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SIGNAL ANALYSIS for INDUSTRIAL COMPRESSOR ROBUST CONTROL under PULSATION CONDITIONS

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ABSTRACT: *The paper describes a non-destructive signal analysis test of an industrial compressor under pulsation. The pulsation induced vibration forces on the critical pipe sections are monitored and used for optimization of pipe clamping and overall compressor mechanical design, installation, monitoring, and optimal compressor robust control, not to exceed the allowable level at all load conditions.*

KEYWORDS: *Compressors, pulsation level, vibration, pressure, signal analysis, control, robustness.*

INTRODUCTION: The paper describes the results of the pulsation study of the installation of a refinery industrial compressor. In the original piping installation the pulsation far exceeds the allowable level at all loading conditions. In order to reduce pulsation orifice plates at the damper line connection and in the cylinder connection of the discharge damper are installed. Besides the diameter of the cylinder connection of the discharge damper is increased to reduce the pulsation near the compressor valves. The pulsation induced vibration forces on the critical pipe sections are used for pipe clamping design and optimal compressor operation, with robust control features, under high pulsation conditions. Flow dynamics simulation suggests whether high pulsation are caused by flow pulses or turbulence, surge effects and operational induced vibrations of the compressor. The objective is to reduce the sensitivity of the system for the main (dominant) frequencies.

THE SYSTEM: The system, fig. 3, consists of two (the operating and the standby) compressors; each compressor has one stage, two double acting cylinders, runs at a speed of 490 rpm. The capacity is controlled by valve lifters.

The gas in the system consists of a mixture of hydrogen and hydrocarbons with a molecular weight 4.86 ÷ 8.89. The suction pressure is 2861 kPa while the discharge pressure is 3378 kPa.

PULSATION STUDY:

Pipe vibration in a compressor system is caused by either gas pulsation or mechanical coupling of pipelines to vibrating objects, i.e. the compressor itself

The pulsation study investigates the gas pulsation by:

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a. experimental measurements and
b. simulating the dynamic behavior of the gas in the pipelines

at several points of the compressor-pipe system, ensuring that pulsation are within specified limits and that no dangerous resonance occur within the possible range of operating conditions.

Generally the limit for allowable pulsation level is given as a percentage of the static line pressure. In the early API standard a 2% limit was prescribed independent of line pressure, diameter and pulsation frequency. An improved standard pulsation limit is given in fig. 1, a logarithmically linear related allowable percentage limit to the line pressure.

A relation between allowable pulsation level and the mechanics of the piping is a function of line pressure, diameter and pulsation frequency. The p-p pulsation limit is specified as:

$$P_{all}(\%) = \frac{300}{\left(P_1 ID . f\right)^{1/2}}$$ where:

$P_{all}(\%)$ = max allowable p-p pulsation in % of average absolute line pressure
P_I=average absolute line side pressure
ID = inside pipe diameter
f = pulsation frequency $\left(f = \frac{rpm.N}{60}\right)$

Limiting pulsation, however, may not be sufficient as shaking forces are equal to a pressure difference times a working area. An increase in area is compensated for by extra stiffness and rigidity. Therefore, special attention is paid to pressure differences across vessels of large diameter, where modest pulsation may build up large shaking forces. These shaking forces will be even more dangerous if a mechanical natural frequency is close to one of the main frequency components.

A passive pipe response method of analysis simulates compressor signal (step function) is applied to the simulated pipe and "bottles". The resulting amplitude response is recorded and plotted versus frequency, see fig. 2. Only the resonance peaks frequencies are of interest. The p-p pulsation levels including the dominant harmonic are classified as:

- pulsation level < 0.5 x APL
+ 0.9xAPL > pulsation level >0.5xAPL
* 0.9xAPL < pulsation level < 1.lxAPL

APL = allowable pulsation level

The magnitude of the shaking forces in axial direction in kN p-p is given for critical pipe sections with their main frequency component.

SYSTEM IMPROVEMENT:

The methods to improve the system are:

A. Lower Limit of Pulsation: The check on damper design, directly gives the lower limit of pulsation to be expected. The interaction between damper and piping will normally increase pulsation. So, if the result of this check is that pulsation exceed allowable limits, dampers or bottles should be redesigned to achieve acceptable pulsation levels and forces exercised on the piping.

B. Shifting and Avoiding Resonance: The compressor applies a complex wave on the piping, that contains frequencies of the compressor speed, twice the compressor speed, etc. For a double acting cylinder the second harmonic is the strongest but the first harmonic is also present as the swept volume of the cylinder halves are not exactly equal. If one cylinder half is unloaded, the first harmonic component increases. The amplitude of the higher harmonics decreases with its number. When compressor speed or velocity of sound changes, the harmonics of the complex wave applied to the piping, vary accordingly. One may verify that the only safe frequency ranges are below 0.8 f and between 0.8 f and 1.6 f.

C. *Damping Resonance:* Often the previously given safe frequency ranges are limited, e.g. when compressor speed is used for capacity control. Another unfavorable condition exists when a resonance peak has a rather broad shape. In both cases the resonance peaks in the passive pipe response curves have to be brought down. This is achieved by inserting orifices or more sophisticated arrangements of filter type dampers at well chosen spots. The effectiveness of orifices depends on the ratio D/d, (D is the pipe diameter, d diameter of the orifice bore); we employ D/d > 1.5 ÷ 2.

SIMULATION RESULTS: The first step in a pulsation study is the check of the damper design. For the detailed simulation the piping has been split up into two parts: the suction and the discharge piping. The piping layout is given with the points indicated, for which the pulsation level have been calculated, see fig.3, 4. The pulsation has not only been calculated at nominal conditions but also at deviating conditions, i.e. changes in temperature, molecular weight of the gas and velocity of sound. The calculated pulsation levels are compared with the allowable levels. In each plot the time function of a pulsation or flow variation is given for one crank revolution.

CONDITION	LINE **CONNECTION**	**CYLINDER PASSAGE VOLUME**
a. Suction dampers		
full load	*0.58 % p-p*	*0.89 % p-p*
unloaded	*1.34 % p-p*	*1.85 % p-p*
b. Discharge dampers		
full load	*1.23 % p-p*	*6.76 % p-p*
unloaded	*1.15 % p-p*	*3.63 % p-p*

Table 1. A summary of the results

No	A	B		**Description of the resonance nature**	**Possible remedies**
		n	*x*		
1	f_1	-2	1	*Helmholtz resonance between dampers*	*Install orifice*
2	f_2	+36 -29 -4 +8	1 1 2 3	*Standing wave between the dampers and the compressor tank*	*plates at the inlet of the dampers*

Table 2. Summary of resonance frequencies in the suction piping system

No	**A**	B		**Description of the resonance nature**	**Possible remedies**
		n	*x*		
3	f_3	-4	4	*Helmholtz resonance between cylinder passage volume and the damper*	*Increase the diameter of piping between cylinder and damper to 8" and install an orifice plate bore 110 mm in the cylinder connection of the damper*
4	f_4	+14	1	*Helmholtz resonance*	*Install orifice*
5	f_5	+36 -15 +32 -13	1 1 2 2		

Column A: peak indicated in the passive pipe response curves
Column B: resonance excited by harmonic component n at x % deviating condition

Table 3. Summary of resonance found in the discharge piping

Table 1 gives a summary of the results, while Table 2, 3 present resonance characteristics at the suction and discharge piping. At the discharge side this level will be exceeded, this is caused by a resonance between the cylinder passage and the damper which is close to 4 $*$ compressor speed. This resonance can be shifted to higher frequencies by shortening the length of the cylinder connection of the damper or increase the diameter of the cylinder connection. The resonance can also be damped to maximum 4.2 % p-p by installing an orifice plate at the cylinder connection of the damper with a bore of 95 mm (max ΔP = 0.2 %). This orifice plate also reduces the pulsation induced forces on the cylinder connection (maximum 3.0 kN p-p at the 4th harmonic) to maximum 2.6 kN p-p at the second harmonic. A further reduction of the pulsation level to 2 % p-p is possible by increasing the cylinder connection to 8", combined with an orifice plate of 110 mm (ΔP= 0.12 %), It should be noticed that in the long cylinder connection the same levels occur as in the cylinder passage, volume.

ROBUSTNESS: All parameters involved in the compressor/piping system pulsation study tend to drift and move along the operating curves, i.e:

a. speed of compressor (and sound)
b. composition, pressure, temperature
c. loading conditions

The robustness is the property of operation under control to perform within specific operating results, under varying (within a range) operating conditions. Robust optimal control is considered as a multivariable problem. Small deviations of compressor speed and speed of sound give better results and wider safe ranges, ensuring robustness. Changes in compressed gases temperature and molecular weight results in deviation of sound velocity.

CONCLUSIONS: The primary check in a compressor pulsation study is the damper and piping design check and vibration analysis. To reduce the pulsation to the allowable levels modifications are recommended that ensure robust operation.

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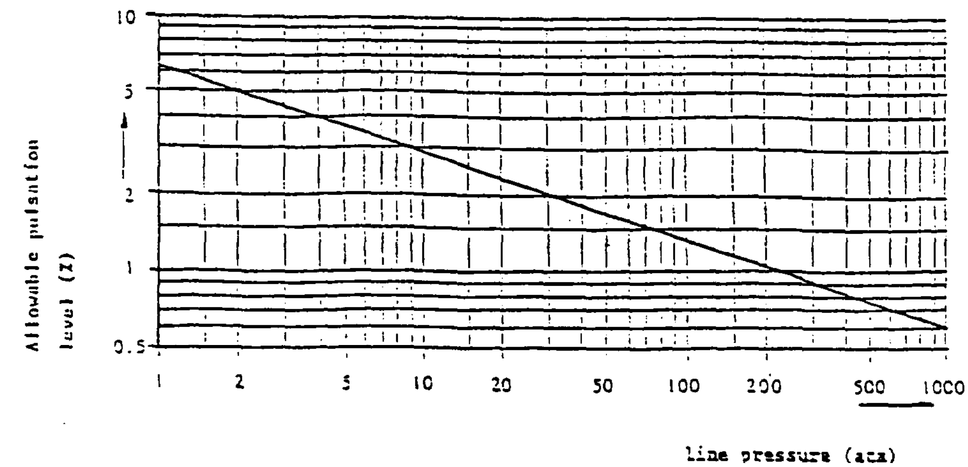
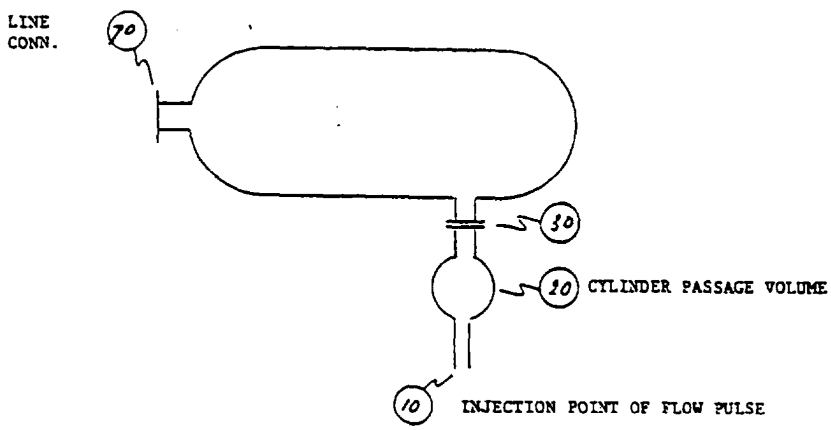


Fig. 1. Allowable pulsation levels



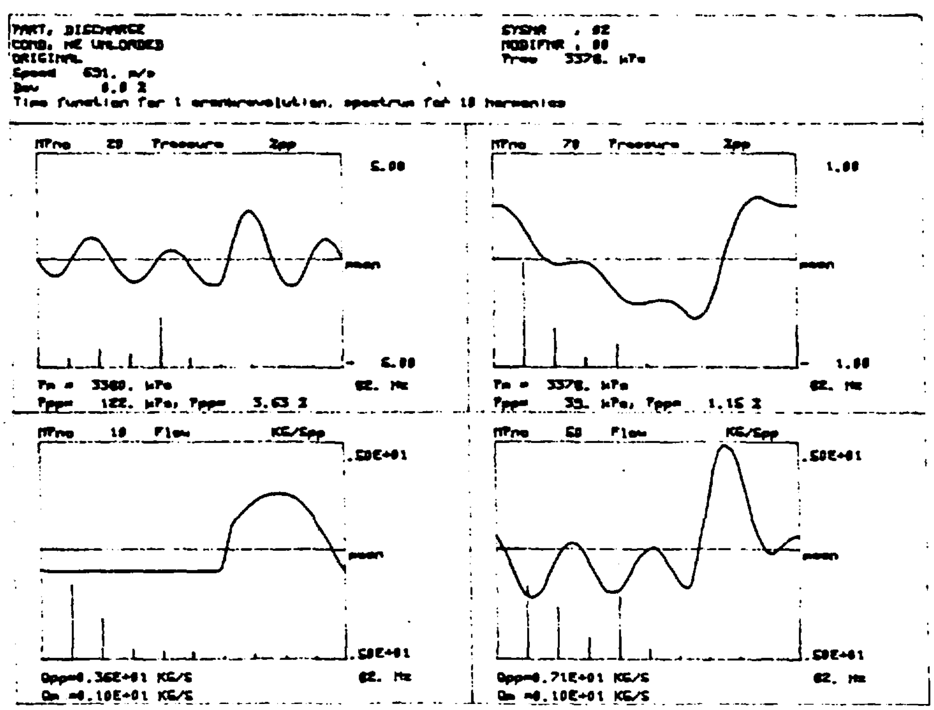


Fig. 2. Compressor amplitude response at critical points

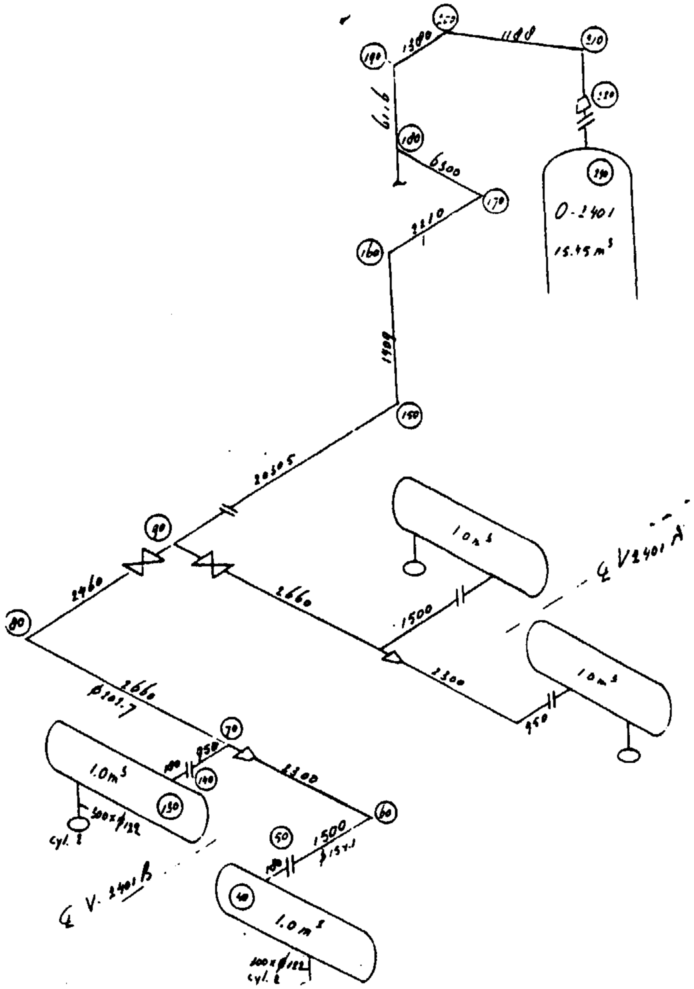


Fig. 3. Lay-out of the suction piping

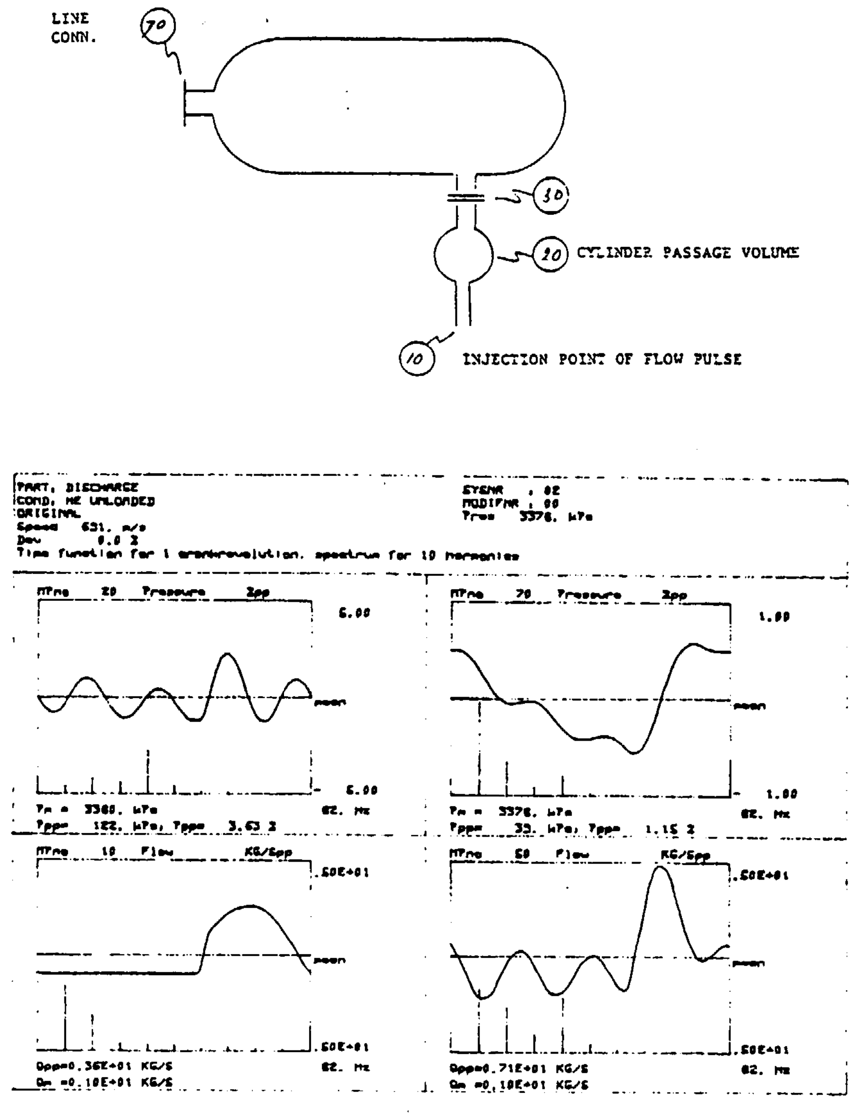


Fig.4. Passive pipe response curves of the suction