Numerical Dynamic Characterization of a Xenon Satellite Propellant Tank Employing Discrete Element Spheres

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1 Introduction

The ecological emergency makes the use of cryogenic or supercritical 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 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 numerical, experimental and analytical approaches, that are strongly linked to each other as part of a material by design study. This paper details the methodology deployed to that end and its validation through an experimental and numerical campaign. Dimensionless numbers are then built through analytical considerations, two of their applications being illustrated further: the extension of results on a reduced scale tank to a full size one, and the ability to determine the granular medium whose dynamic behaviour match those of a given fluid.

2 Methodology

2.1 Modelling strategies

Since the DANKE project is focused on the cryogenic and supercritical fluids, the development of a suitable strategy to represent these fluids is crucial. The Grüneisen equation is chosen for the definition of the relation between pressure and volume depicting the fluid behaviour in the tank. For that purpose, the inner volume of the tank is meshed with hexahedral elements to which is assigned the material **`*MAT_NULL`** associated to the keyword **`*EOS_GRUNEISEN`**.

The targeted substitute metamaterial considered for the fluids mentioned above is composed of hollow spheres, hence the need for an adequate modelling of granular material behaviour. The Discrete Element Method (DEM) available in LS-DYNA meets this need, by allowing the definition of spheres interacting with each other through the keywords **`*ELEMENT_DISCRETE_SPHERE`** and **`*CONTROL_DISCRETE_ELEMENT`**. While hollow spheres compose the targeted metamaterial, DEM confines to the definition of solid spheres only. This limitation is circumvented by adjusting the density, Young modulus and Poisson ratio of the solid spheres in order to fit the behaviour of hollow spheres with the same radius. This approach based on homogenised solid spheres has been developed and successfully evaluated during the prior TANKYOU project [1].

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2.2 Numerical methods

While modal analysis is as efficient and reliable as its CPU cost is low for identifying the normal modes of the empty tank, it suffers major flaws once the tank is filled. Modal analysis is indeed difficult to achieve for the tank filled with fluid, if not impossible depending on the method used to model it. When the tank is filled with spheres, modal analysis is plainly incompatible with DEM. An alternate method is thus developed for the mode identification involving the tank filled with fluid or granular material.

This alternate method is the pulse method detailed in [2] and synthesized in Fig. 1. Using explicit analysis, a local and punctual pulse is applied on the sidewall of the tank, triggering all of the modes at once using a white noise. Corresponding temporal displacements are extracted and submitted to a Fourier transform, resulting in a frequency spectrum where each peak indicates a mode. Each mode of interest can then be isolated by applying Tukey window – a band-pass filter – to the corresponding peak. Inverse Fourier transform is performed on the resulting filtered signal so as to obtain the temporal displacements of the mode of interest only. These temporal displacements are eventually used for modal shape reconstruction.

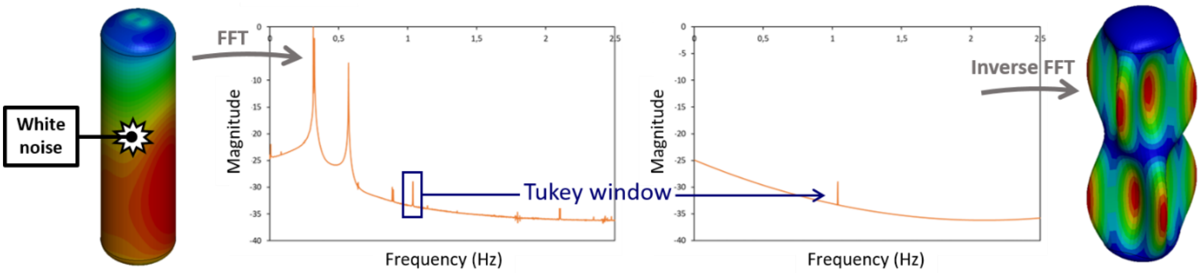


Fig.1: Principle of the pulse method

2.3 Design of the DANKE tank

For the combined experimental and numerical tests to come, the DANKE tank is designed to meet several requirements. First, the DANKE tank has to be representative of most of the existing supercritical xenon tanks. A cylindrical shape closed with semi-ellipsoids at each extremity is selected to that extent. Normal modes for a tank of such shape meet those of a cylinder: mostly lobe modes and bending modes, as shown in Table 1. Then, the DANKE tank is designed smaller than a regular xenon tank, in order to be easier to operate during the experimental campaign, and to need less fluid or granular material for filling it.

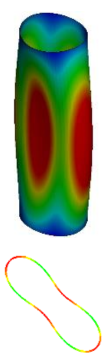
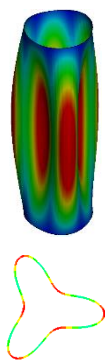
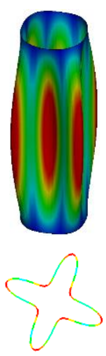
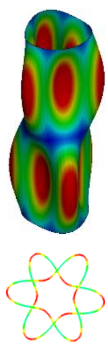
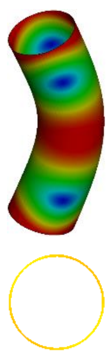
Lobe modes				Bending modes
Ovalization	**Trifoliate**	**Quadrifoliate**	**Lobes (3,2)**	
				

Table 1: Modal shapes of a hollow cylinder

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Ovalization, trifoliate and quadrifoliate modes are the primary modes of interest in the DANKE project. They feature respectively two, three and four lobes on the cylinder circumference. Other lobe modes can be observed at higher frequencies with more lobes on the cylinder circumference and/or height. Such lobe modes will be referred to as lobe mode (m, n), m being the number of lobes on the circumference and n the number of lobes on the height. Occurrence of bending modes has to be minimized: during the prior TANKYOU project these modes were predominant. They could overlap lobe modes, and detection of the latter was consequently harder. The TANKYOU project also proved that numerical simulation was a powerful tool for replicating this pattern. Predimensioning of the DANKE tank therefore relies on numerical simulation in order to avoid such setbacks.

Every geometrical parameter of the tank is evaluated through sensitivity study using modal analysis. The tank is attached by the poles of both semi-ellipsoids: boundary conditions of the tank are chosen as little constraining as possible, in order not to lessen the occurrence of the normal modes. The resulting geometry – maximizing the frequency range between the modes of interest and any bending mode – is shown Fig. 2, along with the experimental device and the matching finite element model. The tank is meshed with fully integrated Belytschko-Tsay shells with 5 integration points through thickness, and the threaded rods used to hold the tank are modelled with Hughes-Liu beams.

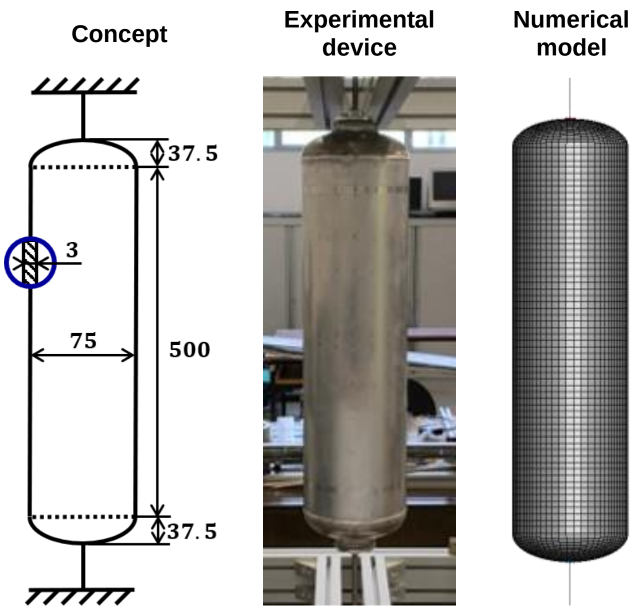

Fig.2: Geometry of the tank

2.4 Experimental device

On the experimental aspect, the tank is installed in a frame and submitted to the pulse method. The tank is excited using an impact hammer, and the frequency response function (FRF) is recorded with accelerometers through 200 points of acquisition distributed on the sidewalls of the tank. This data is then used to recreate modal shapes for each mode that is detected. The experimental device is shown Fig. 3.

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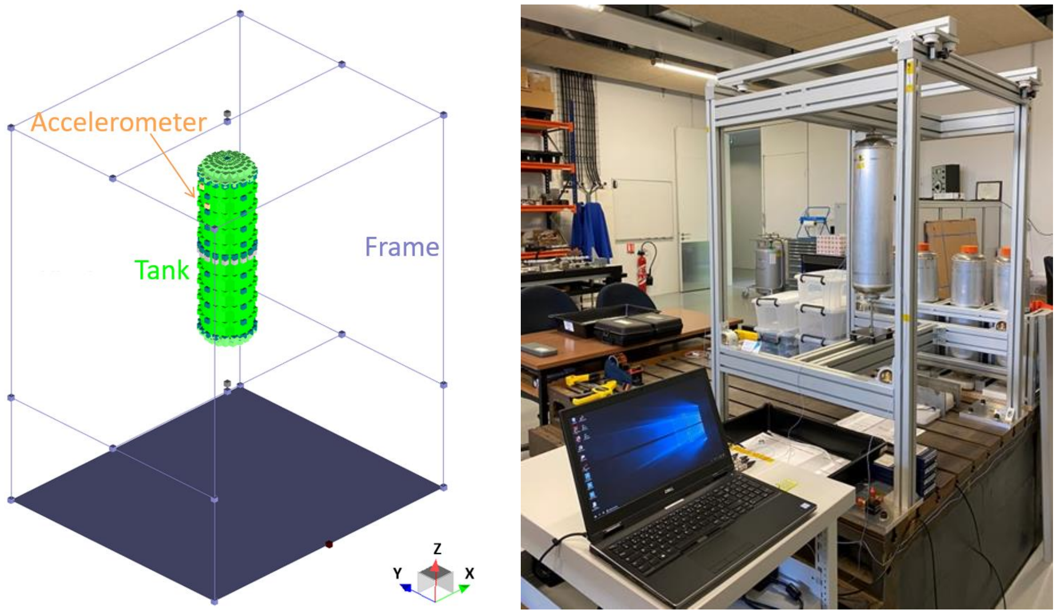


Fig.3: Experimental device

3 Proof of concept

3.1 Empty tank

Experiment and numerical simulation are first compared on the empty DANKE tank, the objective being to validate the finite element model of the tank and the numerical methods employed. Pulse method is performed experimentally on the empty tank, and modal shapes are recreated for each mode detected. On the numerical tank model, modal analysis is performed along with the pulse method. The modal shapes are compared in Table 2.

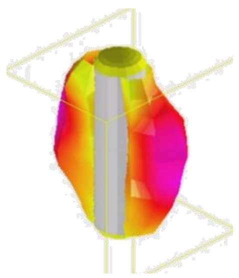
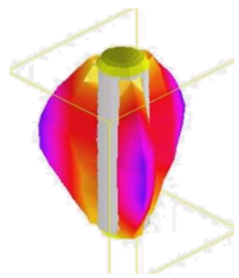
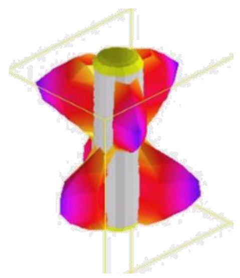
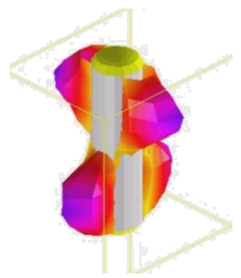
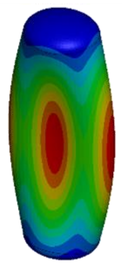
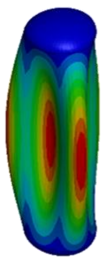
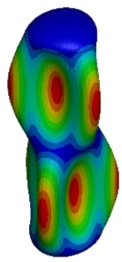
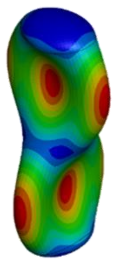
	Ovalization	**Trifoliate**	**Lobes (3,2)**	**Lobes (2,2)**
Experiment				
Simulation				

Table 2: Modal shapes of the tank

This comparison highlights the ability of numerical simulation to accurately replicate modal shapes of the tank, for ovalization and trifoliate modes as well as higher frequency lobe modes. In terms of frequencies, experimental and numerical results are compared in Table 3.

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	Frequency (Hz)			Relative deviation	
	Experiment	Simulation (Modal analysis)	Simulation (Pulse method)	Simulation (Modal analysis)	Simulation (Pulse method)
Ovalization	554	573	571	3.4 %	3.1 %
Trifoliate	1 035	1 041	1 034	0.6 %	0.1 %
Lobes (3,2)	1 333	1 369	1 355	2.7 %	1.7 %
Lobes (2,2)	1 519	1 584	-	4.3 %	-
Lobes (4,2)	2 046	2 069	-	1.1 %	-
Lobes (4,3)	2 342	2 386	-	1.9 %	-
Lobes (4,4)	2 836	2 913	-	2.7 %	-

Table 3: Empty tank

The limited relative deviation between experimental and numerical results brings out the accuracy of the numerical model, and validates the modelling choices made for the tank. Concerning numerical methods, Table 3 reveals that pulse method is unable to detect modes beyond 1.5 kHz for the empty tank. At such frequencies, spectrum can be noisy due to numerical effects: peaks detection thus is harder and modes can be missed using pulse method. For lower frequencies though, modal analysis and pulse method give similar results. Modal analysis reliability being already settled, this similarity legitimates the validity of the pulse method to identify the modes of interest for the next phases.

3.2 Fluid-filled tank

Now that modelling choices for the tank and numerical methods have been verified, tests are conducted to evaluate the use of the Grüneisen equation of state for fluid modelling. The experimental tank is filled with water and submitted to the pulse method. Modal shapes reconstruction using the accelerometers data gives as clear results for the water-filled tank as for the empty tank. Water-filled tank is modelled as detailed in 2.1, also submitted to the pulse method, and experimental and numerical results are compared in Table 4.

	Frequency (Hz)		Relative deviation
	Experiment	Simulation (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	1 092	1 053	-3.6 %
Lobes (4,3)	1 343	1 347	0.3 %

Table 4: Water-filled tank

Frequencies obtained numerically are close to those obtained experimentally, relative deviation does not exceed 1 % in absolute value, except for the quadrifoliate mode whose relative deviation is -3.6 %.

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According to these results, the modelling strategy for fluids based on the Grüneisen equation is validated.

3.3 Sphere-filled tank

Spheres of various materials and radii are used to successively fill the experimental tank with: polymer, glass and steel with a radius of 1.65 or 3 mm. For each type of sphere, FRF is recorded so as to get the shape and frequency of each mode. In order to validate the use of DEM explained in 2.1 to model the sphere-filled tank, the numerical tank is filled with hollow polymer spheres of 1.65 mm radius – the ATECA spheres which have been previously characterized during TANKYOU [3]. Table 5 compares the mode frequencies obtained experimentally and numerically using pulse method.

	Frequency (Hz)		Relative deviation
	Experiment	Simulation (Pulse method)	
Lobes (3,2)	1 081	1 105	2.1 %
Lobes (2,2)	1 498	1 517	1.2 %
Quadrifoliate	1 673	1 692	1.1 %
Lobes (4,3)	1 945	1 954	0.4 %

Table 5: Sphere-filled tank

Numerical results match experimental results: relative deviations between frequencies obtained experimentally and numerically do not exceed 2.1 %, confirming DEM as an appropriate method for modelling granular material contained in the tank.

4 Adimensional approach

4.1 Identifying physical quantities of interest

In order to establish the relation between the properties of the tank and its content and their dynamic response, the adimensional approach is led, through analytical considerations combined with numerical simulation.

Seven or eight physical quantities of interest have been identified, summed up in Table 6: the frequency at which the mode occurs, the properties of the tank, and the properties of the fluid or the spheres depending on the tank content. Sensitivity analysis has shown that bulk modulus of the fluid and Young modulus of the spheres have no effect on the dynamic response of the system, these properties have thus been ruled out of the physical quantities of interest.

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Mode characteristics	
Frequency	f
Tank properties	
Height	H
Diameter	D
Sidewall thickness	e
Density	ρ
Young modulus	E
Fluid properties	
Fluid density	ρ_F
Spheres properties	
Spheres radius	r_S
Spheres density	ρ_S

Table 6: Physical quantities of interest

4.2 Building dimensionless numbers

With H, ρ_F and E as fundamental variables, the application of Vaschy-Buckingham theorem leads to 5 dimensionless numbers. First two dimensionless numbers π_1 and π_2 refer to the tank dimensions, and allow to jump from a representative tank to a real tank. This approach is illustrated in 5.1.

$$\pi_1 = \frac{H}{D} \quad (1)$$

$$\pi_2 = \frac{e}{H} \quad (2)$$

Dimensionless number π_3 involves the modes frequencies, describing the dynamic response of the system: this dimensionless number is of major interest.

$$\pi_3 = Hf\sqrt{\frac{\rho}{E}} \quad (3)$$

Variants π_{4F} and π_{4S} of dimensionless number π_4 – depending on the tank being respectively filled with fluid or spheres – involves density of the tank and its content.

$$\pi_{4F} = \frac{\rho}{\rho_F} \quad (4) \quad \text{or} \quad \pi_{4S} = \frac{\rho}{\rho_S} \quad (5)$$

Dimensionless number π_5 applies to a sphere-filled tank only, and brings in the radius of the spheres composing the granular material compared to the dimension of the tank.

$$\pi_5 = \frac{H}{r_S} \quad (6)$$

4.3 Connecting the dimensionless numbers

According to Vaschy-Buckingham theorem, any of the dimensionless numbers above can be expressed as the function of the four others, hence Eq. 7 is verified.

$$\pi_3 = g(\pi_1, \pi_2, \pi_4, \pi_5) \quad (7)$$

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Validity of Eq. 7 is verified through a numerical tests campaign, on the empty tank at first so as to exclude π_4 and π_5 from this expression. Tank geometries with various values for H, D and e are generated by morphing the mesh of the DANKE project tank and changing the shell thickness. For the first modes of interest – ovalization and trifoliate modes – corresponding frequencies f are determined through modal analysis for each tank geometry. By performing regression analysis on this data, it appears that dimensionless number π_3 can be written as Eq. 8 with P_1, P_2 and P_3 polynomials of degree four.

$$\pi_3 = P_1(\pi_2) \cdot {\pi_1}^2 + P_2(\pi_2) \cdot \pi_1 + P_3(\pi_2) \tag{8}$$

When the tank is filled with fluid, dimensionless number π_{4F} brings in fluid and tank densities. Geometry of the tank is fixed to exclude π_1 and π_2 of Eq. 7, and ovalization and trifoliate modes frequencies are determined using pulse method for various fluid and tank densities. For set values of π_1 and π_2, regression analysis leads to Eq. 9 with A_F, B_F and C_F constants.

$$\pi_3 = A_F \cdot \ln(\pi_{4F})^2 + B_F \cdot \ln(\pi_{4F}) + C_F \tag{9}$$

To investigate the dimensionless number π_{4B} involving spheres and tank densities for a sphere-filled tank, pulse method is used to determine the frequencies of the first modes of interest for various values of ρ and ρ_S, still with a fixed tank geometry. Regression analysis allows to establish Eq. 10 with A_S, B_S and C_S constants, for set values of π_1 and π_2.

$$\pi_3 = A_S \cdot \ln(\pi_{4S})^2 + B_S \cdot \ln(\pi_{4S}) + C_S \tag{10}$$

Functions g_F and g_S such that $\pi_3 = g_F(\pi_{4F})$ and $\pi_3 = g_S(\pi_{4S})$ have a major significance for the purpose of this research. These two functions share the same shape, which confirms the initial assumption stating that a tank filled with a granular material displays the same dynamic behaviour as a tank filled with fluid. g_F and g_S also give leads to define the properties of the granular material whose dynamic behaviour would match those of a given fluid, as illustrated later in 5.2.

Finally, the DANKE tank is filled with spheres of various radii using DEM to identify the function linking π_3 to π_5. No clear influence of sphere radii on modes frequencies is observed in the field of study. However, for values of π_5 below 50, frequency spectrum can be noisier and peaks at higher frequencies can be smoothed, making corresponding modes harder to detect. Lower values of π_5 are thus to be avoided, meaning that a granular material composed of spheres of small radius is preferred.

5 Application

5.1 Scaling

Since they involve tank dimensions – height, diameter and sidewalls thickness – dimensionless numbers π_1 and π_2 can be used to extend the observations made on a representative tank at reduced scale to a real tank. Values of π_1 and π_2 are plotted Fig. 4 for the DANKE tank and various existing xenon and hydrogen tanks based on data found in [4], [5] and [6].

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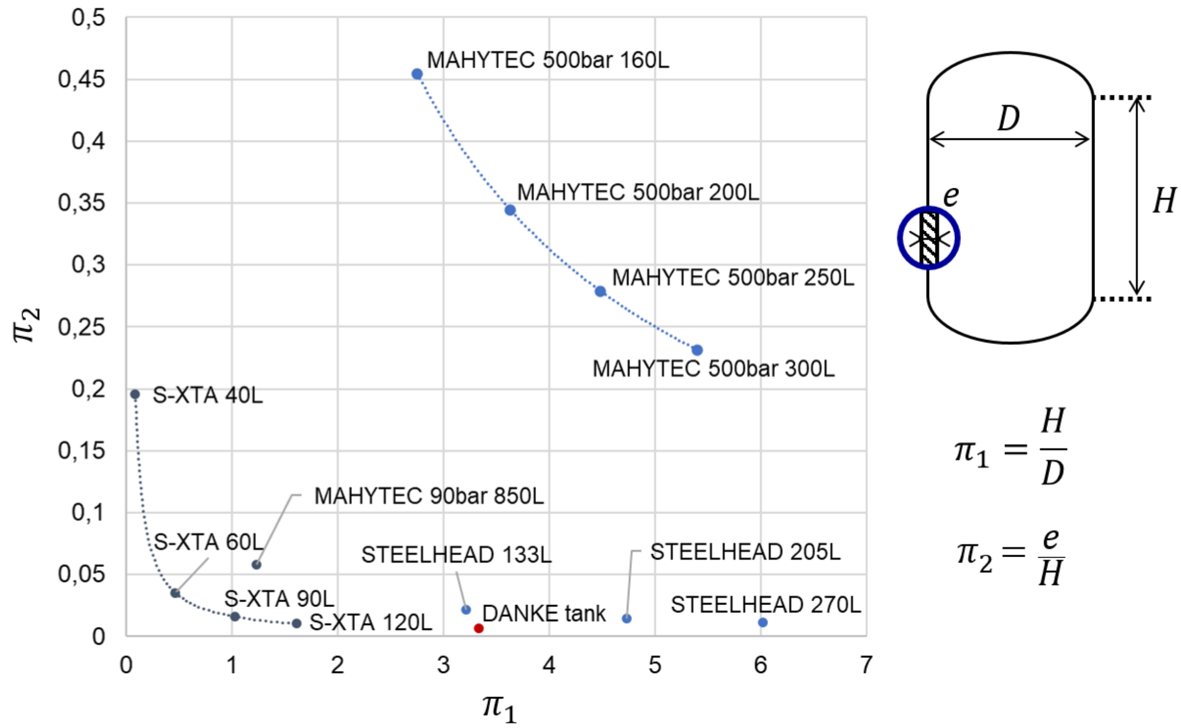

Fig.4: Values of π_1 and π_2

Numerical models are generated for various hypothetical tank geometries – and thus various pairs (π_1, π_2). Modal analysis is performed for each empty tank geometry so as to get the ovalization mode frequency f and the corresponding value of π_3. These values are then used to determine the coefficients of polynomials P_1, P_2 and P_3 of Eq. 8, resulting in the expression of π_3 as a function of π_1 and π_2 for the considered field of study.

Their geometries being quite precisely known, S-XTA-90L and S-XTA-120L tanks whose pairs (π_1, π_2) belong to the field of study are modelled and submitted to modal analysis. Resulting ovalization mode frequency f is used to calculate π_3. Eq. 8 with the coefficients of P_1, P_2 and P_3 determined just before is then used to estimate the values of π_3 corresponding to the pairs (π_1, π_2) of the S-XTA-90L and S-XTA-120L tanks. Resulting values of π_3 – simulated and estimated – are compared in Table 7.

Tank	$\boldsymbol{\pi_1}$	$\boldsymbol{\pi_2}$	**π_3 (ovalization mode)**		
			Simulation	**Estimation**	**Relative deviation**
DANKE	3.33	0.0060	56.3	60.0	6.2 %
S-XTA-90L	2.11	0.0065	65.1	65.0	-0.2 %
S-XTA-120L	3.18	0.0043	58.5	52.7	-11.0 %

Table 7: Simulated and estimated π_3 values

The accuracy of this estimation could be further improved by generating more geometries in order to have more data to base the regression analysis on for determining coefficients of polynomials P_1, P_2 and P_3 in Eq. 8. Yet, estimated values of π_3 are close to the values obtained through modal analysis, with a relative deviation ranging from -0.2 % to 11.0 %. Such limited deviation indicates that the dynamic behaviour of a real size tank – here the frequency f of occurrence of its normal modes, through the dimensionless number π_3 – can be predicted from the behaviour of a representative tank at a reduced scale, even with different proportions.

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5.2 Supercritical xenon

The modelling strategy for fluid-filled tank using the Grüneisen equation and detailed in 2.1 has been validated with the water-filled tank in 3.2. It is now used to represent the DANKE tank filled with supercritical xenon using properties found in [7], and pulse method is conducted on the tank. Resulting frequency spectrum is slightly noisy at lower frequencies, but allows to detect ovalization and quadrifoliate modes at respectively 479 Hz and 1797 Hz. Trifoliate mode – theoretically located between these two modes – does not appear in the spectrum.

Constants A_S, B_S and C_S linking modes frequencies f to spheres density ρ_S through dimensionless numbers π_3 and π_{4S} are determined for the field of study. The density ρ_S leading to the expected value of f is then calculated. Finally, this value of ρ_S is adjusted in an iterative process so as to compensate the uncertainties on A_S, B_S and C_S. Resulting substitute metamaterial to supercritical xenon is composed of spheres with a 1.65 mm radius and an equivalent density of 544 kg/m³.

DANKE tank is filled with such spheres using DEM, and pulse method is performed to detect the modes of interest: ovalization mode at 474 Hz, trifoliate at 1339 Hz and quadrifoliate at 1787 Hz. These frequencies are compared to those of xenon in Table 8.

	Frequency (Hz)		Relative deviation
	Xenon	Meta-material	
Ovalization	479	474	-1.1 %
Trifoliate	-	1 339	-
Quadrifoliate	1 797	1 787	-0.6 %

Table 8: Xenon-filled tank v. metamaterial-filled tank

Relative deviations between mode frequencies of the tank filled with supercritical xenon and the tank filled with metamaterial are around -1 %, reflecting a very good match. Except for the trifoliate mode occurring with the spheres but not with xenon, the considered substitute metamaterial consequently grants the tank similar dynamic behaviour as when it is filled with supercritical xenon.

6 Summary

Based on the foundations set by the EASYNOV TANKYOU project, several numerical and experimental tools have been perpetuated and perfected in the READYNOV DANKE project: modelling strategies for fluids and granular materials inside a tank, and the pulse method, a method allowing to identify the normal modes of a structure when modal analysis is inapplicable. Through numerical and experimental tests, these tools have been validated in order to set the path for the adimensional approach and its applications.

Combining analytical and numerical considerations, the adimensional approach connected the properties of the tank and its potential content to their dynamic response, using the Vaschy-Buckingham theorem. Five dimensionless numbers have been built: π_1 and π_2 describing the tank geometry; π_3 involving the modes frequency; π_4 comparing densities of the tank and of its content; and π_5 comparing tank size to spheres radius for the sphere-filled tank.

Direct application of these dimensionless numbers can be achieved, with promising perspectives. Dimensionless numbers π_1 and π_2 allow to extend the observations made on a representative tank to a real tank. The demonstration made on two existing xenon tanks allowed to predict the frequency of their ovalization modes – through dimensionless number π_3 – with an absolute error lying between 0.2 % and 11 %. Dimensionless number π_4 through its variants π_{4F} and π_{4S} enables to determine the properties of the granular material whose dynamic behaviour in a tank would match that of a given fluid. Applied to supercritical xenon, this approach resulted in a metamaterial to fill the tank with so as to get the same frequency of occurrence for the ovalization and quadrifoliate mode, with an error of approximately 1 % only. This metamaterial composed of hollow spheres proved to be an adequate substitute to xenon for

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the dynamic study of its behaviour inside a tank, as a result of a methodology that can be applied to any other fluid.

7 Literature

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