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Abstract

Since the beginning of the 21st century FFlow-Induced Pulsations (FLIP) has been more and more experienced. The phenomenon is characterized by an acoustic wave that is created inside of the flexible pipe and that may lead to significant fatigue failure of the adjacent equipment. Flexible pipe integrity is not called into question regarding this phenomenon.

In this context, a FLIP joint test involving an Oil Company, a Flexible Pipe supplier and a French research center was conducted end of 2016 at French laboratory in Poitiers. The test was performed in a 6'' internal diameter and 18-meter-long flexible pipe. Both flow directions were tested to assess the influence of the rounded edges of the carcass.

On the one hand, this paper presents the experimental test setup and the main results that came out of the test. On the other hand, this paper also presents the comparison between tests results and analytical model outcome. Moreover, combining experiments and theoretical point of view enabled reproducing the phenomenon. A better understanding of the phenomenon will allow flexible pipes suppliers to propose mitigations or cancellation of FLIP to companies.

Introduction

Since the early 2000's natural gas platforms were more and more subject to Flow Induced Pulsations (FLIP). Moreover, Oil&Gas Companies requirements in terms of flow rates have been increasing each year growing up since the first FLIP experience and for the last few years natural gas field exploitation is drastically increasing. In this context, a partnership between an Oil Company, a Flexible Pipe supplier and a French research center was created at the beginning of 2016 to set up a FLIP test on an industrial scale. This partnership allows on the first hand the Oil Company a better understanding of FLIP phenomenon and on the other hand allows the Flexible Pipe supplier to improve their flexible pipe carcass design. A French laboratory in Poitiers was qualified to perform this FLIP test, because of their knowledge in acoustics, aero-acoustics and adapted air test facilities. This collaboration aimed at studying the influence of flow direction and pressure (i.e. density) on FLIP onset velocities and frequencies. The present paper presents the whole test campaign, test setup and test results versus predicted values.

Context

FLIP only concerns:

1. Rough bore flexible pipes (i.e. gas export, gas lift and flowline): see Figure 1.
2. Dry gas flows, with less than one percent in volume of free liquid phase
3. All kind of flexible pipes configurations (i.e. lazy-wave, free-hanging etc ...)

As a reminder, the so-called FLIP phenomenon may be characterized by high tonal noises up to 110 dB on platforms resulting in high vibrations levels of small piping either on topsides or on subsea equipments. This phenomenon was first experienced on Norwegian platforms in early 2000 and lazy wave rough bore flexible pipe had to be replaced by a patented solution: The Smooth Bore Gas Export (SBGE) [Ref. 1]. The SBGE has an inner surface completely smooth because of the plastic liner that is the first layer instead of a classic interlocked carcass.



Figure 1 – Typical rough bore flexible pipe build up

FULL SCALE TEST

Test description:

The test was prepared and conducted in 2016 at a French laboratory in Poitiers which is a facility to conduct air flow tests. The first aim of the test was to reproduce and experience the singing phenomenon in an actual flexible pipe with real end-fittings. The second aim of the test was to study the influence of the flow direction and pressure on the initiation of the singing. To achieve these two main goals different mass flow rates and different pressures had to be tested with dry air. Test facility is presented in Figure 2.



Figure 2 – Overview of the test facility

Tested flexible pipe was eighteen meters-long with an internal diameter of six inch. Because of its length not all laboratories were able to receive such flexible pipe and adjacent measuring spools, with a total length of approximately forty meters.

Test monitoring:

To achieve the test campaign different sensors were utilized to capture the singing phenomenon. At the downstream and upstream end-fittings two measuring spools were attached. Each measuring spool was equipped with (see Figure 3):

1. Acoustic probes microphones
2. Acoustic probes
3. Hot wire probes
4. Static pressure probes
5. Temperature probe



Figure 3 – Measuring spool equipped with its probes

Figure 4 shows a cross-section of the flexible pipe between its measuring system that includes acoustic probes microphones (MG_i with i going from 1 to 6) and hot wire probes. Acoustic probes microphones were installed in line on the top of the measuring spools and hot wire probes were installed at 90° from the acoustic probes microphones. Since pressure and velocity are dual quantities measuring them respectively thanks to acoustic and hot wire probes enables a complete understanding of the nature of the acoustic wave.

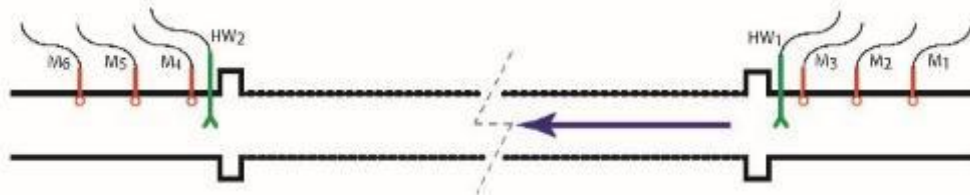


Figure 4 – Sketch of measuring system (acoustic and hot wire probes)

Full scale test setup:

Figure 5 presents a sketch of the test setup, air was flowing out of the pressurized reservoir inside different pipings (approximately forty meters) before reaching the first acoustic measuring spool and flexible pipe. Pressure levels inside of the flexible pipe were controlled thanks to a pressure control valve as shown in Figure 5. To fulfill the test setup mass flow rate had to be imposed at a fixed value, pressure was swept from high value down to small values to get an increasing flow velocity inside of the flexible pipe.

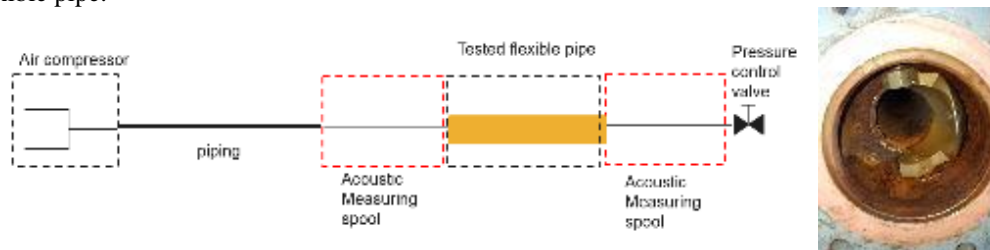


Figure 5 – Test setup overview and pressure control valve

Table 1 describes the range of pressure and mass flow rate tested.

	Q_m [$\text{kg}\cdot\text{s}^{-1}$]	P [bar]	ρ [$\text{kg}\cdot\text{m}^{-3}$]
Mini	0	1	1.2
Maxi	8.3	40	46

Table 1 – test matrix

More than thirty triplets (P, T, Q_m) have been tested.

Flexible pipe was installed straight on its support such as shown in Figure 6.



Figure 6 – Flexible pipe in test

Test results:

Fluctuating signals post-processing

Two hot-wires (HW1 and HW2, See Figure 4) are positioned on the axis of each coupler located just upstream and downstream of the rough bore flexible pipe. These probes are sensitive both to velocity turbulence and acoustics velocity. They detected the emergence of FLIP from the turbulence background with increasing flow rate. Figure 7 illustrates the evolution of the Power Spectral Density (PSD) estimated from velocity hot-films signals when the reference velocity increases from 50 to 70 m.s⁻¹. Upstream hot-wire signal PSDs display many frequencies, associated with the supplying system including air compressor and some bends on the upstream piping. Whereas these large peaks are not detected anymore on the PSDs of downstream hot-wire signal HW2, sharp peaks are highlighted when the velocity reaches around 60 m.s⁻¹. These singular frequencies (1250, 2150, 2600 Hz) are related to the FLIP phenomenon and are confirmed by the following acoustic pressure analyses.

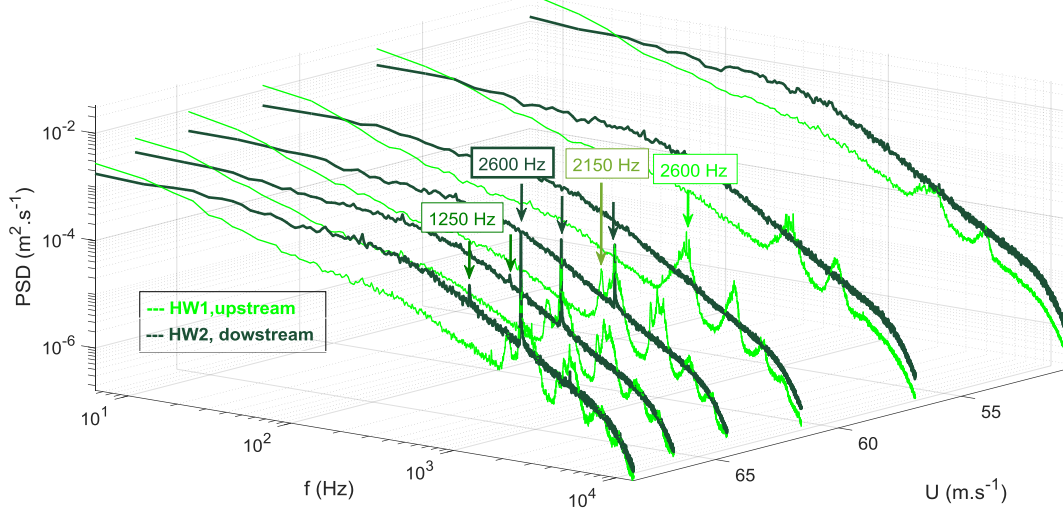


Figure 7 -- For an 80° aperture of control valve - PSD of velocity signals from upstream and downstream hot-wires (test 13, 1.1bar < P_{upstream} < 1.6 bar)

Simultaneous acquisitions of microphone signals (MG_i) are performed with hot-wire signals so that velocity and acoustic pressure can be jointly analysed. The post-processing of recorded acoustic signals reveals that, during the FLIP, the strong acoustics field (170 dB SPL) inside the riser is associated with frequencies identified as the transverse acoustic resonance of the pipe (i.e. 1250 Hz, 2110 Hz and 2650 Hz). The specificity of the FLIP in the present investigated conditions is the significant intermittency in time and frequency of this sound field. Therefore, Gabor-wavelet tools are used to investigate time-frequency characteristics (Figure 8), while Hilbert transform analysis aims at catching the fine structure of the whistling (Figure 9).

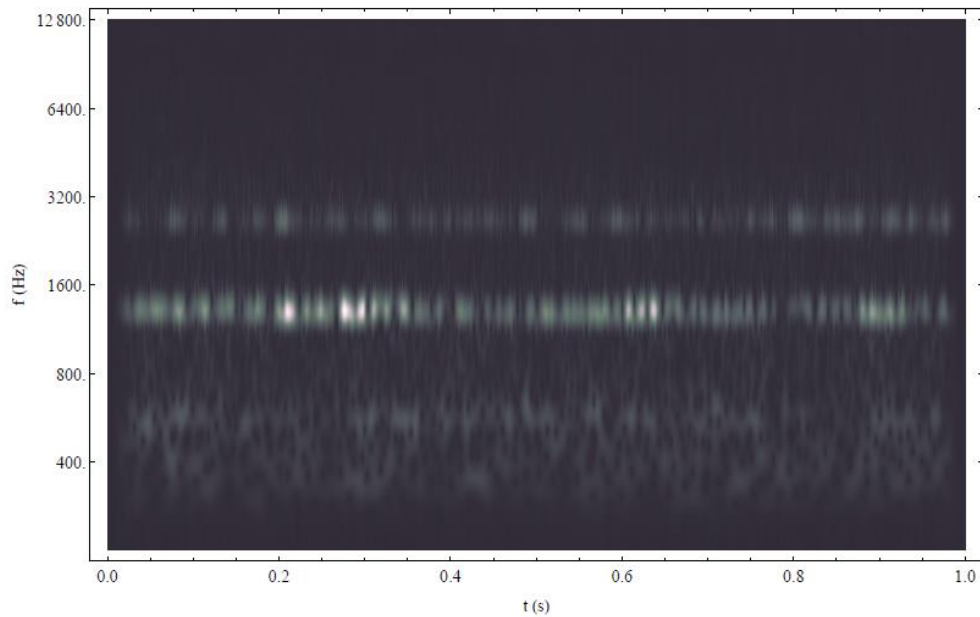


Figure 8 – Gabor analysis during maximum whistling recorded on microphone MG₆

The Gabor wavelet time-frequency analysis (Figure 8) clearly shows that the acoustic signal is composed of two main frequency components around the first transverse modes of the riser (i.e. 1250 Hz and 2500 Hz for a riser with constant radius $R=7.62$ cm). It is also obvious that this whistling process has significant variations in time and frequency. To complete the analysis, a Hilbert transform of the signal filtered around the first mode is applied to compute its instantaneous frequency [Ref 3]. The result is given in Figure 9 for the signal of the microphone MG_4 . In that case, the amplitude is normalised to the maximum recorded during that interval and the curve is plotted with a varying intensity of the shades of grey corresponding to its amplitude in Figure 9. The intermittency on amplitude and frequency is highlighted and one observes that higher amplitudes are associated to lower frequency excursions. Note that the frequency fluctuates around that of the first transversal mode ($f \in [1190; 1290]$ Hz) with a fluctuation corresponding quite exactly to the variation of the inner radius caused by the corrugation ($R \in [7.4; 8.1]$ cm).

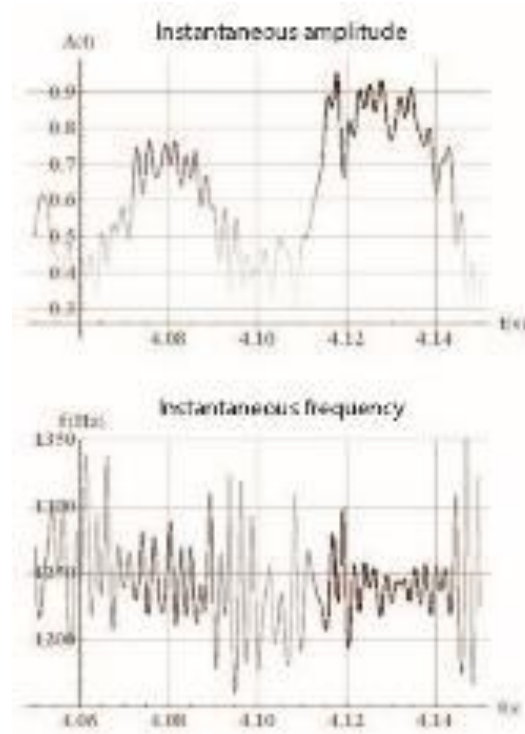


Figure 9 – Instantaneous amplitude and frequency during the whistling phase recorded on microphone MG_4 .

Post-processing via pressure loss analysis

Complete signals post-processing is not necessarily mandatory to detect FLIP onset. Measuring pressure difference between inlet and outlet of the flexible pipe allows quantification of the total energy loss along the flexible pipe. The total energy loss may include viscous, thermal, acoustic and radiated losses depending on whether FLIP is already initiated or not. Thermal losses are negligible relative to of other losses and since amplitude acoustic reflection coefficient were close to unity, radiated losses are close to nul. Therefore, if the measured pressure drop is greater than the pre-estimated viscous losses one may tell that FLIP is initiated. Viscous losses are calculated thanks to an in-house model. This statement may be expressed as follows:

$$FLIP \text{ occurs if } \Delta P_{measured} > \Delta P_{viscous}.$$

Figure 9 shows the application of this concept by plotting $\Delta P_{measured} - \Delta P_{viscous}$ versus average flow velocity. It may be noticed that as long as FLIP is not initiated $\Delta P_{measured} - \Delta P_{viscous}$ remains quasi-constant and almost equal to 0 J/m³. $\Delta P_{measured} - \Delta P_{viscous}$ is not exactly equal to zero as long as FLIP is not initiated because all parameters are averaged along the flexible pipe.

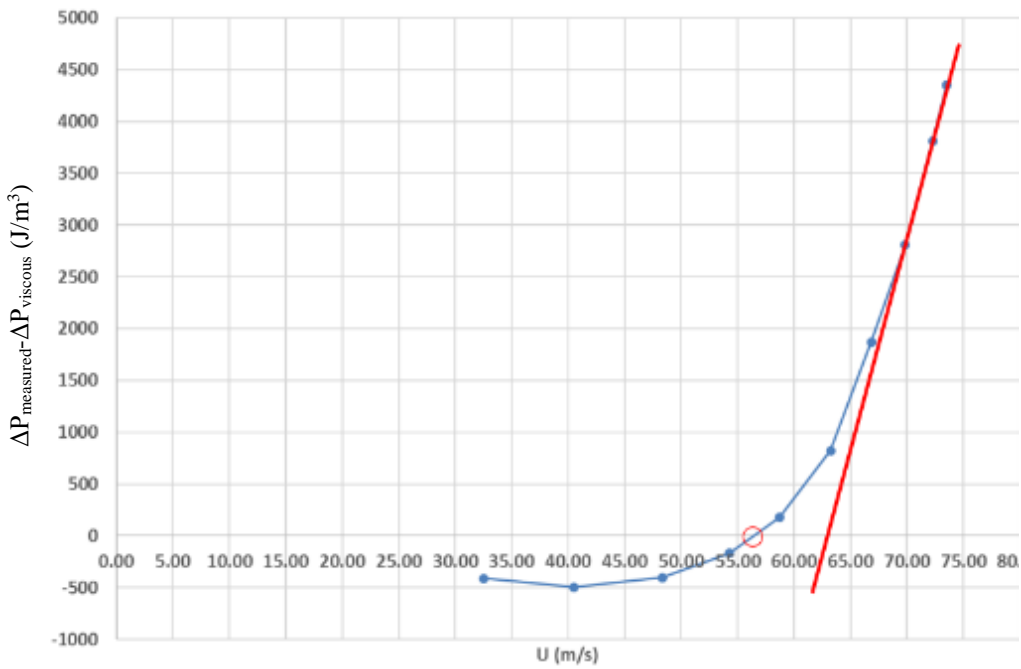


Figure 9 – ($\Delta P_{measured} - \Delta P_{viscous}$) versus U at 1 bara

Test results versus model results

To predict and compare test results the model approached in [Ref. 2] was utilized. The first part of Figure 10 shows the synthesis of all test results compared with calculated onset velocities. Calculated onset velocities values show in Figure 10 were refined thanks to CFD (bottom part of Figure 10) to consider the actual carcass shape and flow conditions. In the upper part of Figure 10, three kinds of family are plotted:

1. **Green circles:** results from model approached in [Ref. 2] where FLIP is **NOT** identified and confirmed by signals post-processing. For each green point, actual flow velocity inside of the rough bore flexible pipe was equal or lower than identified FLIP onset velocity. For example, for the green point with the *(a)* mark, the flow velocity inside of the rough bore flexible pipe was lower than the calculated onset velocity, which means that FLIP onset is not reached and was not identified on the spectrograms.
2. **Yellow circles:** results from model approached in [Ref. 2] where FLIP is probably identified and confirmed by signals post-processing. For each yellow point, actual flow velocity inside of the rough bore flexible pipe was around identified FLIP onset velocity.
3. **Red circles:** results from model approached in [Ref. 2] where FLIP is identified and confirmed by signals post-processing. For each red point, actual flow velocity inside of the rough bore flexible pipe was equal or greater than identified FLIP onset velocity. For example, for the red point with the *(b)* mark, the flow velocity inside of the rough bore flexible pipe was much higher than the calculated onset velocity, which means that FLIP onset is largely exceeded.

The reference line corresponds to $U_{\text{test}} = U_{\text{calculated}}$.

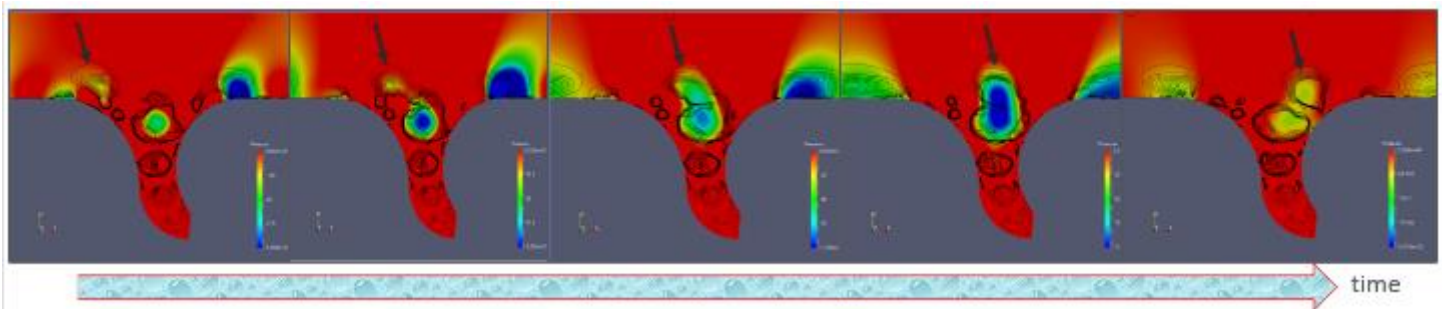
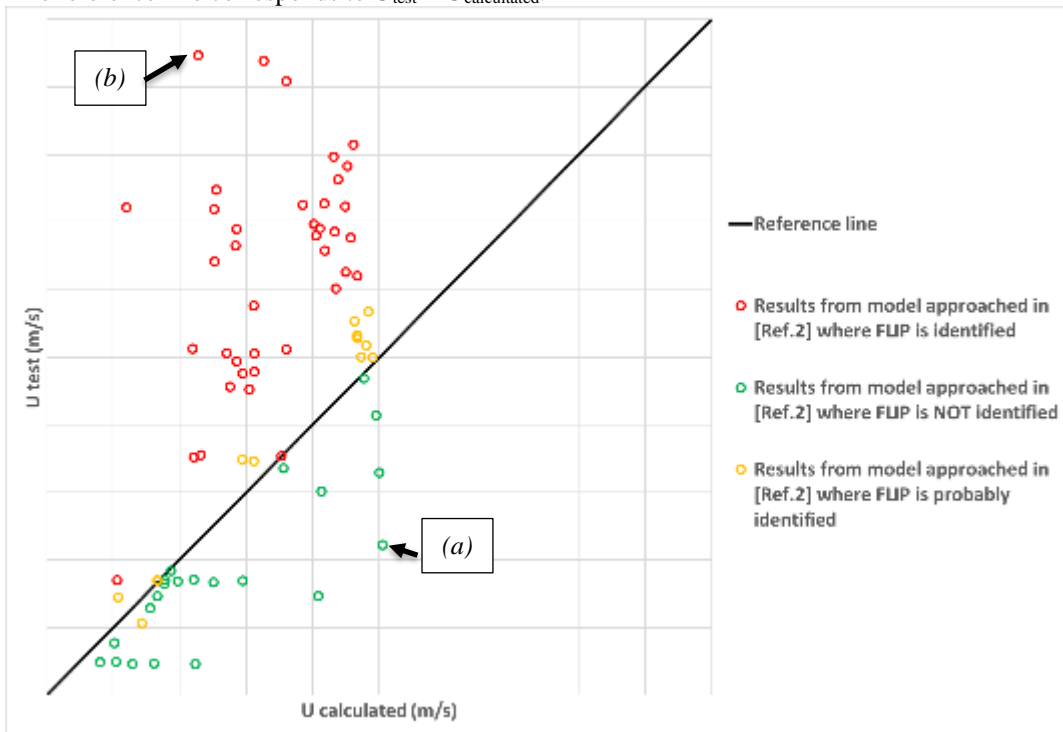


Figure 10 – Test vs model results / Vortex tracking during time

Conclusion

As a conclusion, FLIP phenomenon was successfully reproduced with an actual complete rough bore flexible pipe on an industrial scale with dry air. Thanks to an adequate and accurate monitoring great lessons were drawn either on FLIP phenomenon in general or on the acoustic nature of the phenomenon itself.

Rough bore flexible pipe experienced FLIP on its transverse modes for pressures close to atmospheric.

Thanks to this test model approached in [Ref. 2] is not called into question in terms of onset velocities and frequencies. A simple approach consisting in evaluating viscous pressure losses allowed confirmation of onset velocities.

The whole test campaign was a success thanks to the commitment of the different stakeholders that are involved in the partnership.

Acknowledgements

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Nomenclature

CFD	<u>C</u> omputational <u>F</u> luid <u>D</u> ynamics
CNRS	<u>C</u> entre <u>N</u> ational de <u>R</u> echerche <u>S</u> cientifique (National French R&D center)
FLIP	<u>F</u> low <u>I</u> nduced <u>P</u> ulsations
PSD	<u>P</u> ower <u>S</u> pectral <u>D</u> ensity
SBGE	<u>S</u> mooth <u>B</u> ore <u>G</u> as <u>E</u> xport
SPL	<u>S</u> ound <u>P</u> ressure <u>L</u> evel
$\Delta P_{\text{measured}}$	Total energy losses along flexible pipe
$\Delta P_{\text{viscous}}$	Energy losses along flexible pipe only due to wall viscous forces

Références

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- [Ref. 3] B. Boashash, Parts 1 and 2, Proc. IEEE 80(4) (1992), pp. 520-568, Estimating and interpreting the instantaneous frequency of a signal