Technical Note EST-ESI/97-03

MECHANICAL STABILITY OF PIPING SYSTEMS EQUIPPED WITH BELLOWS EXPANSION JOINTS

Blazej Skoczen[1] / EST

SMCM
Section of Mechanical Calculations and Measurements
EST/ESI

Abstract

Mechanical stability of pipelines containing both the single bellows and the universal expansion joints is discussed. Typical arrangement of guides and anchors for piping systems working at room and at low temperature is presented. Effect of relaxation of the support conditions on local buckling of pipe-bellows-pipe segments is analysed. Also, influence of imperfections (misalignment of pipes) is taken into account. Additionally, evolution of stability conditions when cooling down a pipeline is shown.

Geneve, August 1997

[1] Contribution of T. Kurtyka (EST/ESI) and C. Arnaud (EST/ESI) is gratefully acknowledged.

Contents

1. Introduction.

Mechanical stability of piping systems containing bellows expansion joints belongs to the subjects vividly discussed, especially in the context of cryogenic applications. A number of pipelines subjected to a combination of temperature variations and internal pressure turned out to be unstable as a result of either improper design of the expansion joints or improperly supported tubes. Effect of instability of a pipeline may be drastic: large lateral deformations often lead to a dynamic loss of tightness and may provoke an explosion in the pressurised system. Thus, appropriate design of the transfer lines containing expansion joints is a matter of safety.

The mechanism of instability is related to axial reaction occurring in bellows while subjected to internal pressure. The pressure tends to expand the bellows which, consequently, acts upon the neighbouring tubes and a global compression appears in the system. Since the flexural stiffness of bellows is much lower than the stiffness of the tubes the expansion joints may be regarded as elastic or elasto-plastic hinges. Such a system is in a natural way susceptible to buckling, especially if an imperfection (misalignment of tubes) exists. In order to protect a pipeline against buckling the system has to be well designed which means that:

- the expansion joints have to be properly defined,
- the pipes have to be properly supported.

The present note is dedicated to various design aspects of pipelines. First, a preliminary "rough" approach to design of systems containing bellows will be presented. Than, a more precise analysis leading to a non-standard design of piping systems with respect to their mechanical stability will be shown.

2. Preliminary design of pipelines - standard approach.

A standard approach to preliminary design of pipelines consists in the following steps:

1. building up a general layout of the piping system,
2. determining arrangement of the expansion joints,
3. determining design conditions according to the system operating procedures,
4. designing the bellows expansion joints with respect to minimum/maximum and installation temperature, internal/external pressure and media passing through,
5. determining arrangement of the anchors and guides,
6. verifying that the system components are not subjected to excessive forces.

This approach does not imply optimisation of either the expansion joints or the supporting system. Design of the expansion joints shall be carried out on the basis of the Standards of the Expansion Joints Manufacturers Association (EJMA) [1] or by using one of the national codes like CODAP, ASME, AD Merkblatter etc. The anchors and guides may be determined by using either the Standards of EJMA or recommendations contained in the books of bellows supplied by bellows manufacturers. An example of the guide spacing proposed by EJMA is shown in Fig.1.

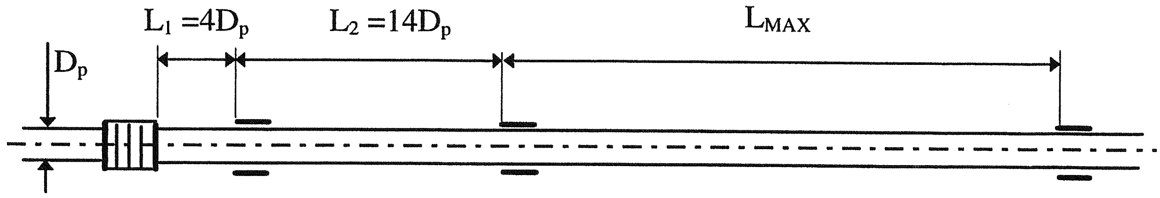

Fig.1 Guide spacing to EJMA [1]

Recommended distance of the two first pipe alignment guides with respect to bellows is fixed to 4 and 14 nominal diameters, respectively. Spacing of all other guides is determined with respect to the nominal diameter and maximum pressure by using special charts. The recommendations are intended to prevent the pipe system from buckling and failure. It is worth pointing out that the recommended guide spacing depends very much on the expansion joint manufacturer and not all of them apply the EJMA rules.

The guides shall provide both the lateral and the angular support to the piping system. Guide clearances shall be kept to a practical minimum in order to limit lateral and angular displacements. A typical guide arrangement for high temperature applications is shown in Fig.2.

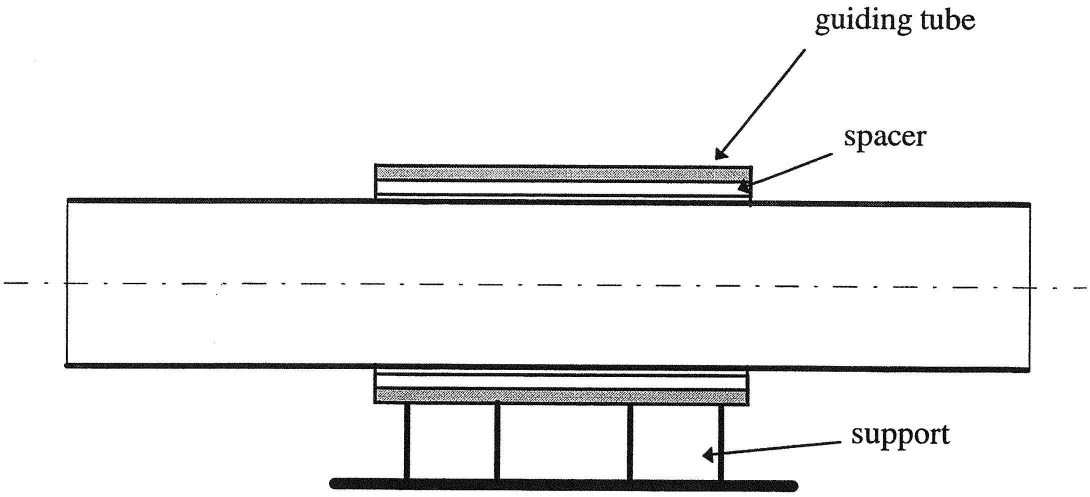

Fig.2 Standard high temperature guide arrangement.

The problem seems to be more complex in cryogenic applications. In order to avoid creation of thermal bridges the contact surfaces between the pipeline segments and the guides shall be restricted to a necessary minimum. An example of arrangement for cryogenic applications which fulfils the conditions of lateral and angular guidance is presented in Fig.3.

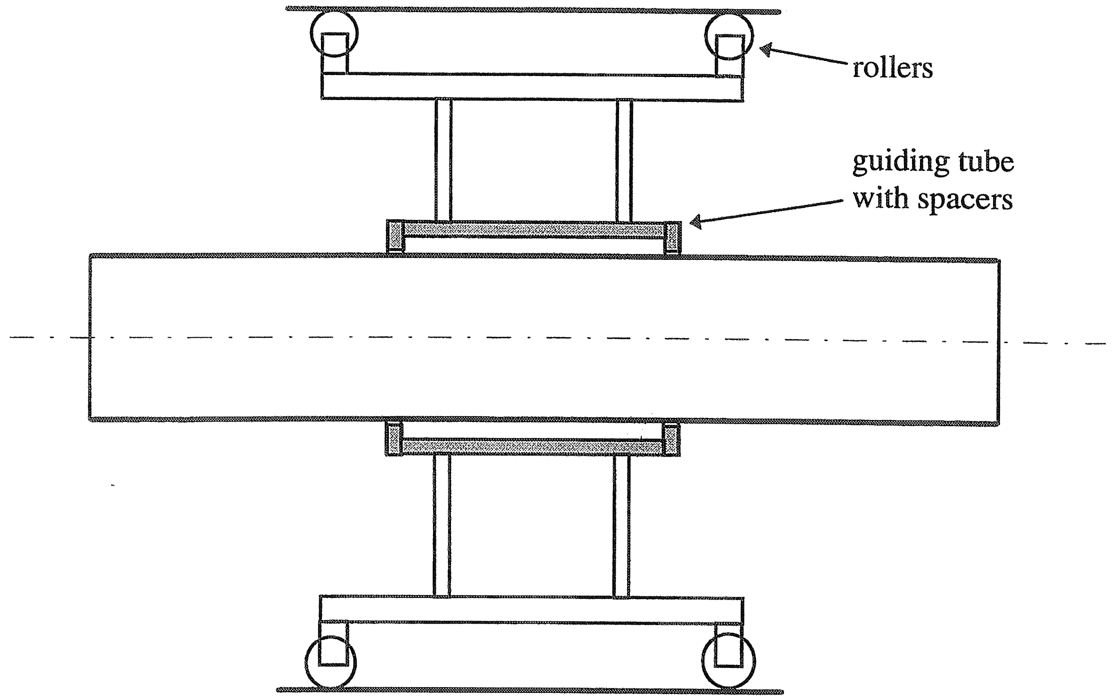

Fig.3 Example of guide arrangement for cryogenic applications.

3. Mechanism of local instability in pipelines.

Local instability in pressurised pipelines may have two sources:

1. insufficient stiffness of the bellows expansion joint ("weak" design),
2. improper arrangement of anchors and guides (relaxation of the support conditions).

In the first case it is the expansion joint that buckles under internal pressure (Fig.4a) whereas in the second case it is a pipeline segment (tube-bellows-tube) which loses stability (Fig. 4b).

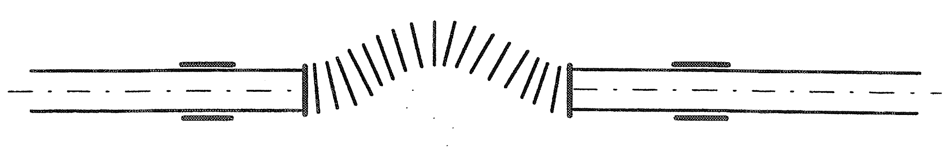

Fig.4a Buckling of bellows.

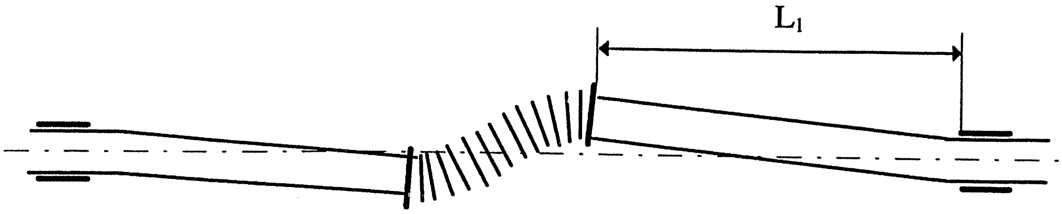

Fig.4b Buckling of a pipeline segment.

The latter is usually provoked by the bellows-support distance (L_l) which often turns out to be large enough to allow buckling (relaxation of the support conditions).

Local instability in pipelines may be analysed by using the equivalent column model (Fig.5). The expansion joint is represented by a column of axial, lateral and angular stiffness equivalent to the bellows stiffness. The elastic support of the equivalent column (system of springs) represents the pipeline segments of length L_{p1}, L_{p2} situated between the bellows and the closest guides. The larger distance L_{pi} the weaker support of the bellows ends which is in the model reflected by reduced stiffness of springs.

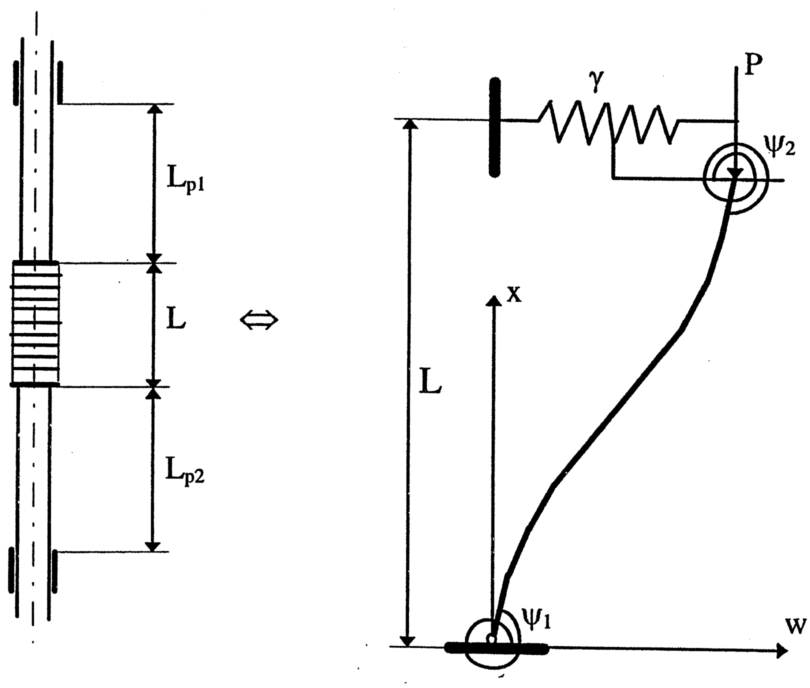

Fig.5 The equivalent column with elastically supported ends.

The stiffness of each of the angular springs (k_1, k_2) is equal to the flexural stiffness of the pipe segments, respectively:

$$k_1 = \frac{(EI)_1}{L_{p1}}, \quad k_2 = \frac{(EI)_2}{L_{p2}}, \tag{1}$$

whereas the stiffness of the lateral spring (c) has been defined as equivalent to lateral stiffness of the pipeline segments (c_1, c_2):

$$c = \frac{c_1 c_2}{c_1 + c_2}, \tag{2}$$

where

$$c_1 = \frac{3(EI)_1}{L_{p1}^{\ 3}}, \quad c_2 = \frac{3(EI)_2}{L_{p2}^{\ 3}}. \tag{3}$$

The definition of c is based on the assumption of an identical post-buckling form for the model with two lateral springs and the model with one lateral spring. For simplicity the non-dimensional parameters ψ_1, ψ_2, γ are introduced:

$$\psi_1 = \frac{k_{bellows}}{k_1}, \quad \psi_2 = \frac{k_{bellows}}{k_2}, \quad \gamma = \frac{2c_{bellows}}{3c}. \tag{4}$$

These parameters were used to formulate the appropriate boundary conditions for the column and to solve the eigenvalue problem (cf. [2]) which takes the form of the following transcendental equation:

$$\begin{gathered} 2 - \left[2 + (\psi_1 + \psi_2)(1 - \gamma k^2 L^2)k^2 L^2\right]\cos(kL) + \\ \left[-1 + \psi_1 + \psi_2 + k^2 L^2 (\psi_1 \psi_2 + \gamma - \gamma \psi_1 \psi_2 k^2 L^2)\right] kL \sin(kL) = 0 \end{gathered} \tag{5}$$

where kL are the eigenvalues. Having solved the above equation for eigenvalues one arrives at the equivalent length of the column:

$$L_r = \mu L, \tag{6}$$

which depends on the initial length L and on the parameter μ calculated as

$$\mu = \frac{\pi}{kL}. \tag{7}$$

Now, using the Euler equation

$$P_{cr} = \frac{\pi^2 B}{L_r^{\ 2}}, \tag{8}$$

where B denotes the flexural stiffness of the column, one may calculate the critical buckling force for the perfect column with the elastic support of the ends.

The Euler critical force may be converted to the instability pressure for the real bellows by using once again the equivalent column concept (cf. [3]). The bellows post-buckling forms are assumed to be identical with the post-critical forms of the column, provided that the support conditions are the same. Relation between the bellows critical pressure and the critical Euler force is as follows:

$$p_{cr} = \frac{P_{cr}}{\pi R_m^{\ 2}}, \tag{9}$$

where R_m denotes the bellows mean radius. Finally the buckling pressure is given by the equation:

$$p_{cr} = \frac{\pi B}{L_r^2 R_m^2} = \frac{\pi B}{\mu^2 L^2 R_m^2} \ . \tag{10}$$

4. Numerical analysis of local instability in a pipeline (String I, line C).

An example of local instability in a pressurised pipeline equipped with bellows expansion joint was observed in String I with respect to line C (Fig.6). The free length of pipes (distances from bellows to the closest supports) were equal to 2484 mm and 2584 mm, respectively. Since the difference in length of pipes is not significant the symmetric model ($L_{p1}=L_{p2}$) is considered. The multiply expansion unit of convoluted length of 115 mm was composed of 18 convolutions.

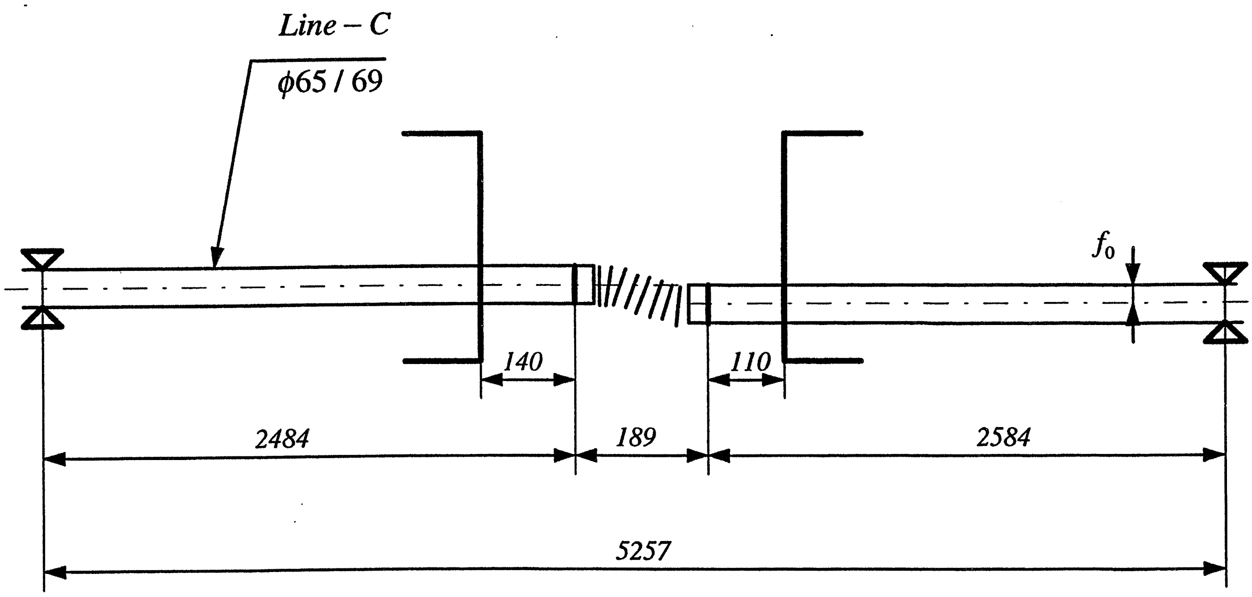

Fig.6 Piping system containing bellows (initial offset f_0).

Numerical solution to the buckling problem was obtained for the range of bellows - guidance distances between 0 and 5000 mm. The solution is presented in Fig.5 in terms of two branches associated with two instability modes:

- branch I - buckling of bellows convolutions (see Fig.4a),
- branch II - local buckling of piping system (see Fig.4b).

Change of active solution branch (always the lower one) at 400 mm causes a rapid decrease of instability pressure. In particular, for the bellows-guidance distance of 2500 mm the buckling pressure drops to around 15.7 bar.

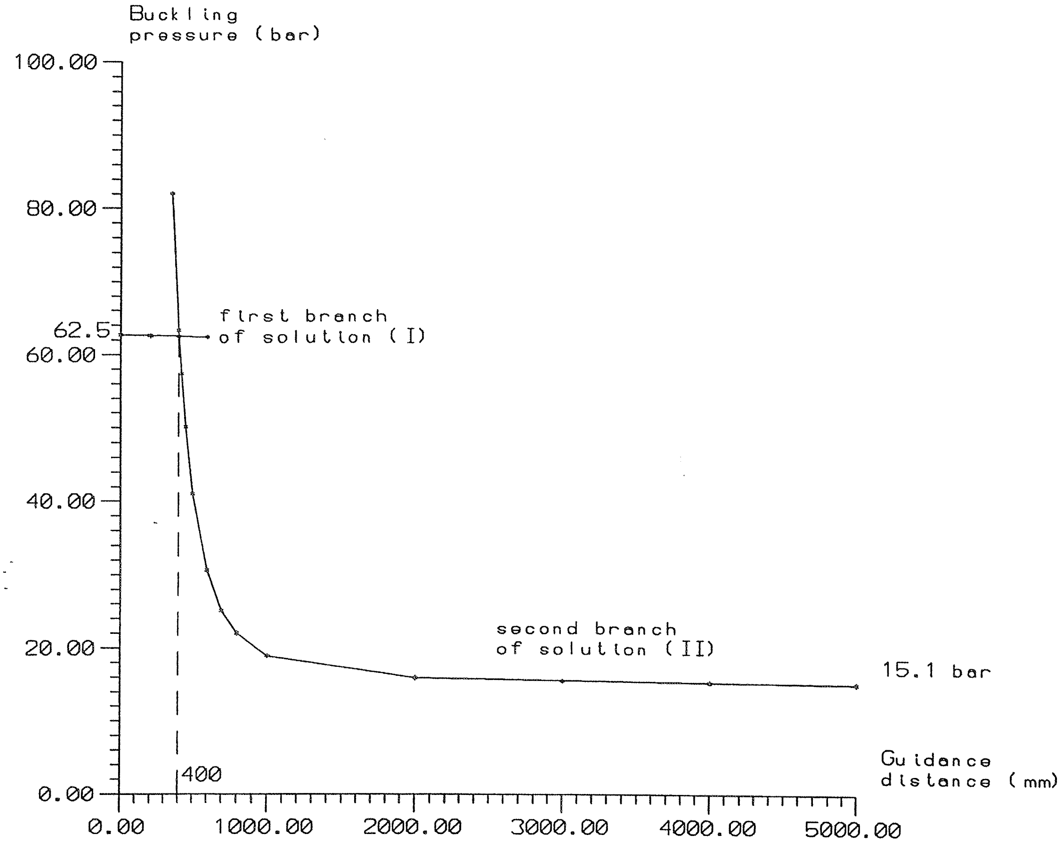

Fig.7 Solution to the problem of local buckling of piping system.

However, the above presented analysis is valid for the bellows-guidance distances not very large (here less than 1000 mm) and is aimed at showing the effect of relaxation of the support conditions on the dramatic drop of buckling pressure for a pipeline. Here we find also an explanation to the $L_l=4D_p$ rule (see Fig.1).

5. Pipelines with large bellows-guidance distances.

The above discussed model (see Fig.5) can not be applied to the analysis of non-standard piping systems supported far from the bellows ends. One finds the examples of such systems among the cryogenic lines where it is of primary importance to reduce the number of thermal "bridges" between the pipeline and the cryostat.

A mechanical model that allows us to predict the critical pressure for the large bellows-guidance distances is based on the mode of buckling shown in Fig.4b. Since the deformed bellows resembles letter "S" - there are two zones of bending and the intermediate straight zone - it may be substituted with two angular springs linked with a centre spool. The model is shown in Fig.8.

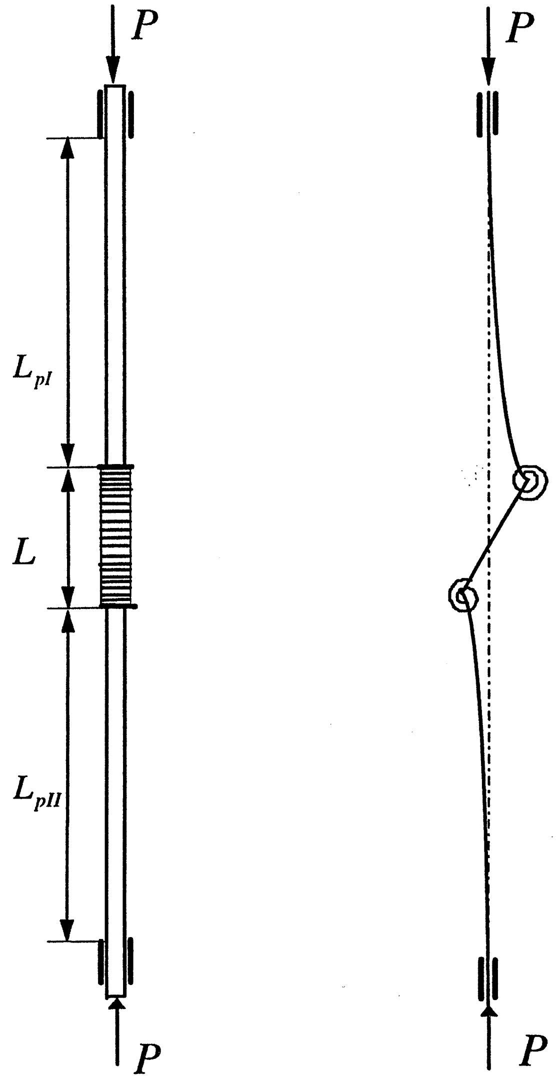

Fig.8 The equivalent column for large bellows-guidance distances.

Analysis based on the above presented model leads again to an eigenvalue problem expressed by the following transcendental equation:

$$\lambda_{II}\frac{L_{II}}{M_{II}}+\lambda_{I}\frac{L_{I}}{M_{I}}-1=0, \qquad (11)$$

where:

$$L_i=\frac{\Gamma_i}{X_i}(1-\cos X_i)+\sin X_i(1-\Gamma_i)-X_i\cos X_i\ , \qquad (12)$$

$$M_i=\Gamma_i\sin X_i+X_i\cos X_i\ ,\ i=I,II\ . \qquad (13)$$

Also, the following parameters were defined:

$$\lambda_i = \frac{L_{pi}}{L} \ , \ \Gamma_i = \frac{k_{bellows}}{k_i} \ , \ k_i = \frac{(EI)_i}{L_{pi}} \ , \tag{14}$$

as well as the eigenvalues:

$$X_i = \sqrt{\frac{P}{(EI)_i}} L_{pi} \ , \ X_{II} = \eta X_I \ , \ \eta = \sqrt{\frac{I_I}{I_{II}} \frac{L_{pII}}{L_{pI}}} \ , \ i = I, II \ . \tag{15}$$

Buckling mode is entirely determined by the eigenvalues X_I and X_{II}.

The above presented analysis can be directly applied to the problem of local buckling in the pipeline, discussed already in the previous pages. In this way one obtains a correction to the existing solution (Fig.7) which is shown in Fig.9.

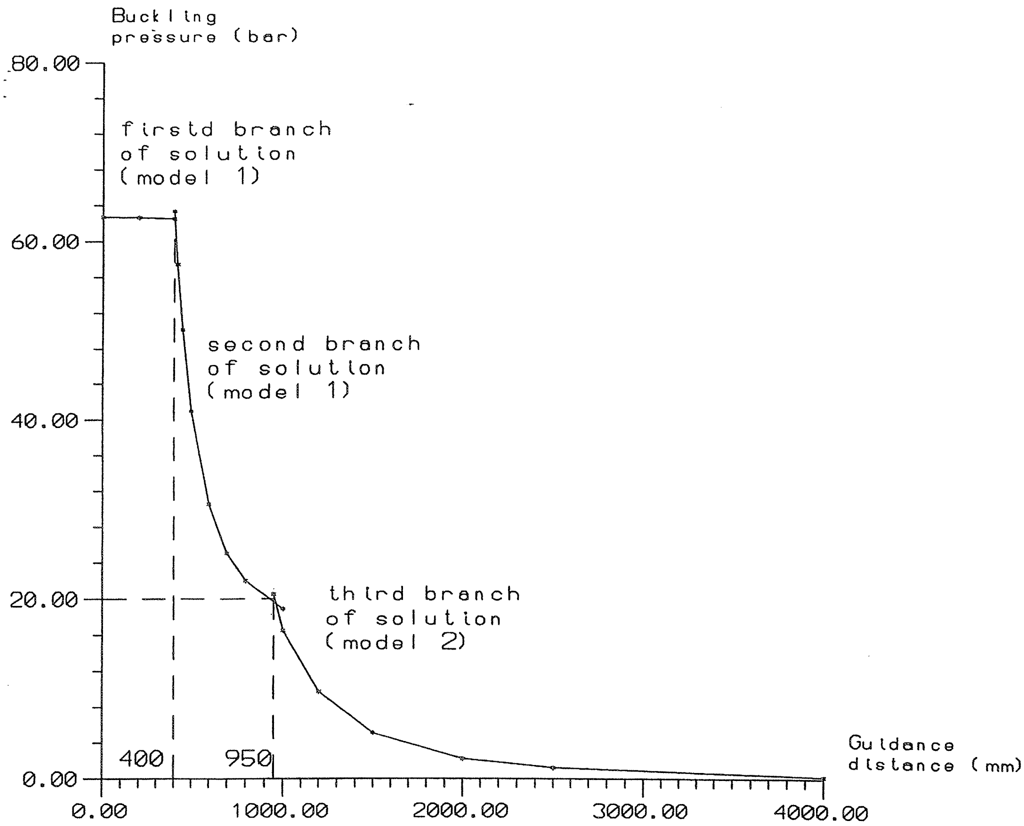

Fig.9 Correction of the previous model for larger bellows-guidance distances.

Now it becomes clear that the susceptibility to buckling increases dramatically with the bellows-guidance distance. This susceptibility is generally amplified by the presence of imperfections (misalignment of pipes) which are inevitably observed in pipelines. Thus, proper positioning of the anchors and guides as well as an appropriate clearance are of primary importance for stability of pipelines.

6. Piping systems equipped with universal expansion joints.

Universal expansion joints are often used in the piping systems where large lateral movements are expected. In order absorb these movements a structure composed of two bellows and a centre pipe spool is applied (Fig.10).

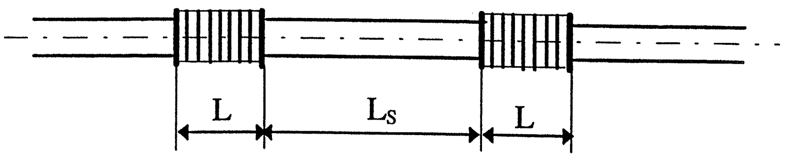

Fig.10a Universal expansion joint.

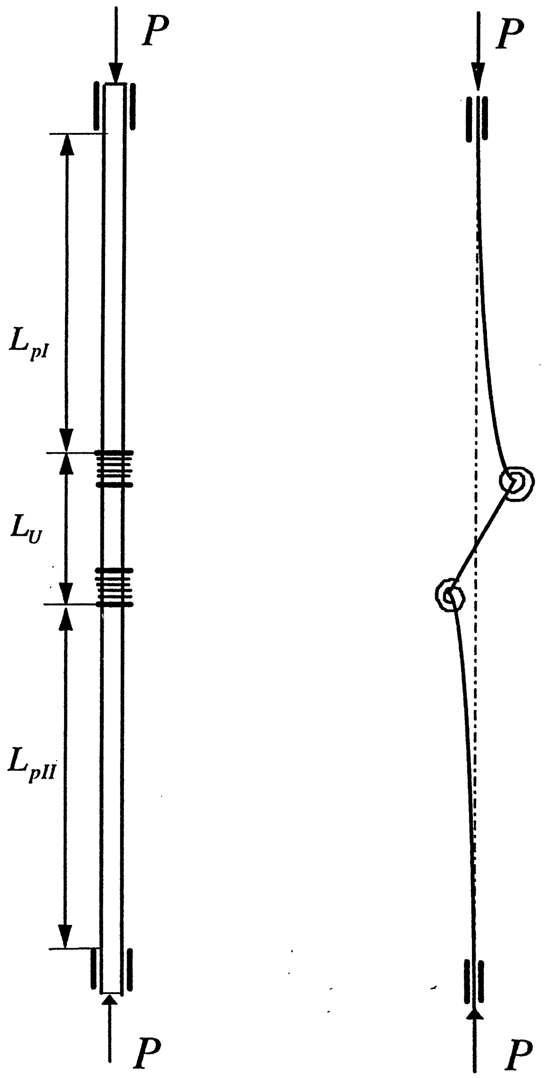

Fig.10b Model of pipeline containing a universal expansion joint.

Generally, the pressurised universal expansion joints are less stable than the standard single bellows unless equipped with a special hardware to stabilise the joint. Stability analysis of a pipeline containing a universal expansion joint is based on a similar model (Fig.10b) to this presented in Fig.8. It means that a universal joint may be regarded with sufficient accuracy as a single bellows of length L_U. Solution to the same eigenvalue problem (cf. equations 11 through 15) leads to estimation of the critical buckling pressure for the system containing universal joint.

7. Effect of imperfections on local instability in pipelines.

Designers of piping systems are usually confronted with the problem of installation tolerances and imperfections. The most common imperfections in pipelines are misalignments leading to offset of the bellows ends (f_0).

An imperfect pipeline does not lose its stability in the classical sense since the standard (basic) notion of buckling is related to the perfect structures. However, an imperfect pressurised pipeline develops a lateral deformation from the very beginning of the pumping procedure.

In order to calculate the admissible pressure for an imperfect pipeline with locally existing offset f_0 one may apply a linear approach which leads to the following simplified formula:

$$P(f) = \left(1 - \frac{f_0}{f}\right) P_{cr} \qquad (16)$$

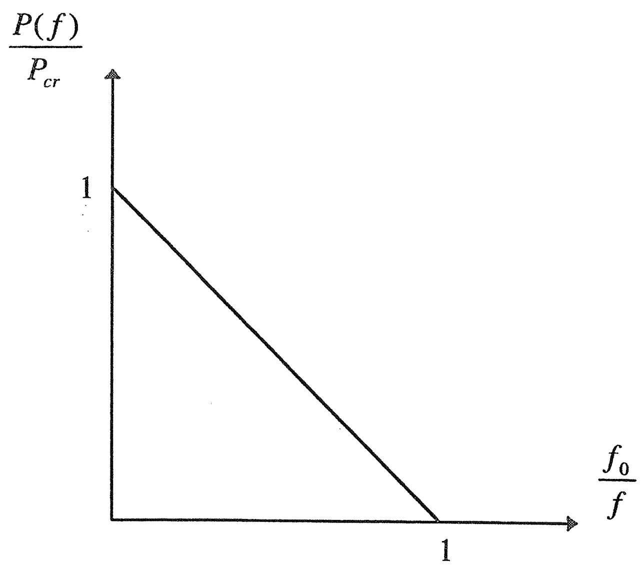

Fig.11 Effect of imperfections on buckling of linear systems.

Here P_{cr} denotes the classical buckling force (pressure) and f denotes the admissible lateral deformation, $P(f)$ stands for the force (pressure) which produces deformation f in the imperfect pipeline segment. In other words the force of $0.5P_{cr}$ is needed in order to double the initial deformation of the system. This approach, however simple, gives a good estimation of the effect of imperfections on the local deformation of a pipeline.

8. Cryogenic piping systems - stability at low temperature.

Service conditions of the cryogenic pressurised pipelines are usually determined by three phases:

- cool-down with simultaneous pumping of cold medium,
- stable work at low temperature,
- warm-up with or without pressure in the system.

Mechanical stability of pipelines is determined by the length and stiffness of tubes, arrangement of anchors and guides as well as by the dimensions and stiffness of the expansion joints. It is the stiffness of the expansion joints which may evolve considerably with temperature variations leading to a change in bellows-to-pipe stiffness ratio.
The axial/lateral/angular effective stiffness of bellows expansion joint is associated with the corresponding movements which may lead to a local plastification of the bellows wall. As a result a hysteresis in terms of force (P) and displacement (Δ) is observed (Fig.8). The effective secant stiffness is defined as:

$$F_{ef} = \frac{\overline{AB}}{\overline{0B}}.$$

Since the yield strength for stainless steels (316L, 304L) at 4K is about twice as large as at room temperature the plastic strain fields develop at 300K rather than at 4K (Fig.12a,b). The energy dissipation at 4K is much smaller for a given stroke (+Δ, -Δ) and the bellows wall remains nearly elastic. This implies higher stiffness of expansion joint and better stability of the pipeline.

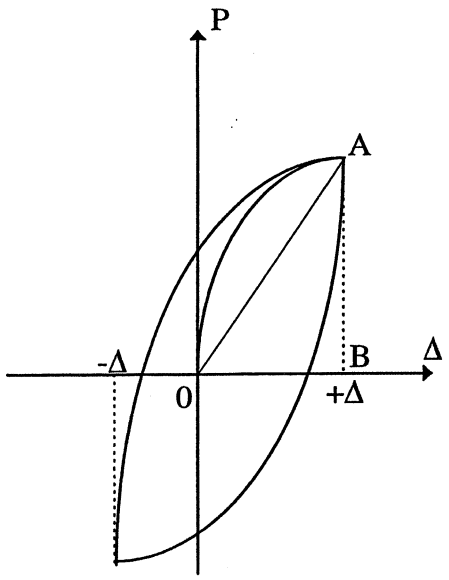

Fig.12a Hysteresis at room temp.

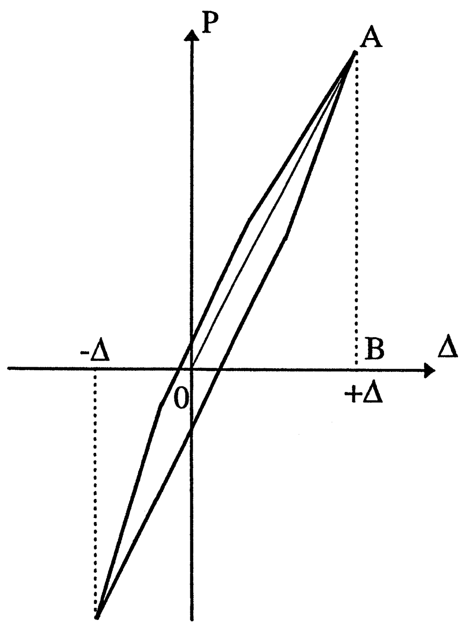

Fig.12b Hysteresis at low temp.

9. Final remarks.

- A special attention should be paid to both the local and the global stability of the pressurised piping systems containing bellows expansion joints.
- Typical arrangement of guides and anchors is given by the international standards like EJMA [1] as well as by the expansion joint manufacturers (books of bellows).
- A non-standard arrangement of guides and anchors for the cryogenic pipelines shall become object of careful mechanical stability analysis in order to protect the system against buckling.
- Conservative approach to mechanical stability of pressurised cryogenic pipelines consists in verifying buckling conditions at room temperature for the complete set of loads (pressure, axial, lateral and angular movements due to temperature variations, mechanical imperfections) as if the system was working entirely at 300K.

References.

1. Standards of the Expansion Joint Manufacturers Association, Inc.(EJMA), sixth edition, New York 1993.
2. M. Zyczkowski et al., “Strength of structural elements”, PWN / ELSEVIER, Warszawa 1991.
3. B. Skoczen et al., “Effect of torsion on buckling of the interconnection bellows for LHC”, Technical Note MT-ESH/95-07.

DISTRIBUTION TECHNICAL NOTE EST-ESI/97-03

B. Skoczen / EST

BONA M.	/ LHC
BRUNET J.C.	/ LHC
CLAUDET S.	/ LHC
CRUIKSHANK P	/ LHC.
DAUVERGNE J-P.	/ LHC
DURET M..	/ LHC
ERDT W.	/ LHC
FAUGERAS P.	/ LHC
GROBNER O.	/ LHC
LEBRUN P.	/ LHC
LEPEULE P.	/ LHC
MOURON G.	/ LHC
PARMA V.	/ LHC
PONCET A.	/ LHC
ROHMIG P.	/ LHC
RUSSENSCHUCK S.	/ LHC
SAVARY F.	/ LHC
TAVIAN L.	/ LHC
TISCHHAUSER J.	/ LHC
VAN WEEDEREN R.	/ LHC
VENESS R.	/ LHC
VLOGAERT J.	/ LHC
WILLIAMS L.	/ LHC
WYSS C.	/ LHC
GEBART R.	/ PPE
HATCH M.	/ PPE
HAUVILLER C.	/ PPE
HERVE A.	/ PPE
NICQUEVERT B.	/ PPE
ONNELA A.	/ PPE
PAILLER P.	/ PPE
PLACCI A.	/ PPE
PRICE M.	/ PPE
ROSSO E.	/ PPE
VUILLEMIN V.	/ PPE
WOTSCHACK J.	/ PPE
EVANS L.	/ DG
CATINACCIO A.	/ TIS
MARGAROLI C.	/ TIS
SZELESS B.	/ TIS
ACHARD C.	/ EST
ANDREEV N.	/ EST
ARNAUD C.	/ EST
BACHY G.	/ EST
BENVENUTI C.	/ EST
BOSTEELS M.	/ EST
BOURQUIN p.	/ EST
CAMERON W.	/ EST
GENEST J.	/ EST
GENET M.	/ EST
GIRARD-MADOUX F.	/ EST
GRUNHAGEL C.	/ EST
GUSEWELL D.	/ EST
JACQUEMOD A.	/ EST
JENNY B.	/ EST
KURTYKA T.	/ EST
LEISTAM l.	/ EST
MATHIEU M.	/ EST
NEMOZ H.	/ EST
PATTI G.	/ EST
POTTER K.	/ EST
QUESNEL J-P.	/ EST
RENAGLIA T.	/ EST
REY R.	/ EST
REYMERMIER C.	/ EST
ROHNER F.	/ EST
TRILHE P.	/ EST
VALBUENA R.	/ EST
VEILLET N.	/ EST
WETERINGS W.	/ EST
WIKBERG T.	/ EST
GODOT J-C.	/ PS