Dynamic behavior of piping section equipped by energy dissipator

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ABSTRACT

The analysis of the primary piping systems has led to define an experimental scaled model to specifically study its dynamic behaviour. The results collected in the experimental campaign will be summarily discussed. Moreover, in parallel with experimental tests a numerical analysis with a finite element code (ANSYS) has been performed. Therefore, a complete description of the behaviour of the piping section has been obtained. Finally, it has been attempted to introduce on the section a viscous-elastic device and a viscous damper in order to improve the system response, limiting displacements and stresses.

STRUCTURE TEST CONFIGURATION

The experimental model (fig.1) tries to represent a dynamic schematization of the steamline. Preliminary studies have allowed to define the correct dimensions and the form of the specimen, which has the C configuration [1] as illustrated in fig.1, together with the damper data. The specimen involved in experimental campaign is derived by a small portion of a thermal power plant steamline. These problems arise from this position:

a) the mock-up configuration and material have to be similar or equal to those of steamline respecting the similitude requirements;
b) the reduction factor selected in scaling down the steamline sizes have to reproduce the same conditions existing in static/dynamic regimes, like maximum level of stresses and some principal frequencies;
c) the specimen position on experimental facility has to be arranged in manner to respect the loading characteristics of real piping or to correspond to its maximum.

As consequence of the preceding consideration the programme of tests has to be optimized taking also some limitations. Firstly the geometrical and physical data have to be determined with the aim to obtain a good correspondence between model and steamline frequencies (at last of the lowest orders). Even in the worst extrapolation the first natural frequencies of the specimen shall never exceed those of power piping by half an order of magnitude. The frequency of interest shall correspond to that generating the maximum influence along the piping axis (i.e., z-axis) consistent with the specimen plane. To adjust the frequency it is possible to increase the model mass by filling with water. The experimental campaign include three typology of tests:

1) Static test: the free end of the C-pipe is move horizontal for +/- 30mm;
2) Forced oscillation;
3) Free release of the free end.

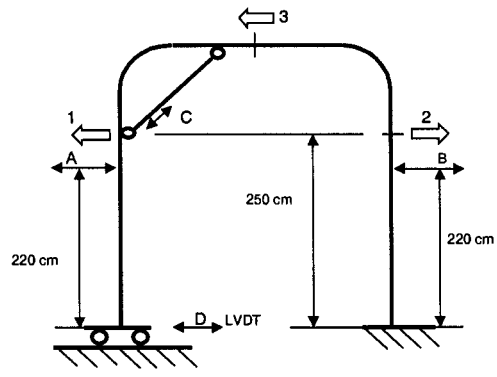

Fig. 1 Mock-up configuration

Testing Parameters
Same characteristics of the experimental campaign and its instrumentation are reported below (see also Fig.1):

- Imposed displacement (piston elongation – LVDT in D);
- Reaction force by the structure (load cell in D);
- Horizontal displacement of point (A) at half of free end leg (potentiometer);
- Horizontal displacement of point (B) at half of built-in end leg (potentiometer);
- Elongation of the Viscous-Elastic damping Device VED placed in position C of the specimen (potentiometer).

Some other sensor (LVDT or potentiometer in other point of the structure, accelerometer, etc.) are used as requested by each series of tests.

EXPERIMENTAL TESTS

Static Test
The main structure parameters for static response are listed in the Table 1. Starting from these data it is possible to define the technical specifications for the next tests. The maximum applicable loading conditions (displacement, frequency, ...) must be exactly calculated. It is very important to perform tests in elastic regime to avoid any permanent distortion into the specimen.

Tab.1 Some results of static tests

Static +30mm displacement of free end:		Static -30mm displacement of free end:
Weight on built-in end: 6424 N		Weight on built-in end: 1011 N
Weight on free end: 1041 N		Weight on free end: 6454 N
Reaction on piston: 2677 N		Reaction on piston: 2842 N
Maximum stress: 76 MPa (second elbow)		Maximum stress: 79 MPa (second elbow)
Stress on built-in base: 30.5 MPa		Stress on built-in base: 29.8 Mpa

Forced Oscillation
A detailed analysis of the dynamic response is carried out, taking also into account the starting phase and the final damping. A complete time-history for f = 6Hz (about at middle of the resonance peak) with 2mm forced displacement is represented in Fig.2.

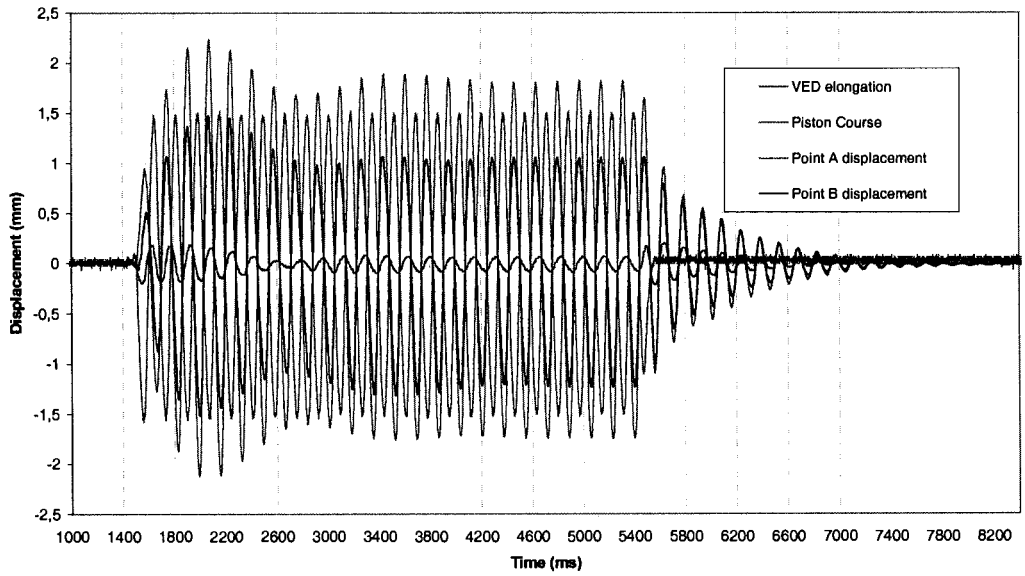

Fig.2 Example of a forced oscillation experimental test: nominal displacement 2mm – frequency 8hz – VED with intermediate damping caracteristic – C-pipe without water

By examining the graphs the following three parts could be individuated:

1. Start-up of piston movement and transient to reach the steady regime of forced oscillations;
2. Steady forced oscillation of the structure;
3. End of input, piston setting at zero displacement: damped free oscillation of the structure.

Taking into consideration the preceding limitations the test programme has to respect the following technical specifications:

- C-pipe with water or without;
- C-pipe with the Viscous-Elastic Device (VED) or without;
- VED in four configuration (four damping constant);
- Frequency field: from 1Hz to 10Hz;
- Displacement range: from 1mm to 20mm.

The total number of the tests, necessary to evaluate the three parts of the oscillations and the technical specification, amounts to 200. The experimental data are elaborated and interpreted with the support of a FEM program (ANSYS [2]) witch is also used during the long phases necessary to optimize the specimen sizes. All the three parts of oscillation fields are interesting. The start zone (1400 – 3000ms in fig.2) indicate that in several points of the structure the maximum displacement falls in this period. Consequently the stress/strain conditions reach their maximal values. In the second zone the VED elongation is less than that registered in the first zone. The damping effect is consequently active. The end zone of the diagram describes an increasing of the damping effect of the VED as well as the transient to arrest the structure motion.

NUMERICAL ANALYSIS

In Fig.3 the sketch of the C-speciment with the viscoelastic damper (1500 mm long across the 2nd elbow) is represented. With this configuration it is possible to calibrated the numerical model. In fact the FEM carries out to simulate all the conditions during the tests performed by Montecuccolino Lab.
Obviously these numerical and experimental results are only a part of those performed on the C-pipe model.
The correspondence between theoretical, numerical and experimental data is very satisfactory. This implies the ability of the process adopted. With this it is possible to deduce a correct relation representing the model response and consequently that of real piping equipped by damper.

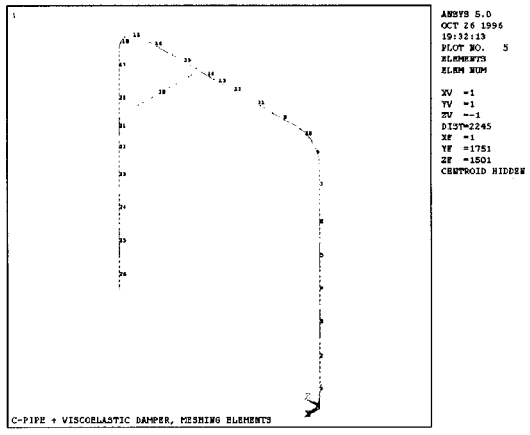

Fig.3 Numerical Model C-pipe with VED device

Modal Analysis

The FEM model is obtained by PIPE elements. The modal analysis was made using the subspace method on the first 40 modes, and expanding the first five as regards the eigenvectors, to visualise the actual deformed shape. The main results are the frequency values (in Hz) of each mode and their participation

Tab.2 First 10 natural frequency and their mass participation along Z

Frequency	Value (Hz)	Mass Fraction
1	2.57	0%
2	4.42	67%
3	5.00	67%
4	9.45	87.6%
5	13.35	87.6%
6	49.27	89.7%
7	51.78	89.7%
8	69.95	94.5%
9	71.35	95.6%
10	76.09	95.6%

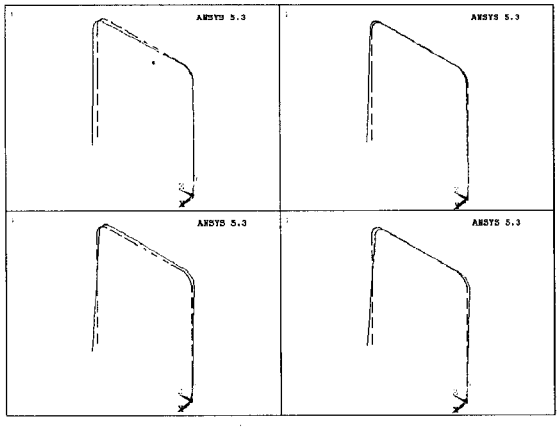

Fig.4 Pipe Modal Analisys

as percentage mass in a normalised vibration along Z-axis, which is the direction arbitrarily chosen for the earthquake. In Fig.4 the deformed shapes of the first 4 modes are graphed.
The value of the first 10 natural frequencies and their mass participation along Z are listed in Table 2. The experimental resonance frequencies along Z direction are in practice the same (4.6 and 9.2 Hz).

Damped Modal Analysis
The ANSYS program offers the way to calculate a damped modal analysis. The results are complex frequencies: the imaginary part is the actual natural frequency of system vibration, while the real part represents the exponential damping factor to be superimposed to obtain the overall time-history.

For a single frequency system, given a complex frequency in the form (a + ib), the free oscillation law is simply the following:

$$x(t) = X_0 e^{2\pi a t} \cos(2\pi b t + \varphi) \quad \textbf{(1)}$$

In our simplified two-degree-of-freedom system we can, as a first approximation, sum the two contributions to figure out the mass centre free oscillation behaviour. This allows, even if it is not a rigorous process, to save the huge amount of time taken for dynamic analyses also for these simplest cases.

Free Oscillation
As a control of the reliability of damped modal frequencies, we performed a complete dynamic analysis of free oscillation of the C-pipe. An initial displacement of 30mm along Z axis at the free end was applied. The graphs of the results, as regards the displacements as well as at other critical points are in Fig.5.
The results are perfectly consistent with the damped modal analysis results.

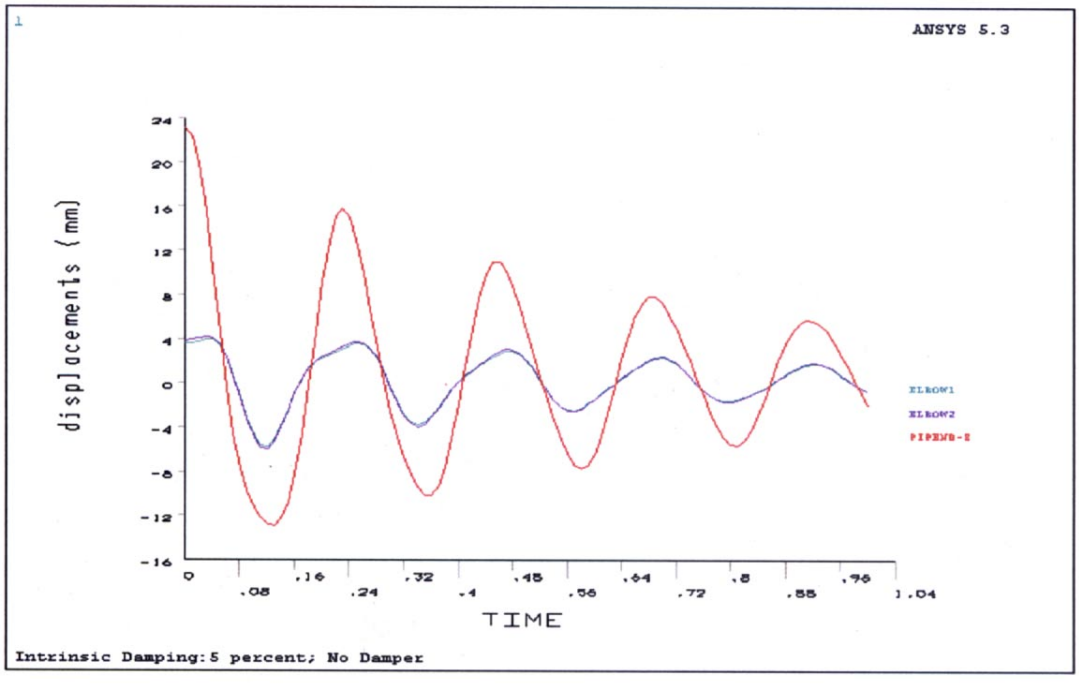

Fig.5 Free oscillation displacements

NUMERICAL COMPARISON BETWEEN DAMPING DEVICES

VED – Viscous Elastic Device

The relation between stiffness and damping constant it results from the manufacturer's [3,4] specifications is:

$$K = 1.25C\omega \tag{2}$$

with: K = stiffness of the VED;
C = damping coefficient;
ω = pulse

The presence of an elastic constant across the elbow stiffens the whole structure, rising its frequencies. But then, by using the preceding expression (2), also the damper stiffness rises and so on. Thus, once chosen the damping constant, an iterative modal calculation is required to obtain the correct frequency and damper stiffness.
Interpolating the results, a simple quadratic fit could be proposed for the C-pipe (see Fig.6). Considering this graph it not so easy to judge the behaviour of the VED device insert in the C-pipe structure. But it is evident that the fast increasing of the K value with the rise of the damping constant produce a saturation effect of the

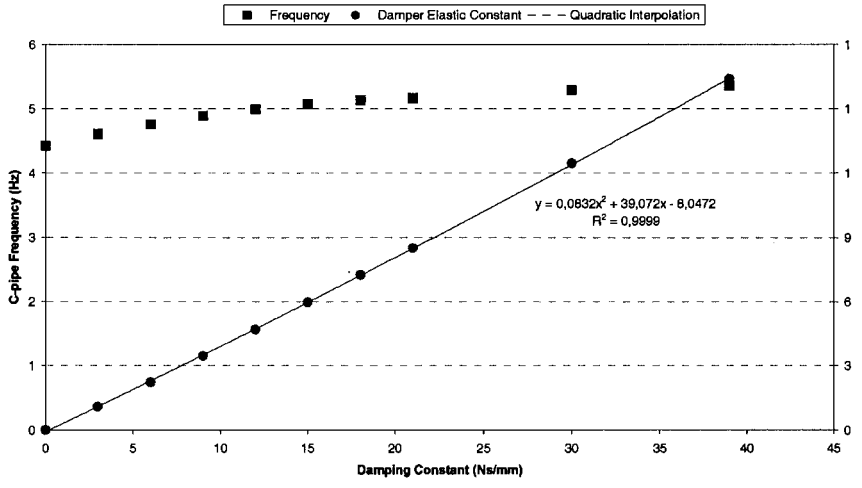

FIG.6 Mechanical Characteristic of VED Device

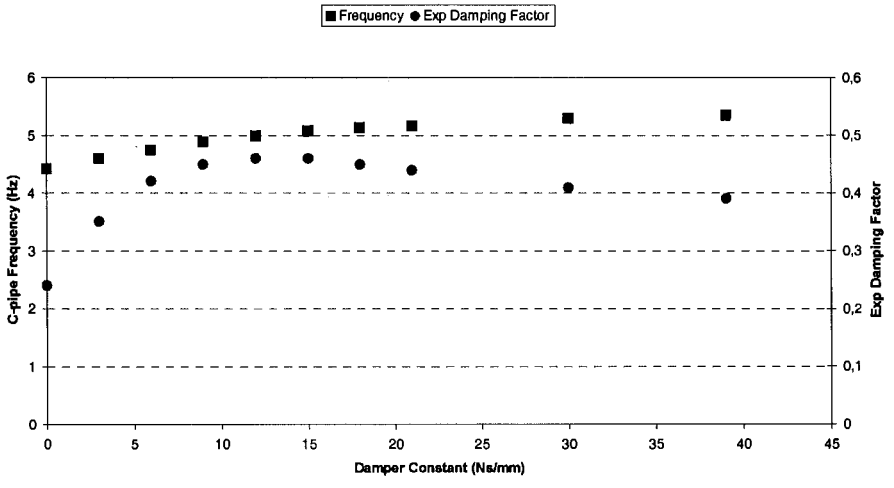

FIG.7 Damped modal analysis results for C-pipe structure with several VED device

device. With height stiffness value (K) the VED device has a behaviour similar to a rigid spar.
In Fig.8 the value of the fundamental frequency and of its exponential damping are shown versus the device damping constant of the VED device. A maximum damping efficiency of the structure as regards free oscillation corresponds to a damping constant of the device of 15 Ns/mm (C). There is no value of C for a maximum resonance damping efficiency, instead the damper effect on the structure tends to saturate with rising C.

In Table 3 the effect of the viscous elastic damper (VED) installed on the pipe elbow is summarized. Free oscillation time is considered the period taken to reach 1/10 of the starting displacement.

Table 2 – Comparison of the behavior of the C-pipe structure with the VED in optimal condition and without device

Pipe – 2nd elbow	No Damper	Viscoelastic Damper	Δ%
Resonance Maximum Stress (MPa)	212 (at 4.44 Hz)	125 (at 4.52 Hz)	-41%
Resonance Maximum Displacement (mm)	23 (at 4.44 Hz)	16.5 (at 4.52 Hz)	-28%
Free Oscillation Time (s)	6.75	4.04	-40%

VD Viscous Damper
We have considered a VD device. In this moment the device is in construction and so we can perform only a numerical campaign. The physical and mechanical data to be used in the FEM calculation are supposed. In any case the manufacturer suggested some data regarding dimensions and mechanical characteristics of the VED. The length of 3000 mm was chosen by the requirement of the manufacturer to have a damper elongation of several mm.
Lacking a precise characterization from the manufacturer, a simple linear dependence between force and speed was considered. Six different values for the damping constant were selected, from 10 to 50 Ns/mm. In fig.8 the results of the modal damped analysis on the C-pipe structure equipped by the six different VD devices are presented. The red curve illustrates the damping effect on the structure. It is evident that in this case the absolute value is grater than that obtained with the VED device (0,92 respect 0,48 N/s mm). Moreover above the device damping value of 20 Ns/mm, the damper effectiveness as regards the free oscillation doesn't improve anymore.

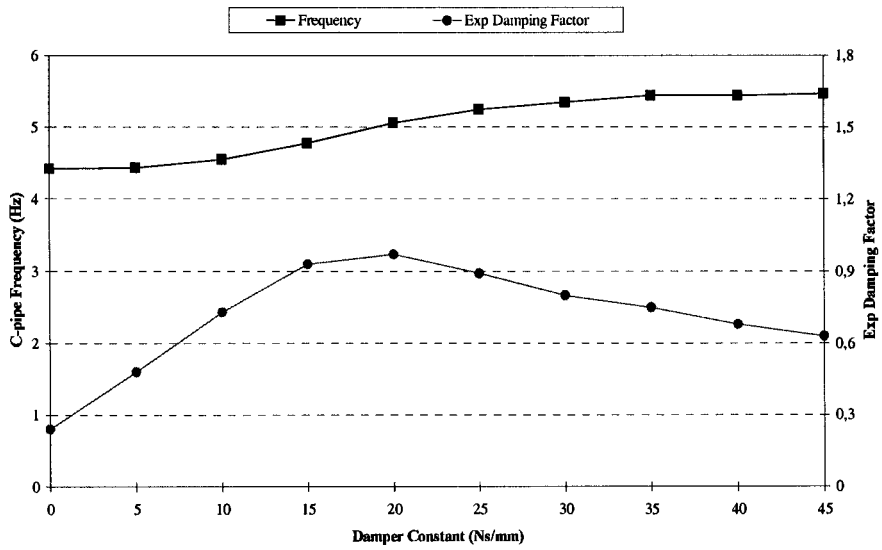

FIG.8 Resulting complex frequencies of the fundamental mode

Harmonic Response

A 1000 N sinusoidal force was applied to the free pipe end. The harmonic response of the structure, in the frequency range 3-

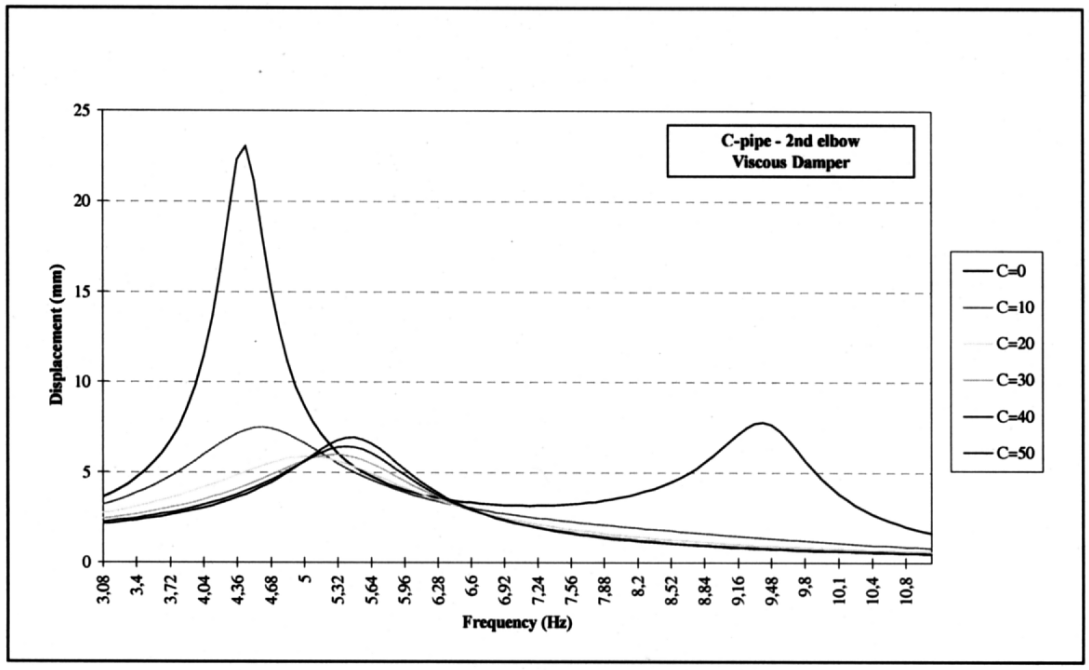

Fig.9 Harmonic response - Displacement

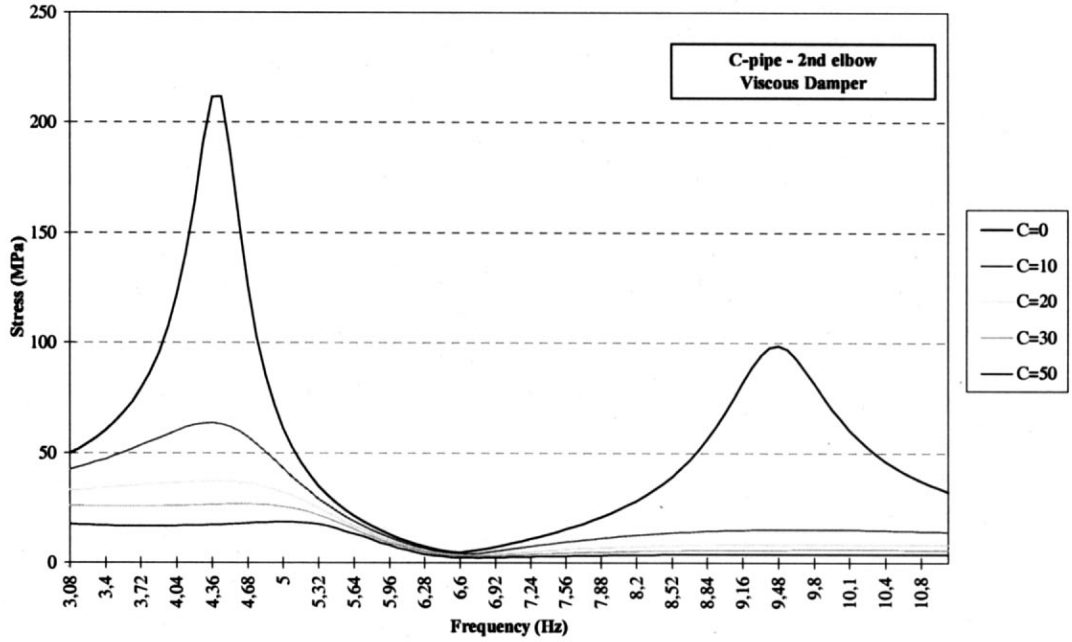

Fig.10 Harmonic response - Stress

11 Hz has been calculated in six different cases with a viscous damper constant variable from 10 to 50 Ns/mm. The values of displacement and stress in the 2nd pipe elbow are shown in Fig.9 and Fig.10, compared with the case of the pipe with no damper (correspond t C=0 curve).
From the figures it is clear that the use of the damper strongly and positively impacts both displacement and stress values. It is also evident that above 20 Ns/mm the damper has no more positive effect on displacements, and only a slight one on stress, confirming the conclusions from the damped modal analysis.
As a result of this analysis, a damping constant C=20 Ns/mm is chosen.
In Table 3 the effect of the viscous damper on the pipe elbow is summarized. Free oscillation time is considered the period taken to reach 1/10 of the starting displacement.

Table 3 – Comparison of the behavior of the C-pipe structure with the VD in optimal condition and without device

Pipe - 2nd elbow	No Damper	Viscous Damper	Δ%
Resonance Maximum Stress (MPa)	212 (at 4.44 Hz)	37.3 (at 4.44 Hz)	-82%
Resonance Maximum Displacement (mm)	23 (at 4.44 Hz)	5.9 (at 5 Hz)	-74%
Free Oscillation Time (s)	6.75	1.91	-72%

CONCLUSIVE REMARKS

From the comments to the figures and tables included in this paper it is evident the positive effect of dampers on piping. The large advantage of this device is represented by its capability to reduce the stress level and the dynamic response without any request of external structures. By positioning the device inside a bend and in its same plane the results discussed can be easily reproducible. Another positive aspect consists with the cost, taking into consideration that its price is not relevant and its procedure of application can be applied even at piping completely mounted or already in operation configuration.

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