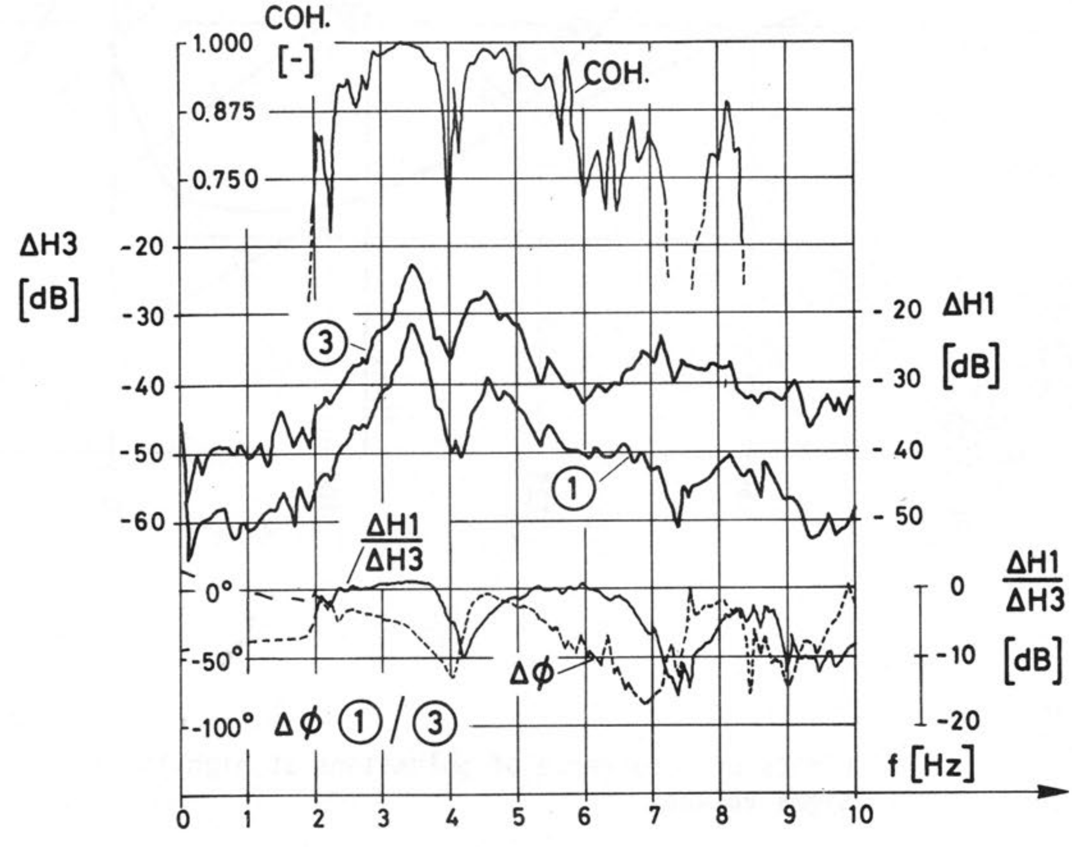




Fig. 7 Analysis of pressure signals before (top) and after (bottom) occurrence of pulsations at high load.

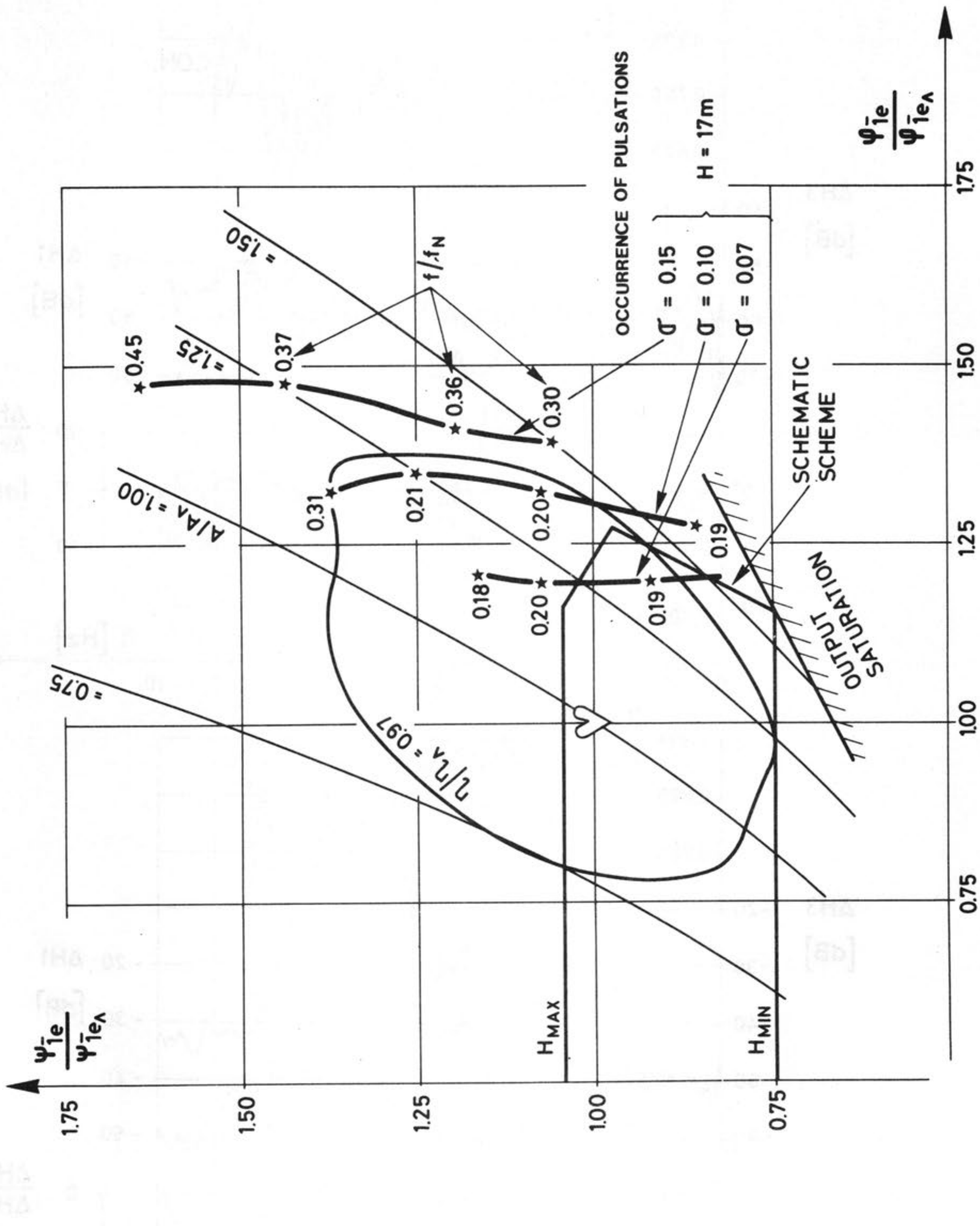



Fig. 8 Limits of occurrence of pulsations at high loads at different sigma values.