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Preliminary study of the high-frequency instability of an aerospike rocket engine

Federico Rossi*, Roman Marchan, Olexiy Nikolayev**, Inna Bashliy****
***Pangea aerospace, C/Roc Boronat 117. 08018, Barcelona, Spain**
****Flight Control, 103A, Gagarina str, Dnipro 049050, Ukraine**
federico.rossi@pangeaaerospace.com, aleksey.nikolaev@flightcontrol.space, inna.bashliy@flightcontrol.space, roman.marchan@flightcontrol.space

Abstract

A demonstrator aerospike engine, developed by Pangea Aerospace, has a thrust of 2 metric tons and features a toroidal (annular) combustion chamber powered by liquid oxygen and liquid methane. Predicting the parameters of high-frequency processes of the engine chamber, issuing recommendations to ensure engine performance, high-frequency stability and dynamic strength of its structure, monitoring and analyzing the technical condition of the engine during testing are all important topics to be addressed before conducting static fire tests of the engine.
A mathematical model of a coupled 'shell structure with an annular configuration – gas' dynamic system for the engine with a toroidal combustion chamber has been developed. Based on the model, the preliminary predictive computations of the shapes and frequencies of natural oscillations have been performed, as well as computations of the amplitude of stresses and displacements of the combustion chamber structure under resonant excitation of this dynamic system. The results of such evaluations can ultimately be useful in ensuring the structural strength of the engine combustion chamber.
The natural oscillation modes of the 'shell structure with an annular configuration – gas' dynamic system, obtained from the analysis of the results of mathematical modeling, are due to the manifestation of natural acoustic properties of the chamber cavity, taking into account the influence of the combustion chamber structure.
The results of the theoretical studies are summarized and preliminary recommendations are formulated to increase the stability of the combustion chamber to possible high-frequency oscillations based on design measures (baffles, absorbers and parameter adjusting of the engine injectors).

1. Introduction

The demonstrator aerospike engine DemoP1, developed by Pangea Aerospace [1], has a thrust of 2 metric tons and features a toroidal (annular) combustion chamber (propellants: liquid oxygen and liquid methane). Predicting the parameters of high-frequency processes in the thrust chamber, issuing recommendations to ensure engine performance, high-frequency stability and dynamic strength of its structure, monitoring and analyzing the technical condition of the engine during the tests are all important topics [2] to be addressed prior to conducting the static fire tests of the DemoP1 engine.
The development of high-frequency instability (HF instability) of liquid-propellant rocket engines (LRE) during their firing tests is often accompanied by a significant increase in dynamic loads on the combustion chamber structure, which typically leads to its destruction. The successful experimental development of a LRE is largely dependent on the prediction, development and implementation of measures that ensure reliable operation of a LRE with sufficient resistance to high-frequency thermoacoustic oscillations of combustion products in the combustion chamber within the limits of its operating modes.
The exceptional complexity and poor knowledge of the physical phenomena leading to combustion instability were the reasons why the search for rational design options for mixing heads and damping devices for suppressing acoustic oscillations was carried out mainly empirically [3-7,10, 13] - on the basis of LRE bench tests performed at the engine main operational modes and subsequent analysis of the obtained results. At present, the development of methods for analyzing the combustion products oscillation processes in LRE combustion chamber, which are based on modern computer technologies, makes it possible to assess which frequencies of acoustic oscillations are the most dangerous

DOI: 10.13009/EUCASS2022-4543

from the point of view of LRE high-frequency instability development, as well as to develop measures to improve the stability of oscillation processes in LRE combustion chambers.

High-frequency instability in the LRE combustion chamber is developed as a dynamic process caused by the interaction of gas pressure oscillations (with the frequencies of acoustic oscillations in the chamber) and thermal processes during their combustion. Acoustic disturbances affect the burning rate and the oscillations improve the propellant mixing rate and reduce the combustion zone. As a rule, [3, 4, 13], the hazardous dynamic processes in case of HF instability of the combustion chamber occurs mainly at the lowest tangential acoustic modes, with oscillation frequencies above 1000 Hz. It is worth emphasizing that the aforementioned phenomena have resonant behavior. In addition, as a result of the dynamic processes development in the combustion chamber, we can observe such dynamic phenomena as bifurcations of the combustion process, with a sharp transition from one auto-oscillating mode to another mode (or realization of auto-oscillations at other 'pressure - mixture ratio' operating parameters) [5].

Vibration overloads of combustion chamber structural elements can reach 1000 g and even larger values [3, 4, 5]. If HF instability occurs with significant amplitudes of pressure oscillations, the strength limits of the combustion chamber structure can be exceeded. In addition, a disruption of the gaseous boundary layer in the combustion chamber is possible, followed by a burnout of the wall and destruction of the engine structure [4].

In accordance with classical approaches to the analysis of resistance to HF oscillations (for example, [3]), the studied LRE combustion chamber as a dynamic auto-oscillating system is divided into subsystems that describe the processes, namely: supply of propellants to the combustion chamber mixing head; mixing and combustion of propellants; motion of combustion products up to their outflow from the nozzle.

On the basis of a coupled system of equations describing these processes, the stability of the system to infinitesimal disturbances is analyzed, as well as, if necessary, to a certain level of steady-state oscillations and dynamic influences which are characterized as noise. In the linear analysis of the system stability, the system matrix coefficients are calculated, on the basis of which the characteristic values are determined, which serve to determine the stability of the coupled system, modes and frequencies of oscillations of thermoacoustic processes in the combustion chamber.

The mathematical description of the processes of mixing and converting propellants into combustion products (i.e. combustion processes) at the present stage is one of the most difficult problems to be solved when designing rocket engine combustion chambers. Unfortunately, at the stage of designing the DemoP1 LRE, due to uncertainty and complexity of simulation of the propellants mixing and conversion into the combustion products (which can be extremely specific for each engine), there are no possibilities for a numerical study of these processes. At present, these problems can be confidently solved only with involvement of experimental research data on dynamic processes in combustion chambers, especially in case of new original chamber designs.

In addition, when studying high-frequency instability of the DemoP1 engine on the basis of mathematical modeling, the dynamic processes determined by the system of propellant supply to the combustion chamber mixing head and the propellant flow through the chamber injectors were not considered.

In this paper, with respect to the conditions of the DemoP1 combustion chamber bench tests, the following tasks were solved:

1. Determination of modes and frequencies of acoustic oscillations based on the study of combustion products acoustic properties in the DemoP1 engine chamber, taking into account the elastic characteristics of its structure;
2. Development of recommendations for increasing the DemoP1 combustion chamber stability to high-frequency oscillations basing on the results of numerical analyses of forced acoustic pressure oscillations at the combustion chamber inlet.

2. Mathematical modeling of natural acoustic oscillations of combustion products in the DemoP1 engine combustion chamber, taking into account the dynamic interaction of combustion products with the chamber structure

2.1 Geometrical and operating parameters of the combustion chamber and construction of a finite-element model of the DemoP1 combustion chamber spatial oscillations. The main operating and design parameters of the DemoP1 engine annular combustion chamber, which were used in the calculations, are presented in Table 1.

DOI: 10.13009/EUCASS2022-4543

Table 1: DemoP1 high-level specifications

Parameter	**value**
Propellants	LOX/LNG
Cycle Pressure-fed Thrust (sea level)	20 kN
Specific impulse (sea level)	268 s
Mixture ratio	2.8
Expansion ratio	5
Dimensions, mm	240 x 240 x 260
Inlet gas pressure, bar	45
Inner radius of the outer cylinder, m	0.0815
Radius of the inner cylinder, m	0.055
Gas temperature, K	3345
Length of CC cylindrical section, m	0.1
Length of the section up to the throat, m	0.137
Speed of sound in combustion products in the chamber, m/s	1273
Speed of sound in combustion products in the throat, m/s	1230
Combustion products density in the chamber, kg/m^3	3.181
Combustion products density in the throat, kg/m^3	1.962
Average wall thickness, mm	8
Wall material Young's modulus, GPa	110

The computer mathematical model of the ‘shell structure – gas’ dynamic system spatial oscillations has been developed using modern finite-element techniques [19]. The parameters of combustion products (speed of sound, temperature, pressure) were calculated using the ASTRA software [8] in order to determine the thermodynamic equilibrium of the ‘methane - oxygen’ pair combustion process.

Figure 1 gives a finite-element representation of the combustion chamber gas cavity, with a toroidal design, and the design of the LOX downcomer. The total number of finite elements used in the model is 172272.

2.2 Research method and calculated acoustic oscillation modes in the DemoP1 combustion chamber with annular (toroidal) configuration. The method for calculating the parameters of high-frequency acoustic oscillations in the combustion chamber can be attributed to the group of the so-called hybrid methods (for example, [18]) for analyzing the combustion stability in the combustion chamber, in which the parameters of acoustic oscillations of combustion products in the combustion chamber are calculated separately from combustion dynamics.

The calculation of the combustion products acoustic oscillations parameters was carried out on the basis of a coupled dynamic system model - ‘shell structure of an annular configuration – gas’. This approach (modal analysis) makes it possible to take into account the structure elasticity influence on the combustion products acoustic properties in the studied configuration of the combustion chamber. The boundary conditions in solving the problem of natural oscillations were determined by the geometry and method of fastening the combustion chamber structure to the bench

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base, as well as by the conditions associated with the flow on the hot-gas wall and with the supersonic outflow of the combustion products from the nozzle.

By means of the computer-aided engineering system [16] the parameters of the DemoP1 combustion chamber oscillations (natural frequencies and effective masses of the 'shell structure – gas' dynamic system applied to the selected directions) was performed.

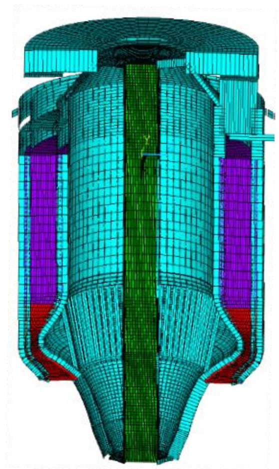


Figure 1: The graphic representation of the finite-element model of the DemoP1 engine annular combustion chamber (172272 elements)

The results on computation of the parameters of the coupled 'shell structure – gas' dynamic system: natural oscillations depending on the direction of the coordinate axes are given in Table 2.

Table 2: Parameters of oscillation dominant modes (frequencies and effective masses) of the DemoP1 thrust chamber

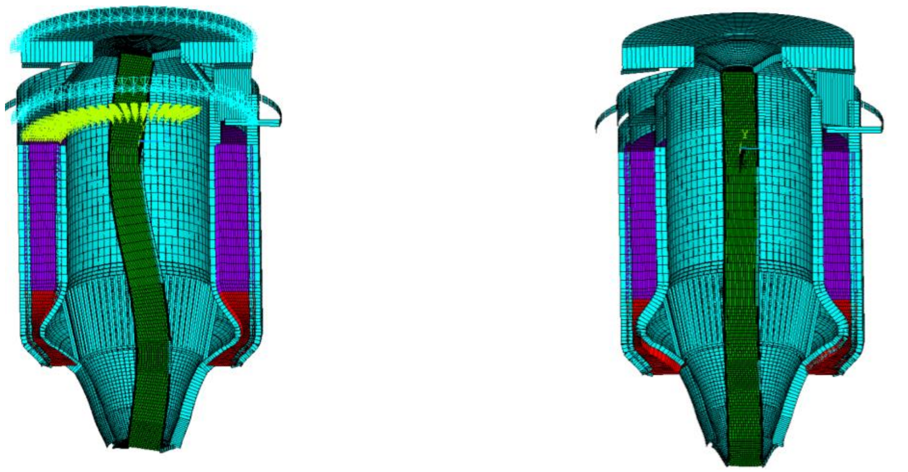
Mode number j	Frequency f_j, Hz	Effective mass M_j, kg	
Longitudinal direction			
1	2069	3.06	**1L**
2	3212	1.19	**2L**
3	5045	3.59	**3L**
Transverse direction			
1	654.9	1.93	
2	672.8	2.07	
3	1943.0	1.94	**1T**

Table 2 contains the dominant (with the most significant effective masses of the dynamic system in the indicated direction of the calculated coordinate system) natural oscillation frequencies. It should be noted that the calculated oscillation frequencies characterize the dynamic properties of the coupled dynamic system 'shell structure of annular

DOI: 10.13009/EUCASS2022-4543

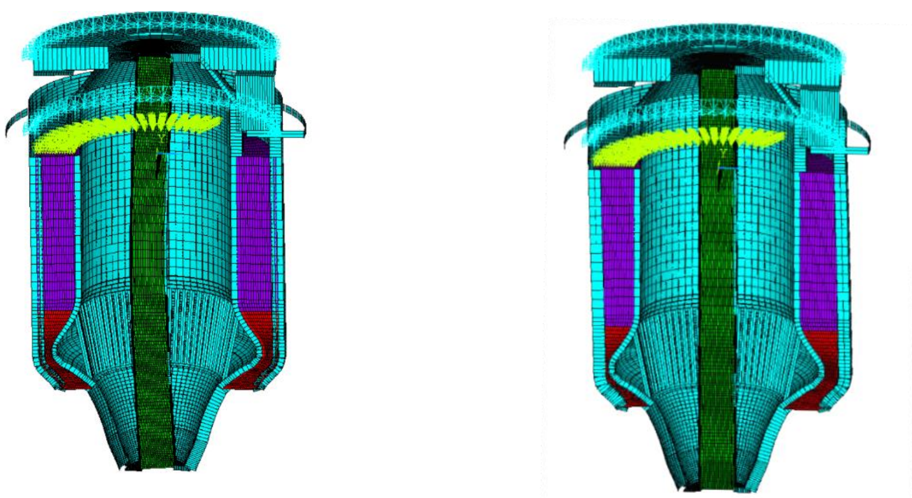
configuration – gas', meaning that, in general, these are the frequencies of coupled oscillation modes. In Table 2, some oscillation frequencies, which are closer to 'pure' acoustic longitudinal or tangential modes,are designated as **1L - 3L** or **1T**.

The shapes of the natural longitudinal modes of the DemoP1 engine are presented in Fig. 2, while the transverse oscillation modes are given in Fig. 3. It should be noted that the natural oscillation mode shapes shown in the figures are given in relative (not actual) displacements for maximum clarity.



a) b)

Figure 2: The natural longitudinal oscillation mode shapes of DemoP1: a) 2069 Hz frequency oscillation mode, b) 3212 Hz frequency oscillation mode



a) b)

Figure 3: Natural transverse mode oscillation shapes of DemoP1: a) 673 Hz frequency mode, b) 1943 Hz frequency oscillation mode

Based on the analysis of the above results, the following conclusions can be drawn.
The most undesirable oscillations for the vibration strength of the DemoP1 engine chamber can be the oscillations with a frequency of 1943 Hz due to the acoustic **1T** oscillations of combustion products in the chamber, and those with a frequency from 654 Hz to 672 Hz due to transverse oscillations of the LOX downcomer.

DOI: 10.13009/EUCASS2022-4543

The **1T** frequency of acoustic oscillations of combustion products in the chamber (about 1943 Hz) is numerically close to the frequency of 2060 Hz of the system longitudinal oscillation modes. In this situation, the dynamic interaction of the subsystems (structure and gas) is possible, in which a resonant increase in the amplitudes of pressure oscillations in the combustion chamber and structural vibration amplitudes in the lower part of the combustion chamber could appear during firing tests.
The transverse oscillation frequency of the coupled system 'shell structure – gas' (from 654 Hz to 672 Hz) is due to the dynamic interaction of oscillations from the LOX downcomer and the structure of the combustion chamber itself. These oscillations can be adjusted in amplitude and partial frequency by introducing additional means for constraining this pipeline, which will create conditions for increasing the strength of this structural element.
It should be noted that the numerical values obtained for the natural oscillation frequencies (tangential mode **1T**) of combustion products in the DemoP1 combustion chamber are lower than the **1T** frequency value of the first tangential oscillation mode calculated by the formula [11]

$$f_{\tan g} = \frac{2 * C}{\pi (D_{in} + D_{out})},$$

following from the theoretical solution of the problem of natural oscillations of a gas in an annular cavity with absolutely rigid walls. For example, for the combustion products speed of sound C = 1273 m/s, the **1T** frequency value of the first tangential mode of the annular chamber is $f_{1\ tang}$ = 2979 Hz.
To analyze the effect of the chamber structural stiffness, the calculation of the DemoP1 engine natural oscillation parameters was carried out with a doubled structural stiffness (with an increased value of the Young's modulus *E*=220 GPa, corresponding to steel alloys). As a result, the calculated dominant frequency **1T** of tangential (transverse) oscillations was increased to 2561 Hz, which is approximately 30 percent higher than the **1T** frequency from Table 2 and approaches the acoustic frequency $f_{1\ tang}$. For the DemoP1 engine structure, the rigidity of the wall material used for additive manufacturing of the chamber is two times lower (with Young's modulus of *E* =110 GPa). Therefore, the decrease in frequency to ~ 1943 Hz is a consequence of taking into account the stiffness of the walls, as well as the configuration of the combustion chamber, that differs from a cylindrical one.
The influence of the combustion chamber configuration aspects and physical properties of the chamber gas sound speed are also impress for the traditional cylindrical combustion chamber. In modern experimental studies (for example, in [14]) performed for a cylindrical chamber, it follows that the dynamic interaction of the gaseous medium with the combustion chamber structure can lead to a certain decrease in the speed of sound and, consequently, to a decrease in the experimental values of the first tangential mode frequency compared to the theoretical values [6, 11, 12]).
In order to assess the effect of an increase in the operating temperature of the chamber walls up to 700 K (at which the Young's modulus will decrease to *E*=91 GPa) on the dominant longitudinal modes, the frequencies and shapes of natural oscillations of the annular gas cavity were calculated for this wall temperature. In this case, the dominant frequency **1T** (1943 Hz in Table 1) of tangential (transverse) oscillations went down to 1834 Hz. In addition, in the same calculation, a more rigid constraint for the liquid oxygen downcomer in its upper section was taken into account.

3. The analysis of the coupled dynamic 'shell structure – gas' system forced oscillations by harmonic excitation of chamber combustion products amplitudes in the DemoP1 combustion chamber has been performed, in particular, for an amplitude ΔPcc =3 bar for the forced, non-symmetric pressure oscillations in the inlet part of the chamber volume. This value represents from 5% to 7 % of the nominal combustion chamber pressure *Pcc*. This value is determined considering the limiting values of allowable disturbance amplitudes (including the permissible experimental noise level [5]) in the combustion chambers of former Soviet liquid rocket engines.

According to Fig. 4, a non-symmetric harmonic (with 3 bar pressure amplitude) disturbance ΔPcc of the combustion products generates a maximum dynamic stress σ_i (up to ~31 MPa) in the DemoP1 engine structure, occurring in the upper part of the combustion chamber outer shell, where it joins the mixing head (see Fig. 4). The distribution of the dynamic displacement components *U* over the outer shell, with frequency 1T of 1834 Hz, is shown in Fig. 5.

DOI: 10.13009/EUCASS2022-4543

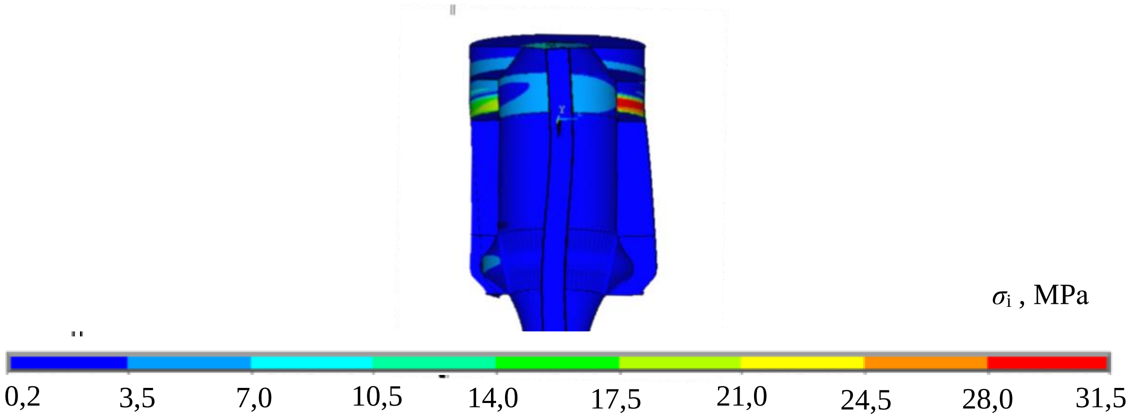


Figure 4: Dynamic stress components in the DemoP1 engine structure at non-symmetric harmonic disturbance with a 3 bar pressure amplitude and transverse oscillation frequency of 1834 Hz

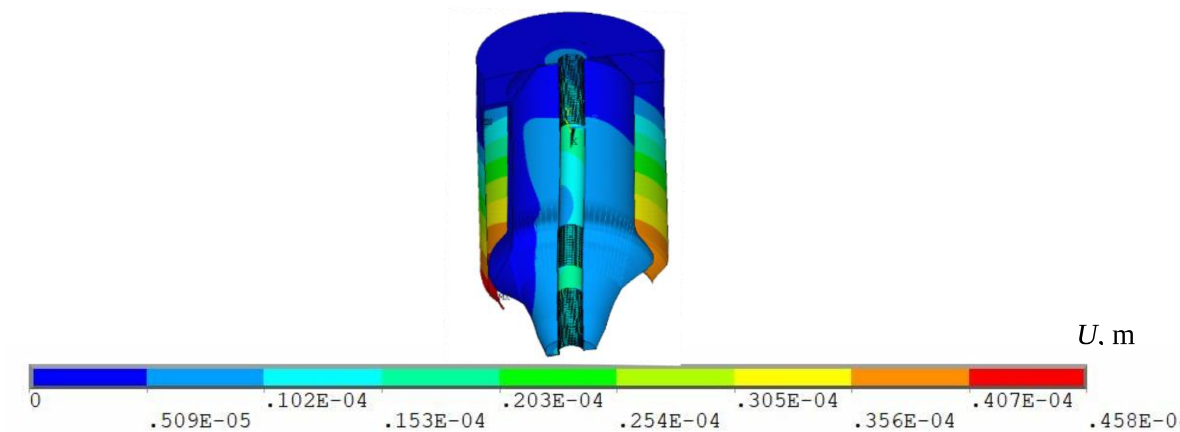


Figure 5: Distribution of dynamic (vibration) displacement components over the outer shell of the DemoP1 engine structure at non-symmetric harmonic disturbance with 3 bar amplitude and a transverse oscillation frequency of 834 Hz

At the same time, the pressure oscillation amplitude *P* of the combustion products close to the throat section rises to ~14 bar, for a 3 bar non-symmetric harmonic disturbance (see Fig. 6).

After preliminary discussion of the results shown in the figures (from Fig. 2 to Fig. 6) a decision was taken to strengthen the central liquid oxygen downcomer with internal stiffeners, as well as to add fins to the outer shell of the DemoP1 engine structure. In order to assess the effect of these measures on the combustion chamber vibrational strength, calculations were conducted for the updated design of DemoP1 at the higher value of the equivalent modulus of elasticity (E=110 GPa), outer wall thickness varying from 22 mm to 8 mm, and inner wall thickness of 13 mm.

As shown by results, the frequency of the combustion chamber oscillations (determined by the natural oscillation of the LOX pipeline**)** increased from 673 Hz to 1030 Hz, and the oscillation frequency of the tangential mode **1T** increased to 2107 Hz after strengthening the pipeline and outer shell structure **(**E=110 GPa**)**. The amplitudes of transverse displacements with 1030 Hz frequency, in the least-constrained section of the LOX downcomer, decreased (by 2.6 times) down to 0.41 10^{-4} m (see Fig. 7). The maximum dynamic stress components in the DemoP1 engine structure at the transverse oscillations frequency of 1030 Hz decreased by 1.8 times down to ~40 MPa (see Fig. 8).

DOI: 10.13009/EUCASS2022-4543

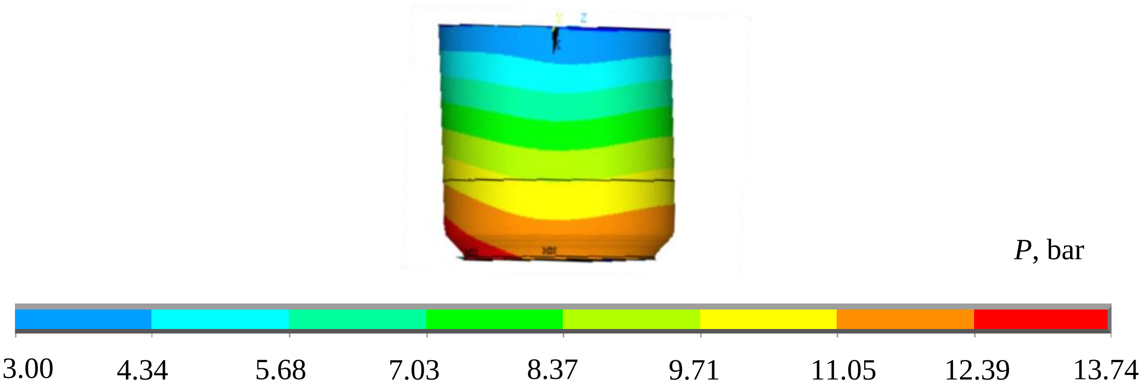


Figure 6: Distribution of gas pressure dynamic component in the annular chamber of DemoP1 for a non-symmetric harmonic disturbance with 3 bar amplitude and a transverse oscillations frequency of 1834 Hz

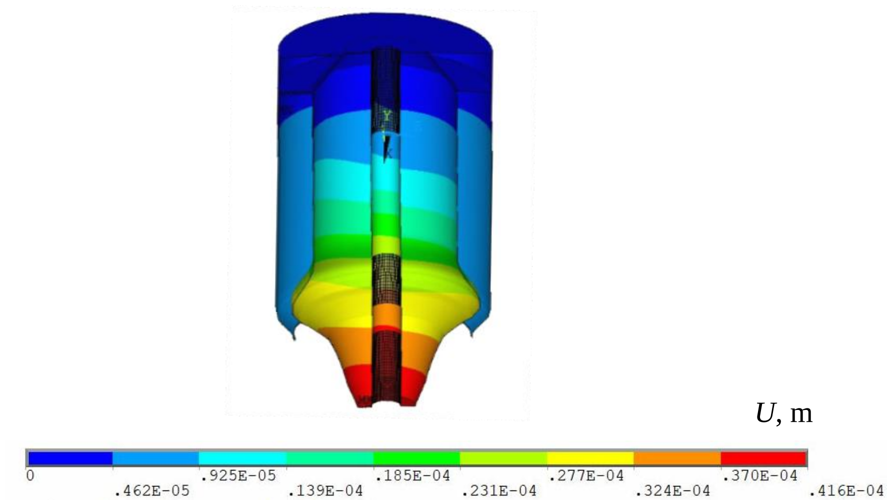


Figure 7: Dynamic displacement components in the DemoP1 engine structure for a non-symmetric harmonic disturbance with 3 bar amplitude and a transverse oscillations frequency of 1030 Hz after strengthening the pipeline and outer shell structure

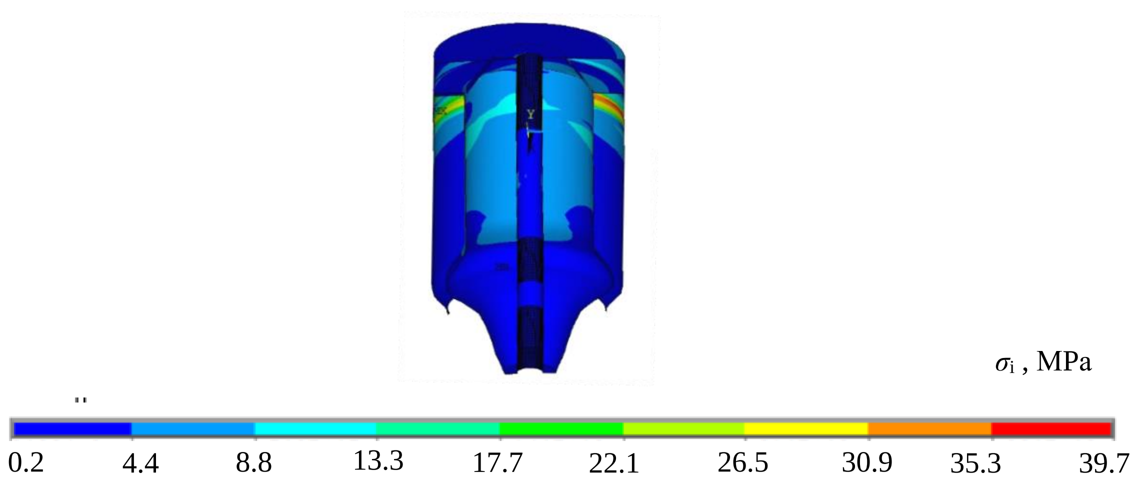


Figure 8: Dynamic stress components in the DemoP1 engine structure for a non-symmetric harmonic disturbance with 3 bar amplitude and a transverse oscillations frequency of 1030 Hz after strengthening the pipeline and outer shell structure (*E*=110 GPa)

DOI: 10.13009/EUCASS2022-4543

Similar results (Fig. 9, Fig. 10) were obtained for the cases with given dynamic disturbance of pressure in the upper section of the combustion chamber with a frequency **1T** – 2107 Hz and an amplitude of 3 bar. The maximum amplitudes of the transverse displacements (Fig. 9) decreased by 2.56 times, if compared with the option without strengthening the chamber structure (see Fig. 7)). At the same time, pressure oscillation amplitude level of the combustion products in the section close to the throat was about 4.8 bar (see Fig. 11), which is 2.8 times less than in the case without strengthening the pipeline and outer shell structure (see Fig. 6). The analysis results showed that the zone with maximum stress is located near the place where the injector head is connected to the outer shell of the chamber and, in the studied cases, the zone of maximum transverse displacements is located near the throat on the outer wall of the chamber.

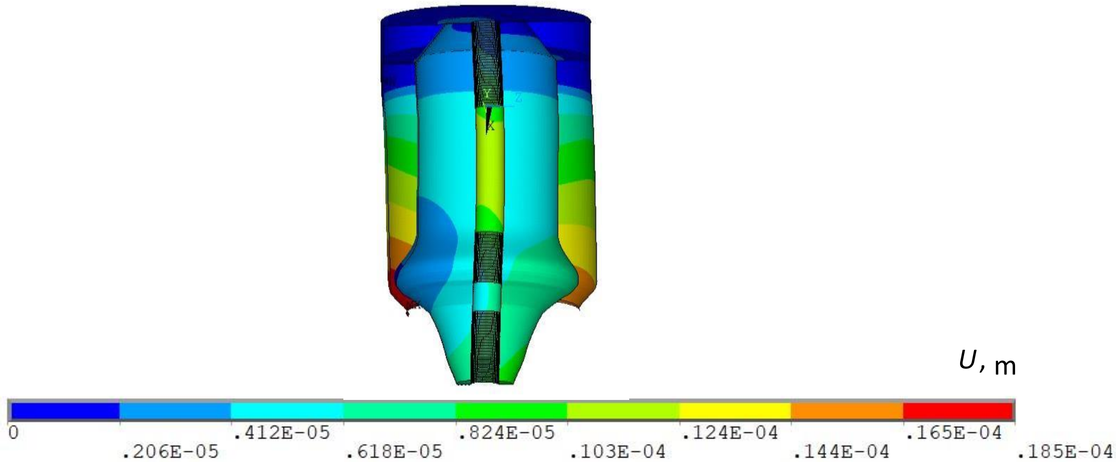


Figure 9: Dynamic displacement components in the DemoP1 engine structure at non-symmetric harmonic disturbance with 3 bar amplitude and transverse oscillations frequency of 2107 Hz after strengthening the pipeline and outer shell structure

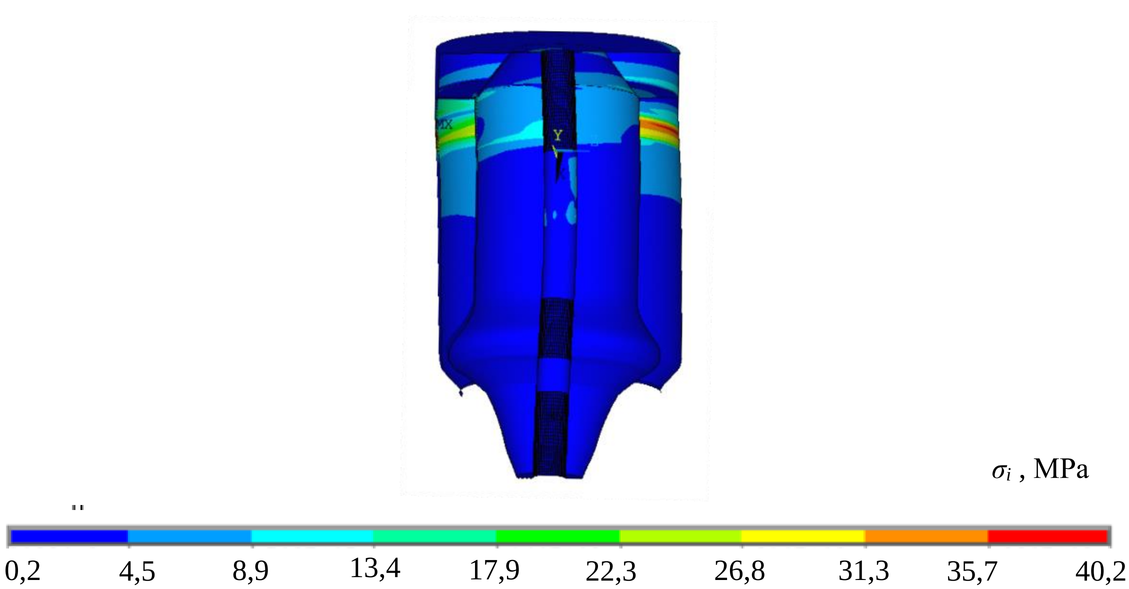


Figure 10: Dynamic stress components in the DemoP1 engine structure at non-symmetric harmonic disturbance with 3 bar pressure oscillation amplitude and transverse oscillations frequency of 2107 Hz after strengthening the pipeline and outer shell structure

DOI: 10.13009/EUCASS2022-4543

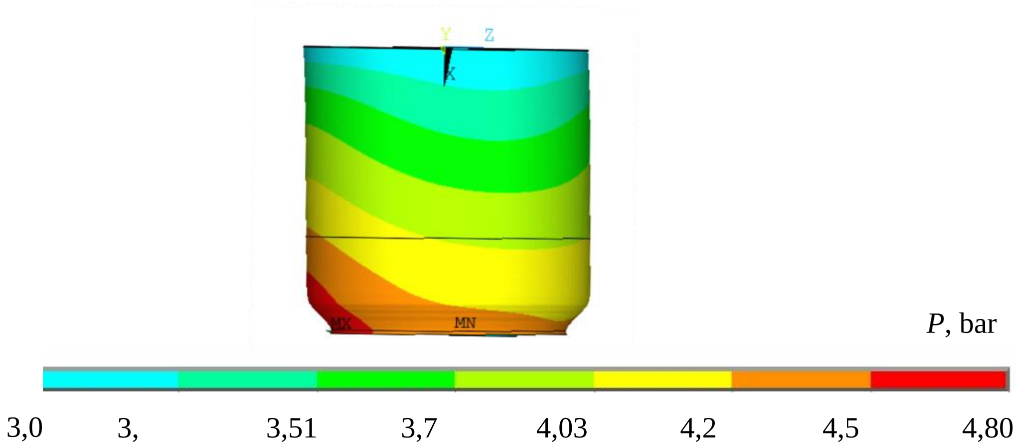


Figure 11: Distribution of gas pressure dynamic component in DemoP1 engine annular chamber at non-symmetric harmonic disturbance with 3 bar amplitude and transverse oscillations frequency of 2107 Hz after strengthening the pipeline and outer shell structure

4. Preliminary results from the hot-fire tests of DemoP1

Pangea Aerospace successfully fired the DemoP1 aerospike engine in a series of tests at the P8 facility in Lampoldshausen, Germany in 2021 (Fig.12).

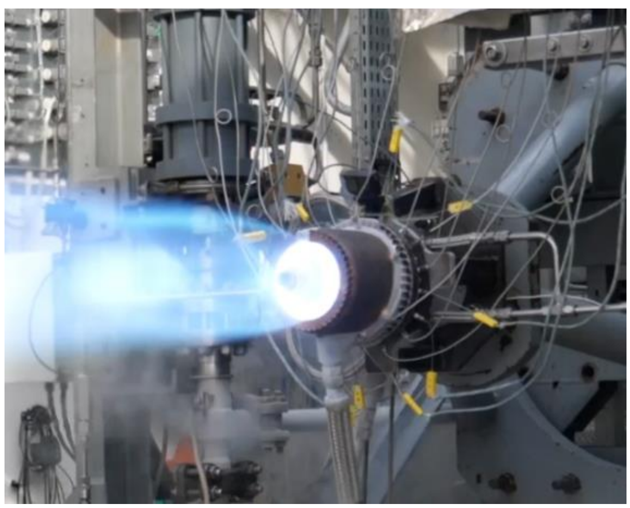


Figure 12: The LOX/LNG aerospike engine DemoP1 during a firing test

Those tests, performed over a month, included one test where the 20-kilonewton engine ran for two and a half minutes. Measurements of liquid oxygen pressure oscillations at the combustion chamber inlet, as well as structural acceleration measurements (in the longitudinal and transverse direction) confirmed a rather high accuracy of the earlier predictions of oscillation frequencies per oscillation modes (within the error margin in determining the speed of sound in combustion products). According to Fig. 13, the oxidizer pressure spectral density has resonance maxima of the lowest vibration modes with frequencies of 838.5 Hz; 2292.2 Hz (in the theoretical analysis, these oscillation frequencies were from 654.9 Hz to 1030 Hz and 2107 Hz).

DOI: 10.13009/EUCASS2022-4543

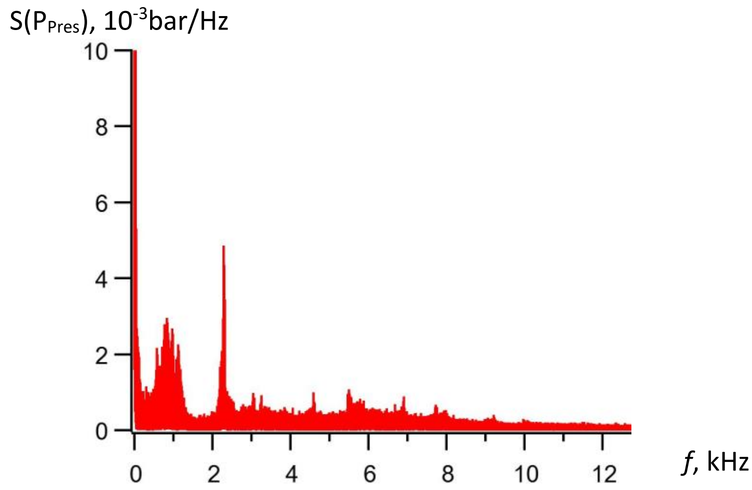
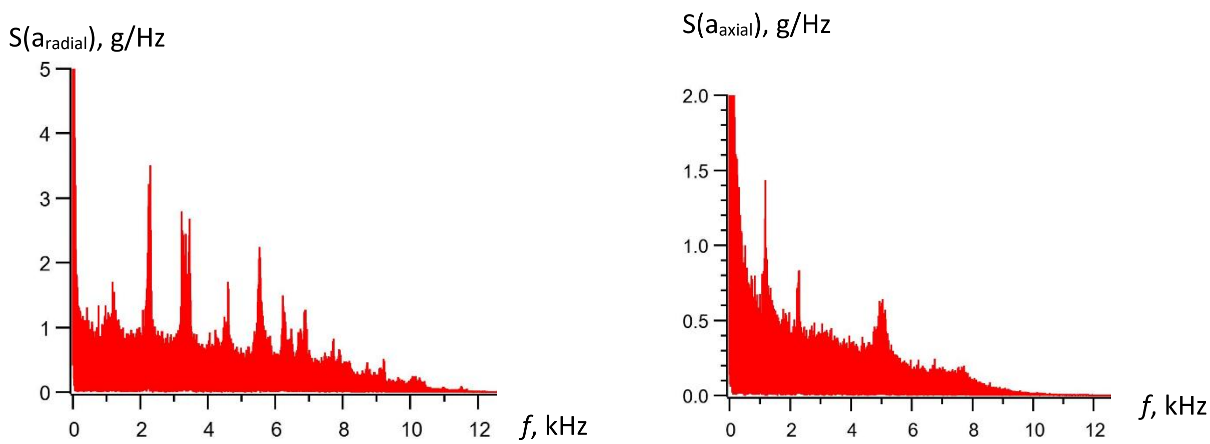


Figure 13: Spectral densities of *S* signals obtained after processing the oxidizer pressure oscillation sensor data P_{Pre} at the DemoP1 engine inlet within frequency range from 0 kHz to 12 kHz

The study of the spectral analysis of the experimental longitudinal and transverse accelerometer signals also confirmed the reliability of the developed dynamic system model ‘shell structure of annular configuration - gas (combustion products)‘. The experimental spectral densities are shown in Fig. 14. Based on the analysis of this set of data, it follows that the design values of the dominant mode frequencies of 1030 Hz and 2107 Hz (reinforced design of the chamber structure) in the predictions made earlier are close to the values obtained in the resonant frequency analysis of the spectral densities of the longitudinal (1176 Hz; 2273 Hz) and transverse (1182 Hz; 2246 Hz) vibration accelerations during the firing tests.

The measures to strengthen the DemoP1 chamber design, which were developed on the basis of the analysis of the combustion products pressure dynamic component, made it possible to carry out its fire tests without deterioration of the engine performance and high-frequency instability of the structure within the limits of its operating modes.



a) b)

Figure 14: Spectral densities of *S* signals obtained after processing the transverse a_{radial} and axial a_{axial} accelerometer data from DemoP1 engine structure within frequency range from 0 kHz to 12 kHz

5. Conclusion

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DemoP1 is a LOX/LNG aerospike engine demonstrator developed by Pangea Aerospace. The demonstrator has been designed, manufactured and tested to characterize low-TRL technologies that are becoming central in the rocket propulsion field, such as the use of liquid methane, additive manufacturing and reusability. Prior to the DemoP1 engine firing tests, Flight Control has developed a mathematical model, predicted its dynamic characteristics and developed recommendations to ensure its resistance to high-frequency oscillations. The main conclusions based on the results of the study are as follows:

1. The model of the 'shell structure of annular configuration – gas' coupled dynamic system of the engine with a toroidal combustion chamber has been developed. The computer model was the basis for the preliminary calculations of frequencies and modes of natural oscillations, as well as for the evaluation calculations of the combustion chamber structure stress and displacement amplitudes under resonance excitation of this dynamic system. After analyzing the results of dynamic loads on the combustion chamber, its structure was strengthened. The results of such analysis were ultimately used to ensure the strength of the combustion chamber structure of the DemoP1 engine during firing tests.
2. The dominant natural frequencies of the DemoP1 engine 'shell structure of annular configuration – gas' system were obtained based on the analysis of the mathematical simulation of the high-frequency dynamics of the acoustic chamber cavity taking into account the influence of the structural properties of the DemoP1 engine combustion chamber. For the studied annular combustion chamber, it has been determined that the most dangerous oscillation frequency of the first tangential mode of combustion products acoustic oscillations is the 1943 Hz frequency of the coupled dynamic system 'shell structure – gas', and after reinforcement of the chamber structure – 2107 Hz. The increased oscillation amplitudes and stresses of the chamber structure can also occur at a frequency of 1030 Hz (654 Hz prior to reinforcement of the chamber structure), which is due to the natural transverse oscillations of the LOX downcomer.
3. The evaluation of the pressure oscillation amplitudes in the DemoP1 combustion chamber has been performed with specified frequencies and 3 bar amplitude of forced non-symmetric pressure oscillations at the combustion chamber inlet. This amplitude pressure oscillation value is set based on the usual maximum chamber noise level (from 5 % to 7 % of the nominal combustion chamber pressure). Based on the preliminary analysis results, it has been demonstrated that at forced pressure oscillations with a frequency of 1834 Hz the transverse pressure oscillation amplitudes of the outer chamber shell can reach dangerous values at the chamber throat section.
4. After modeling the dynamic system with the changes implemented in the chamber structure (reinforcement of the LOX downcomer with internal stiffeners, as well as adding fins to the outer shell of the engine structure) at forced combustion products pressure oscillations with the frequency of 1030 Hz, the maximum stress amplitude was decreased by 1.8 times. The results of the analyses of the oscillation parameters with tangential mode frequency of 2107 Hz for the new chamber design have demonstrated that the amplitude of the transverse displacements decreased by 2.5 times in comparison with the original design, and the combustion products pressure oscillation amplitudes in the section close to the throat were 2.8 times lower.
5. The analysis of the measurements of the liquid oxygen pressure oscillations at the combustion chamber inlet, as well as structural vibration acceleration measurement results (in longitudinal and transverse direction) during the DemoP1 engine firing tests have confirmed the reliability of the performed prediction of oscillation frequencies per oscillation modes (within the small error margin in determining the speed of sound in combustion products basing on thermodynamic calculation of the processes in the chamber). The design modifications on the DemoP1 chamber structure developed on the basis of these prediction made it possible to carry out firing tests without deterioration of the engine performance nor high-frequency instability.

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