Dynamic behaviour study of a satellite propellant tank using numerical and experimental vibratory tests

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Abstract

The ecological transition necessity makes the use of cryogenic fluids more and more relevant. However, experimental tests and associated modelling of those liquids dynamic vibratory behaviour remain extremely challenging. Indeed, security, control and conditioning are critical issues due to the intrinsic fluid instabilities. Among those critical fluids, liquid hydrogen and supercritical xenon are both highly used in the spatial propulsion domain. Because of their hazardous behaviour, only few experimental dynamic tests have been performed to improve the knowledge of their behaviour inside a vibrating tank.

Following the EASYNOV TANKYOU project, the READYNOV DANKE project, also funded by the French Occitanie region, aims at finding a safe substitute metamaterial that would be able to represent the supercritical xenon vibratory behaviour in a fully filled tank. The main objective is to find the granular medium properties that enable to match the modal shapes and frequencies of the tank filled with this granular medium with the one filled with supercritical xenon. The generalisation of this work will lead to a methodology combining numerical predictions, experimental validations and dimensional parametrization which should enable its uses to any other supercritical or cryogenic fluid and larger applications.

The project combines analytical, numerical and experimental approaches, that are strongly linked to each other as part of a material by design study. To this end, the project has been conducted in two main parts:

- *Design and validate, using numerical simulation, an experimental device highlighting the structural modes of the fluid and tank assembly,*
- *Evaluate the abilities of the numerical approach, developed in the TANKYOU project and based on the Discrete Element Method, to reproduce the dynamic behaviour of a fluid inside a vibrating tank.*

This paper especially focuses on the numerical designing step of the experimental device and on the tank structural modes identification. The experiments use a simplified closed cylinder filled with spheres of various materials. The combination of those different approaches is the guiding thread leading to disruptive innovative research opportunities.

Introduction

Since the 1980s, long-term space missions and satellites station-keeping increasingly rely on ionic propulsion due to the relatively low but long-lasting thrust this propulsion method provides. After decades of resting on caesium and mercury as propellants, environmental and technical issues led these components to be abandoned in favour of xenon, despite its heavy costs and the constraining logistics surrounding its use. Storage pressure of supercritically-stored xenon can reach several dozen bars, performing experimental dynamic testing on full tanks can consequently be hazardous. In order to facilitate and secure vibration testing involving xenon, an option could be to resort to a substitute metamaterial with a dynamic behaviour similar to supercritical xenon.

The purpose of the DANKE project is to tackle this problem by providing the space sector with a generic tool facilitating the certification of fluid propellant tanks. This tool would lead to a substitute metamaterial consisting in a granular medium composed of hollow spheres with dynamic vibratory properties equivalent to the fluid of interest. In the context of the DANKE project, this tool will preliminarily be applied to supercritical xenon as a demonstration.

This article exposes the numerical investigation that is first led to pre-dimension the experimental device. The experimental device has to be representative of a xenon tank at a reduced scale, and should enable the observation of the phenomena of interests. Results of the first experimental campaigns are presented in parallel with those of numerical simulations conducted with LS-DYNA on the representative tank being empty, filled with fluid or filled with spheres. Combination of both experimental and numerical approaches sets the path for the definition of the targeted substitute metamaterial.

1 Pre-dimensioning of the experimental device

1.1 Definition of the tank shape and dimensions

The general shape of the tank used in the experimental device is chosen by reviewing xenon tanks already in use in space programs. The two most common shapes are cylindrical tanks closed with semi-ellipsoids at each extremity and spherical tanks, such as those shown in fig. 1. The first shape is preferred for its similarity with the experimental device considered in the prior TANKYOU project, which involved a cylindrical tank [1-2]. Because of its mass and mechanical properties, aluminium is chosen for composing the tank shell.

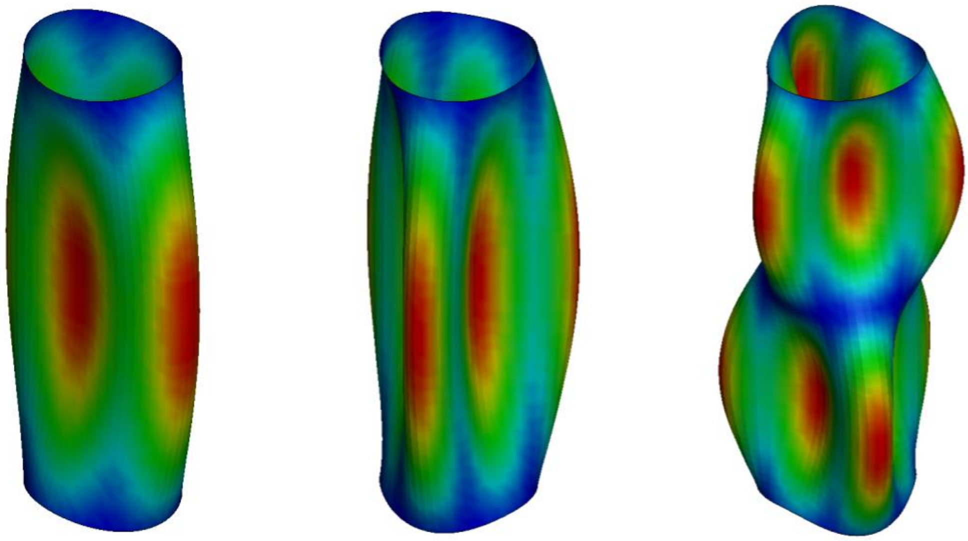
S-XTA-60 (MT Aerospace AG)

XST (Airbus DS/Stelia Aerospace Composites)

Xenon Tank (Rafael)

Fig.1: Examples of xenon tanks used in space programs

Dimensions of the tank are then to be determined. First of all, the experimental tank is at a reduced scale so as to be easier to handle during the experiments, and to require less fluid or spheres to be filled with. In the TANKYOU project, identification of the lobe modes (fig. 2) has been complicated in some cases by the overlapping of the bending modes with these modes of interest. Numerical simulation – through modal analysis and the “pulse method” described below – has proven to be a powerful tool for reproducing this pattern. Numerical simulation is thus used to determine the geometrical parameters of the DANKE experimental tank, with the objective of maximizing the frequency range between the lobe modes of interest – mostly ovalization and trifoliate modes – and the bending mode.



Ovalization mode **Trifoliate mode** **Lobes (3,2)**[1]

[1] In the following article, the denomination "Lobes (x,y)" will refer to a deformation mode displaying x lobes on the circumference of the tank on each one of the y rows distributed on the height of the tank.

Fig.2: Examples of lobe modes

Thickness of the walls and height and diameter of the cylinder composing the tank are determined iteratively using modal analysis. The ranges of these three parameters are consecutively narrowed around optimal values that meet the objective. Final iterations of the sensitivity study are shown in fig. 3.

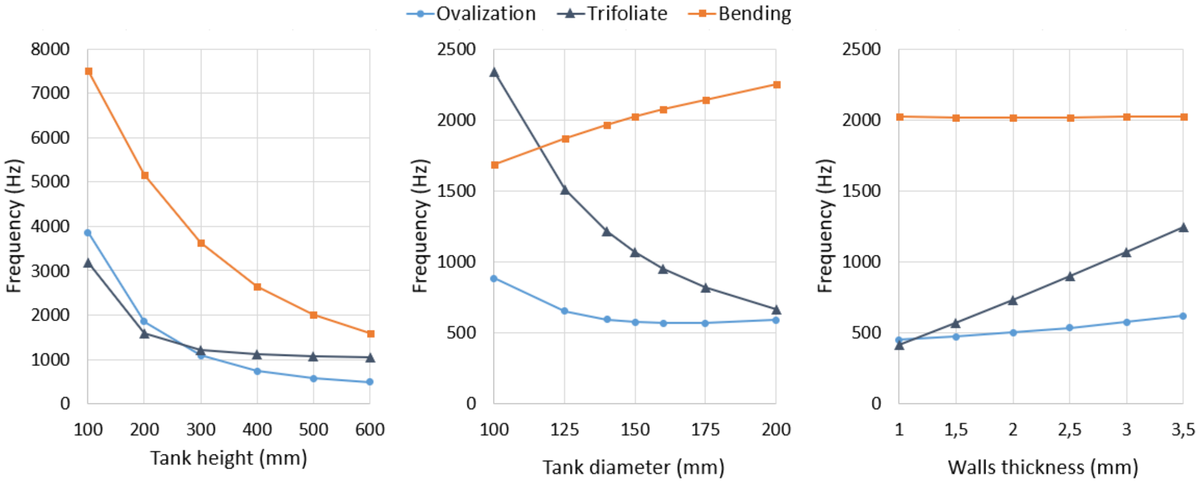
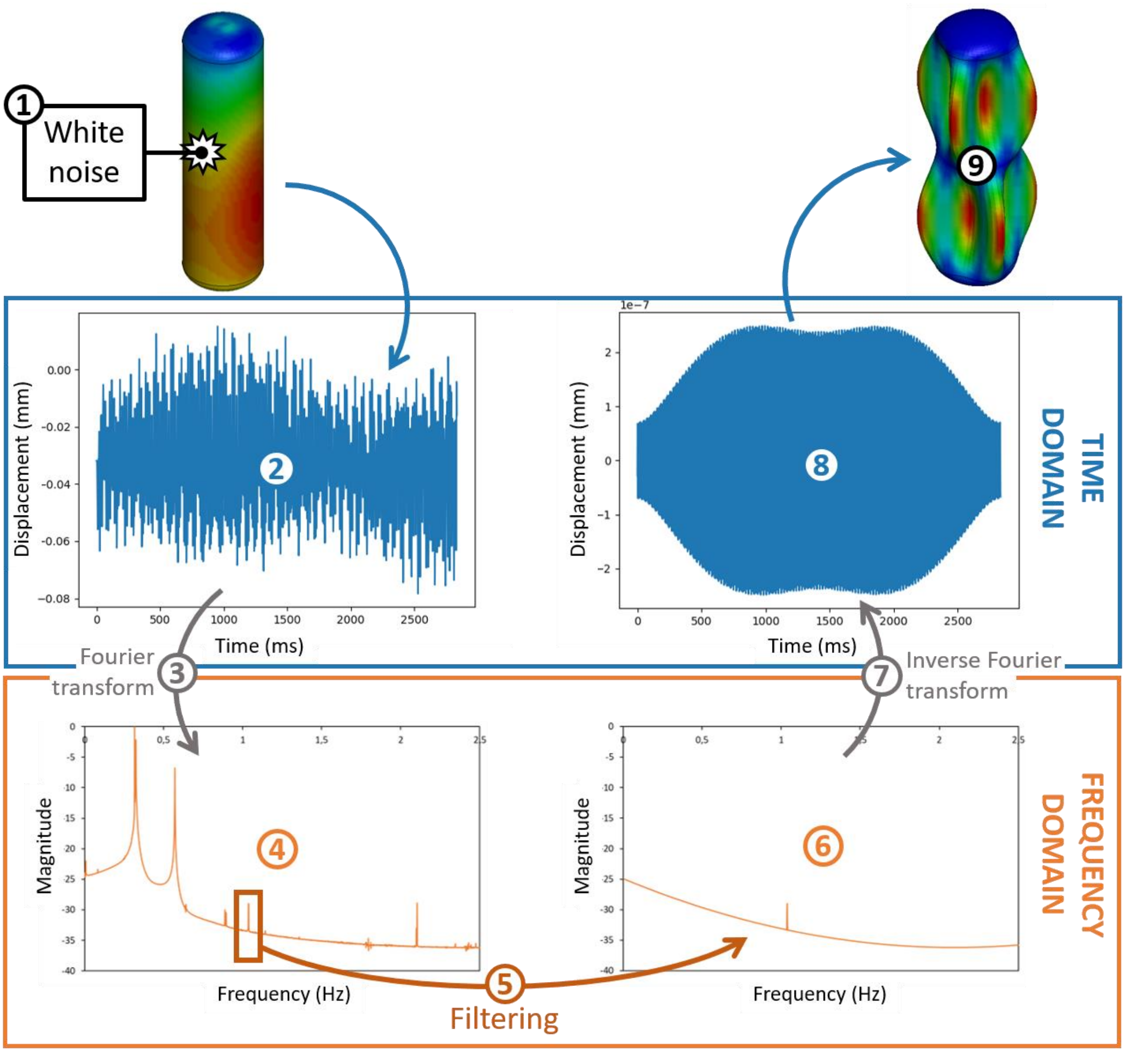


Fig.3: Influence of the tank dimensions on the modes frequencies

The first two lobe modes and the bending mode frequencies decrease with tank height. At low height, lobe modes tend to overlap, while at more significant height the bending mode frequency gets closer to the lobe modes frequencies. An intermediate height of 500 mm is thus ideal to separate each mode from each other. Ovalization and trifoliate modes frequencies decrease with diameter, meeting at high diameter, while bending mode frequency increases with diameter, leading to pick a 150 mm diameter. Finally, walls thickness has little to no effect on bending mode frequency. Lobe modes are confounded with a thickness value close to 1mm, but their frequencies increase at a different rate: with a 3 mm thickness, they do not overlap anymore while bending mode frequency is kept away.

1.2 Boundary conditions: introducing the "pulse method"

In the TANKYOU experimental device, the cylindrical tank was clamped at the bottom to a vibration table. This boundary condition was a rather severe constraint and could penalize the apparition of certain deformation modes in favour of others – mostly bending modes. More permissive boundary conditions are chosen for the DANKE experimental device, in order not to favour these bending modes. Two configurations are considered: suspending the tank by the pole of the upper semi-ellipsoid, or attaching it by the poles of both semi-ellipsoids. In either of these configurations, a vibration table cannot be used to bias the tank: the “pulse method” has to be used. Already implemented in the TANKYOU numerical simulations [1], the “pulse method” consists in applying a local and punctual pulse on the sidewall of the tank in order to excite all of the modes at once thanks to a white noise. The method principle is detailed in fig. 4. Experimentally, the “pulse method” loading can be performed with an impact hammer.



A white noise is applied on the wall of the tank (1) so as to trigger all the modes at once and to extract the corresponding displacements (2). Fourier transform is applied to the temporal displacements (3): each peak of the frequency spectrum (4) corresponds to a specific mode. A band-pass filter is applied around a peak of interest (5), leading to the filtered signal with only the isolated peak of interest (6). Inverse Fourier transform is applied to the filtered signal to go back to the time domain (7), resulting in the temporal displacements of the isolated mode (8). Based on these temporal displacements, modal shape of the isolated mode is reconstructed (9).

Fig.4: Principle of the “pulse method”

When this loading is applied to the tank suspended only by the upper pole, numerical simulation reveals the prevalence of the swinging mode – whose shape appears in fig. 5 – complicating the other modes detection. This can be observed on the Fourier transforms shown in fig. 6.

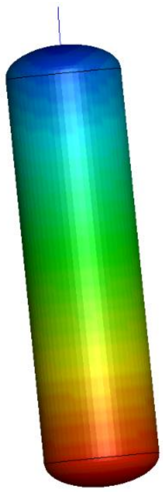


Fig.5: Modal shape of the swinging mode

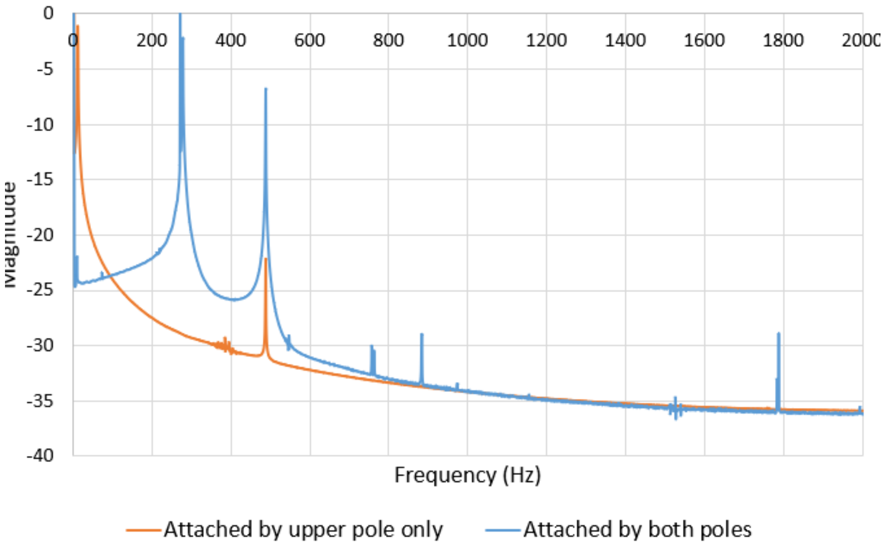


Fig.6: Influence of the configuration used to hold the tank on the modes detection

Only a low frequency peak – corresponding to the swinging mode – and a peak at 572 Hz are observed when the tank is suspended by the upper pole, while several more modes are detected when the tank is attached by the poles of both semi-ellipsoids. Consequently, the configuration with the tank suspended only by the top is ruled out and the tank is chosen to be attached by both lower and upper poles.

The nature of the components used to sustain the tank is then to be chosen among rods, wires and springs. They are respectively modelled with beam, truss and discrete elements, and the Fourier transforms obtained are compared in fig. 7.

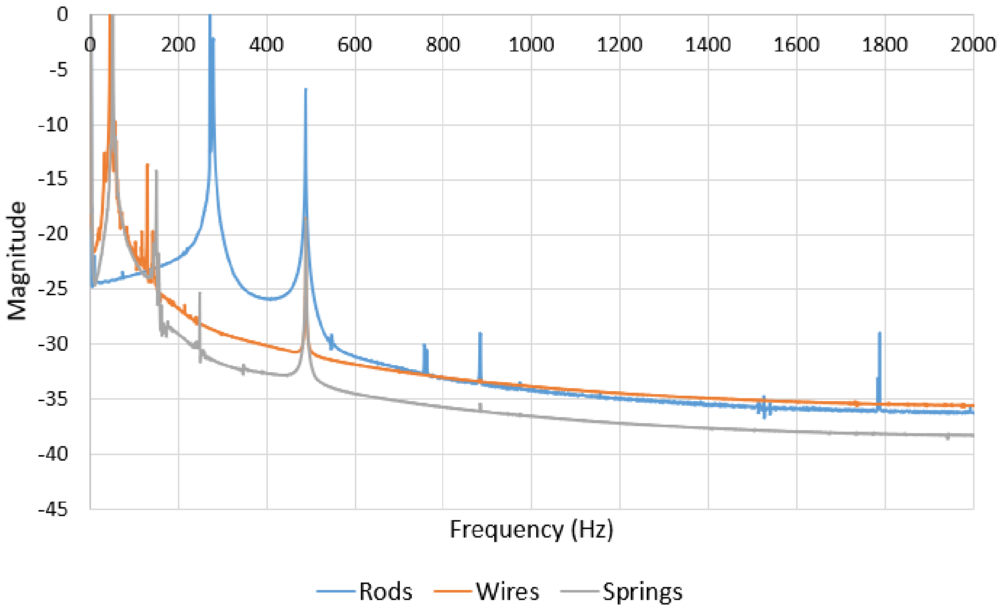


Fig.7: Influence of the components nature on the modes detection

Due to their lack of stiffness, wires and springs favour a rigid body mode – the peak around 50 Hz – masking other modes with lower magnitude: rods are consequently preferred.

Length and diameter of the rods used to hold the tank are then determined so as to prevent rigid body modes and rods deformation modes from overlapping the modes of interest. As for the tank pre-dimensioning, these two characteristics are determined iteratively with modal analyses. Final steps of the sensitivity study on the rods dimensions are shown in fig. 8.

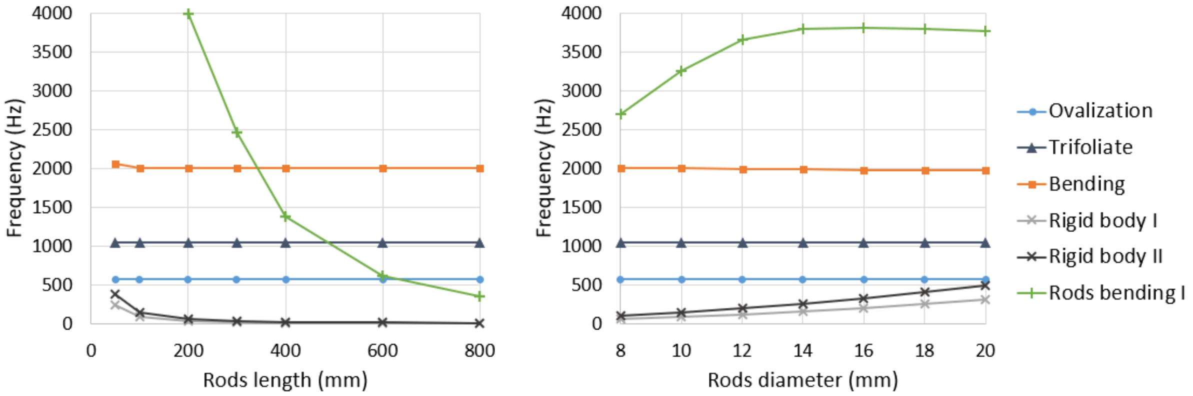


Fig.8: Influence of the rods dimensions on the modes frequencies

Except for the tank bending mode whose frequency slightly increases for shorter rods, the three tank deformation modes – ovalization, trifoliate and bending modes – are not affected by the rods dimensions. A rod length of 200 mm is ideal, but a length of 125 mm – which is still acceptable – is selected due to technical constraints. In order to keep the rigid body modes away from the modes of interest, the rods diameter has to be minimized. However, the rods section has to be large enough to ensure their mechanical strength and avoid plastic strain. Numerical simulation is performed for the most disadvantageous case to be conducted experimentally, which is the tank filled with steel balls representing an added mass of 50 kg. This simulation reveals that a 10 mm diameter is required to prevent plastic strain to occur in the rods with an acceptable safety margin.

1.3 First experiments and simulations on the resulting device

The first experiment set is led on the experimental device with the empty tank (*i.e.* filled with air at standard pressure and temperature). The tank is shock-stimulated with an impact hammer, and the deformation modes are then reconstructed from the data acquired by sets of accelerometers evenly distributed on the tank sidewalls. Impact force (entry), acceleration acquisitions (output) and post-processing leading to the deformation shapes and the modal analysis are conducted through the Simcenter Testlab software (formerly LMS Test.Lab) version 2019.1. The first four lobe modes detected are shown in fig. 9.

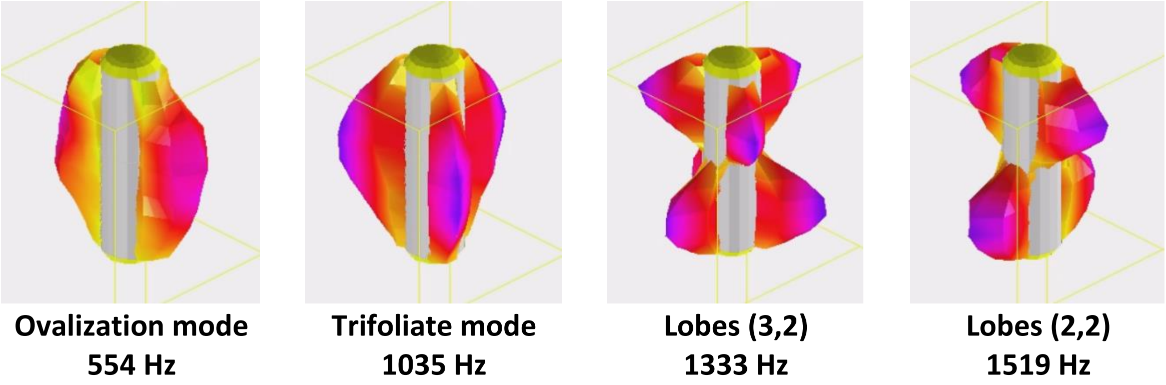


Fig.9: Lobe modes detected experimentally for the empty tank

The first lobe modes can be clearly identified experimentally thanks to the reconstruction of their modal shapes. In table 1, the experimental results are compared with the numerical results obtained with modal analysis and with the “pulse method”.

Mode	**Frequency (Hz)**			**Relative error**	
	Experiment	**Modal analysis**	**Pulse method**	**Modal analysis**	**Pulse method**
Ovalization	554	573	571	3.4%	3.1%
Trifoliate	1035	1041	1034	0.6%	-0.1%
Lobes (3,2)	1333	1369	1355	2.7%	1.7%
Lobes (2,2)	1519	1584	-	4.3%	-
Lobes (4,2)	2046	2069	-	1.1%	-
Lobes (4,3)	2342	2386	-	1.9%	-
Lobes (4,4)	2836	2913	-	2.7%	-

Table 1: Comparison of the experimental and numerical results for the empty tank

The correlation between the experiment and the numerical model is very satisfying for the lobe modes, the relative error never exceeding 5%. However, the numerical “pulse method” displays a limitation: while the ovalization and trifoliate modes are detected even more precisely than with the modal analysis, it does not allow to detect the higher frequency lobe modes. The difficulties encountered in detecting these modes numerically are explained by the frequency spectrum displaying more noise at high frequency, due to numerical artifacts.

2 Study of the tank filled with fluid

2.1 Starting simple with the water-filled tank

In order to examine the full tank in a simple case and to validate the numerical method used to model a fluid, the experimental tank is filled with water. The reconstruction of the modes based on the accelerometers data displayed fig. 9 for the empty tank is just as effective for the tank filled with water.

As a first approach only the mass variation induced by the filling of the tank with water is represented in the numerical model. The additional 9.6 kg of water are modelled by a mass distributed on the nodes of the tank walls via the keyword **`*ELEMENT_MASS_NODE_SET`**. The results obtained numerically using this modelling with modal analysis and the “pulse method” are compared with the experiment in table 2.

Mode	**Frequency (Hz)**			**Relative error**	
	Experiment	**Modal analysis**	**Pulse method**	**Modal analysis**	**Pulse method**
Ovalization	260	264	264	1.5%	1.5%
Trifoliate	539	480	479	-11%	-11%
Lobes (3,2)	701	631	-	-10%	-
Lobes (2,2)	727	729	-	1.5%	-
Quadrifoliate	1092	894	-	-18%	-
Lobes (4,2)	1163	953	-	-18%	-
Lobes (4,3)	1343	1099	-	-18%	-

Table 2: Comparison of the experimental and numerical results for the tank filled with water

While this model gives reasonably consistent results at low frequency with a relative error ranging from 1.5 to 11%, it reaches 18% for higher frequency modes such as the quadrifoliate mode. A more exhaustive model is thus to be developed in order to distribute mass to the whole volume, but also to take into account the effects of pressure inside the tank. To do so, the inside of the tank is meshed with hexahedral elements, and the water behaviour is modelled with the Grüneisen equation of state using the keyword **`*EOS_GRUNEISEN`** associated with **`*MAT_NULL`**. Table 3 compares experimental results with the numerical results obtained with the “pulse method”, the **`*MAT_NULL`** keyword being incompatible with modal analysis.

Mode	Frequency (Hz)		Relative error
	Experiment	Pulse method	Pulse method
Ovalization	260	260	0.0%
Trifoliate	539	534	-0.9%
Lobes (3,2)	701	702	0.1%
Lobes (2,2)	727	725	1.0%
Quadrifoliate	1092	1053	-3.6%
Lobes (4,2)	1163	-	-
Lobes (4,3)	1343	1347	0.3%

Table 3: Comparison of the experimental and numerical results for the tank filled with water

Except for the quadrifoliate mode, relative error between experiment and simulation does not exceed 1% with the water behaviour being described by the Grüneisen equation of state. This fluid modelling strategy is thus validated for water, and is going to be used to model the tank filled with xenon.

2.2 Getting to the point with the supercritical xenon-filled tank

In default of doing it experimentally, the tank is numerically filled with supercritical xenon modelled with the combination of the keywords **`*MAT_NULL`** and **`*EOS_GRUNEISEN`**. Frequency spectrum resulting from the “pulse method” appears in fig. 10.

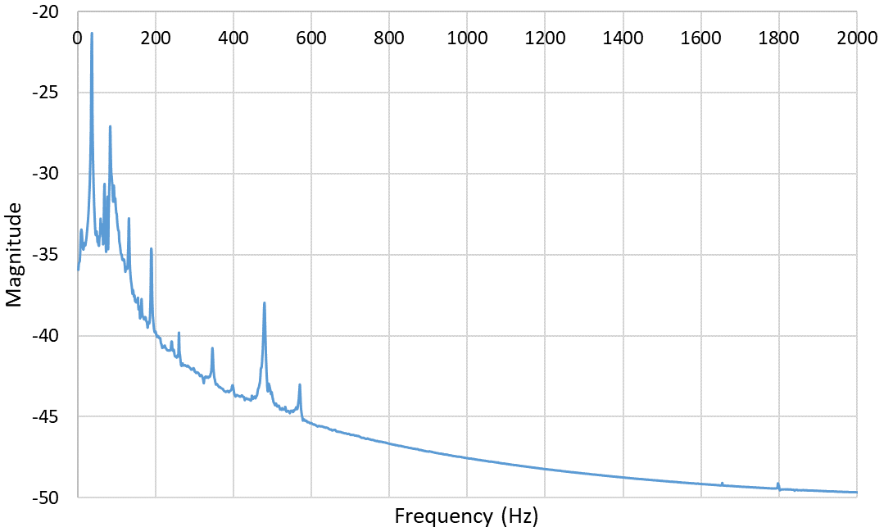


Fig.10: Frequency spectrum of the numerical tank filled with supercritical xenon

The frequency spectrum obtained for the tank filled with supercritical xenon features significant noise at lower frequencies, but still allows to clearly identify several peaks, one of which corresponding to the ovalization mode. The spectrum is smoother at high frequency, except for two faint peaks between 1600 and 1800 Hz, the second one corresponding to the quadrifoliate mode. The reconstructions of the modal shapes of these two lobe modes – the trifoliate mode not being detected – appear in fig. 11.

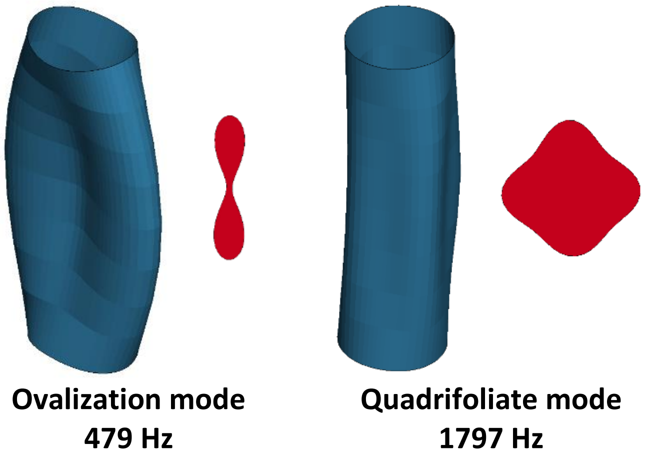


Fig.11: Isometric view (in blue) and cross-sectional view (in red) of the lobe modes detected numerically for the tank filled with supercritical xenon

3 Tank filled with spheres

3.1 Spheres characteristics for the forthcoming experimental campaign

Experimentally, the tank is planned to be filled with the 8 types of spheres listed in table 4.

Name	**Material**	**Diameter (mm)**	**Mass (g)**
ATECA	Polymer	3.3	0.07
Frost glass	Glass	6	0.28
Polished glass			0.28
AS012	Acrylonitrile butadiene styrene (ABS)		0.12
AS020			0.20
AS025			0.25
304L	304L stainless steel		0.88
420C	420C stainless steel		0.88

Table 4: Characteristics of the spheres to be used experimentally

The ATECA spheres are the same polymer hollow spheres as those used and characterized in the TANKYOU project [1-2]. The two types of glass spheres only differ in their surface finish, so as to investigate the influence of friction on the granular medium behaviour. Frost glass surface has an average roughness of 0.42 µm while polished glass surface has an average roughness of 0.31 µm, as characterized experimentally in [3]. The three types of ABS spheres have different masses, with 0.12 g, 0.20 g and 0.25 g. Finally, stainless steel spheres differ in their surface finish (average roughness of 0.33 µm for 304L, and 0.14 µm for 420C).

3.2 ATECA spheres: heading for the metamaterial equivalent to supercritical xenon

Anticipating the experimental campaign, numerical simulation of the “pulse method” is performed on the tank filled with spheres. The spheres are modelled with the Discrete Element Spheres (DES) method, which was proven in the TANKYOU project [1-2]. The filling of the tank is done geometrically using the algorithm detailed in [4]. This algorithm allows to reach a compacity of 57 to 60%, while the target compacity is around 62%. In order to increase compacity the tank is vibrated, rearranging the spheres and vacating the upper part of the tank. This void is filled again with spheres, leading to a sufficient compacity for applying the “pulse method” to the tank.

The “pulse method” is first applied to the tank filled with ATECA spheres, since their properties have been already validated [1]. The frequency spectrum obtained is displayed in fig. 12.

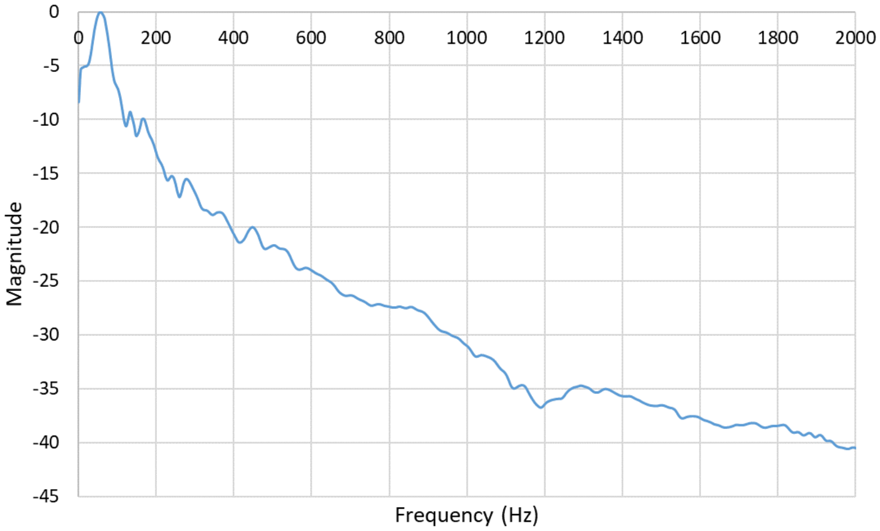


Fig.12: Frequency spectrum of the numerical tank filled with ATECA spheres

The granular medium constituted by the spheres induces a significant damping, smoothing the frequency spectrum. The peaks appearing in the frequency spectrum are consequently less pronounced than in the frequency spectrums of the empty tank (fig. 6) or for the tank filled with fluid (such as with xenon in fig. 10).

Nevertheless, the first three lobe modes – ovalization, trifoliate and quadrifoliate modes – can be detected. The reconstructions of their modal shapes appear in fig.13.

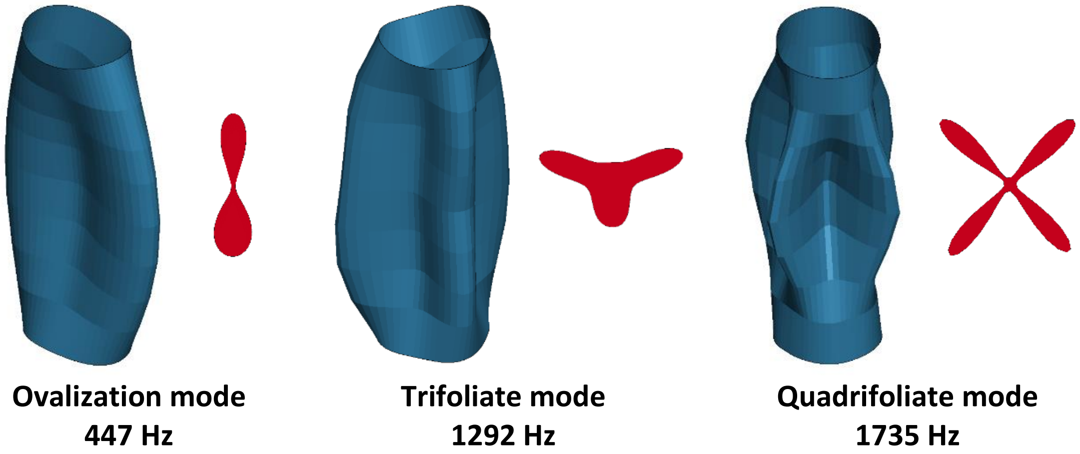


Fig.13: Isometric view (in blue) and cross-sectional view (in red) of the lobe modes detected numerically for the tank filled with ATECA spheres

The results obtained for the tank filled with spheres are encouraging: the first lobe modes are clearly identified, even though their modal shapes might display minor differences with those obtained for the tank filled with fluid. These results are even more encouraging since the frequencies of the ovalization and quadrifoliate modes for the tank filled with ATECA spheres are unexpectedly close to those obtained for the tank filled with supercritical xenon, as outlined in table 5.

Mode	**Frequency (Hz)**		**Relative deviation**
	Supercritical xenon	**ATECA spheres**	
Ovalization	479	447	-6.7%
Quadrifoliate	1797	1735	-3.5%

Table 5: Comparison of the numerical results for the tank filled with supercritical xenon and for the tank filled with ATECA spheres

Ovalization and quadrifoliate modes have frequencies respectively differing from 6.7% and 3.5% between the tank filled with xenon and the tank filled with ATECA spheres. The granular medium constituted by the ATECA spheres thus seems to be close to the metamaterial with dynamical vibratory properties equivalent to those of supercritical xenon – at least for the two lobe modes mentioned above.

The forthcoming experimental campaign led with spheres will have two main roles in the search of this metamaterial. The first one will be to confirm the results obtained numerically for the tank filled with ATECA spheres. The second and main role of the experiments – conjointly with the numerical simulations – will be to investigate the influence of the spheres properties on the granular medium behaviour, using the variety of spheres that have been picked out listed in table 4. This better understanding of the physical phenomena involved will enable the definition of the metamaterial characteristics.

4 Summary

Capitalizing on the experience gathered during the prior TANKYOU project, numerical simulation has been used to pre-dimension the experimental device used for the DANKE project. The main goal kept in mind during pre-dimensioning was to maximize the frequency range between the lobe modes of interest and the bending mode, so that the formers are not masked by the latter. Pre-dimensioning has resulted in a cylindrical tank closed with semi-ellipsoids at each extremity, held by two rods fixed at the poles of each semi-ellipsoid. Since this configuration does not allow the use of a vibration table, the “pulse method” – which consists in applying a white noise as a local and punctual pulse on the sidewall of the tank – is used to bias the tank, exciting all of its modes at once. Each mode is then isolated thanks to filtering in the frequency domain, and the corresponding modal shape is reconstructed. First tests led on the empty tank have validated the methodology used to detect and identify modes, and have shown very good correlation between experimental and numerical results, with a relative error on the frequencies of less than 5% for each mode.

The tank has then been filled with water in order to assess the strategies considered to model fluids. While an equivalent mass distributed on the walls of the tank has given poor results, especially at high frequency, using the Grüneisen equation of state to model the water behaviour has led to a very good correlation between numerical simulation and experiment, the relative error on frequencies never exceeding 4%. Grüneisen equation of state has consequently been used to model supercritical xenon, making possible the identification of the ovalization and quadrifoliate modes of the tank filled with xenon, among other modes.

Finally, the tank has been numerically filled with the ATECA spheres previously characterized during the TANKYOU project, and modelled with the DES method. Even though the spheres have brought in significant damping, various modes have been detected including the first three lobe modes – ovalization, trifoliate and quadrifoliate modes. In addition to the modal shapes being similar to those observed on the tank filled with fluid, the frequencies of the ovalization and quadrifoliate modes are unexpectedly close to the frequencies of the same modes for the tank filled with supercritical xenon. These results are promising for the search of the metamaterial with dynamical vibratory properties equivalent to supercritical xenon. This search for an equivalent metamaterial will be led further by combined experimental and numerical testing on the tank filled with spheres with various properties. A better understanding of the phenomena occurring in the granular medium composed of spheres will then allow, for a given fluid, to define the characteristics of the equivalent metamaterial.

5 Literature

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