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Experimental study on the dynamics of a pull-tab multi-chamber arched inflatable membrane structure

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Abstract

The pull-tab multi-chamber arched inflatable membrane structure has attracted considerable attention in fields such as emergency rescue engineering due to its lightweight, high storage efficiency, and convenient transportation and installation. However, the vibration characteristics of this typical structure remain unclear. Therefore, this paper focuses on investigating the vibration characteristics of this structure under different internal inflation pressures. To this end, a modal test system for a pull-tab multi-chamber arched inflatable membrane structure is developed to conduct vibration tests on the typical structure in air. An inflation pump is used to adjust the experimental structure's internal pressure. The application of a laser displacement sensor array is to obtain the vibration data of observation points. The combined application of Fast Fourier Transform (FFT) and Stochastic Subspace Identification (SSI) methods is to process the vibration data and obtain the frequency and mode shapes of the structure. Experimental studies indicate that with the increase in internal inflation pressure, the span of the structure gradually decreases, but the magnitude of the change is small. Meanwhile, the vibration frequency increases with the increase in internal pressure but gradually tends to stabilize. The mode shapes of the structure conform to the characteristics of arched structures. This research broadens the understanding of the vibration characteristics of the pull-tab multi-chamber arched inflatable membrane structure and contributes to the further application of this structure.

Keywords: Pull-tab multi-chamber arched inflatable membrane structure; Vibration characteristics; Internal inflation pressure

1. Introduction

The sudden onset of the COVID-19 pandemic has greatly increased the demand for medical resources in a short period, especially the need for many medical facilities to ensure public access to healthcare and the implementation of epidemic prevention policies[1]. However, the limited traditional medical facilities obviously cannot meet the demand for many medical resources in a short time. Therefore, it is essential to install rapid and easily transferable emergency medical structural facilities, which are key to improving emergency medical capabilities. In addition to the demand for emergency medical services, military field deployments, logistics support, and other tasks also require building structures with good environmental adaptability and easy installation.

Due to their advantages, such as lightweight, quick installation, small storage volume, and convenient transportation, inflatable structures have attracted considerable attention as a new type of building structure in the field of rapid application structures[2–7]. Inflatable structures consist of external membrane materials, membrane strips, and fixings, forming a structure supported by gas within the membrane cavities. Compared to traditional structures, inflatable structures can achieve large-span architectural structures with fewer support components. The rapid inflatable forming method greatly shortens the construction period and reduces costs, and the high storage efficiency is also conducive to transportation. Large-span inflatable structures are now widely used in public buildings such as airports, stations, exhibition centers, and stadiums[8].

In 2013, Spain designed and produced the H54 inflatable hangar, the largest inflatable structure in the world at that time. Spain broke the record again in 2019 by designing and producing the H75 inflatable hangar, which is currently the largest inflatable structure in the world[8]. The H75 inflatable hangar has a diameter of 7.5 meters, a width of 99 meters, a height of 33 meters, and a total length of 95.8 meters. It can accommodate wide-body aircraft such as the B777-200 and A330-300, as shown in Figure 1. The installation time of the H75 inflatable hangar, including loading and unloading time, is one month, fully demonstrating the advantages of rapid installation of inflatable structures.

Figure 1: Buildair H75[8]

Although installing traditional inflatable structures is already quite convenient, installing inflatable structures still requires many on-site assembly, strapping, and other steps, which still take a long time. However, the pull-tab multi-chamber arched inflatable membrane structure effectively addresses this issue[1]. Compared with traditional inflatable structures, the pull-tab multi-chamber inflatable membrane structure also has the advantages of lightweight, high storage efficiency, quick installation, and convenient transportation. In addition, the pull-tab multi-chamber arched inflatable membrane structure can be prefabricated in the factory, and the inflatable structure framework can be transported to the site for inflation and molding. This structural form eliminates on-site assembly, strapping, and other steps, greatly reducing the installation time of inflatable structures.

The more expedited installation method gives the pull-tab multi-chamber inflatable membrane structure broad application prospects. The analysis of the vibration characteristics of arched inflatable membrane structures plays an important role in ensuring the safety, stability, and comfort of the structures. However, research on the vibration of pull-sheet multi-chamber inflatable membrane structure has not yet received attention. Therefore, this paper conducts relevant research on the vibration characteristics of this structure. A modal test system is designed and produced in this paper to explore the vibration characteristics of the structure under different internal inflation pressures. The application of laser displacement sensor arrays is to obtain vibration information at observation points. The detailed content is described below.

2. Experimental system

This paper designs and constructs a modal test system for the pull-sheet multi-chamber inflatable membrane structure to explore the vibration characteristics of the pull-tab multi-chamber arched inflatable membrane structure. The test system comprises the experimental inflatable membrane structure and the modal identification subsystem. Figure 2 depicts the on-site layout of the test system. The detailed introduction of the test system is described below.

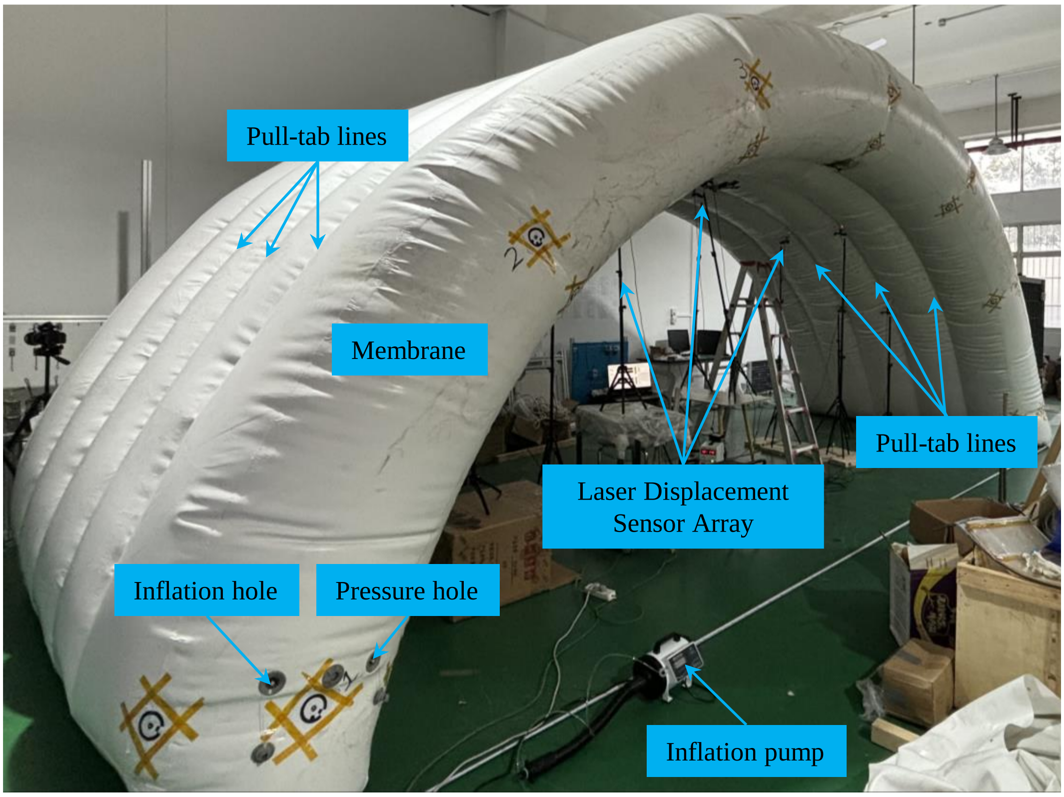

Figure 2: Layout of experimental system

2.1. Pull-tab multi-chamber arched inflatable membrane structure

The pull-tab multi-chamber arched inflatable membrane structure consists of a framework composed of membrane and multiple pull-tabs forming multiple air chambers supported by internal air. The structure framework is prefabricated in the factory according to the design plan. The final formation of the structure is achieved by an intelligent inflation pump directly inflating it on-site.

2.1.1. Experimental membrane structure

The structural framework is mainly composed of membrane and pull-tabs. The membrane mainly includes upper and lower membranes, sealing, and bottom membranes. The structure adopts four pull tabs, dividing the structure into five chambers, as shown in Figure 2. The net span of the structure is designed to be 6 meters, the net height is 2.996 meters, and the thickness is 0.6 meters. The width of each chamber is 0.6 meters. The membrane and pull-tabs use Common PVDF materials, and the main parameters of the materials are listed in Table 1. The framework of the structure is prefabricated in the factory according to the design plan.

Table 1: Major parameters of membranes and pull-tabs

Item	Thickness (mm)	Density (kg/m^3)	Poisson's ratio
Membrane	0.84	1500	0.42
Pull-tab	0.25	750	0.35

2.1.2. Inflation device

The main task of the inflation device is to inflate the structure framework to create internal pressure, and the inflated structure is supported by the internal gas pressure to achieve its final form, as shown in Figure 2. This paper utilizes an intelligent inflation pump to achieve the inflation function. It can automatically replenish air, release pressure, and measure pressure, ensuring the inflated structure remains stable at the preset internal pressure. Corresponding to the inflation pump, there is an inflation hole and a pressure testing hole on the structure framework.

2.2. Modal identification subsystem

The application of the modal identification subsystem is to obtain the vibration displacement information of observation points on the inflated structure and identify the structural vibration frequencies and modes through the vibration displacement information of observation points. The modal identification subsystem mainly includes displacement measurement devices and modal identification methods. A detailed introduction of the modal identification subsystem is provided below.

2.2.1. Displacement measurement device

The applied displacement measurement device is used to record the vibration information of the inflatable membrane structure, namely, time-displacement information. Laser displacement sensor arrays are a non-contact method for measuring vibration information and have been widely used in experiments on modal information of membrane structures[9–13]. Table 2 lists the main parameters of the laser displacement sensors. Five laser displacement sensors are evenly distributed along the length of the central chamber. The five laser displacement sensors are evenly distributed on the membrane surface. The arrangement scheme of the laser displacement sensors is shown in Figure 3, where adjustable-height tripods support the laser displacement sensors. By adjusting the height and position of the tripods, the laser displacement sensors are placed within the measurement range to ensure effective sensor utilization.

Table 2: Technical specifications of the laser displacement sensors

Item	Value
Measurement center distance	50mm
Measurement range	±15mm
Repeatability	30μm
Response time	1.5ms

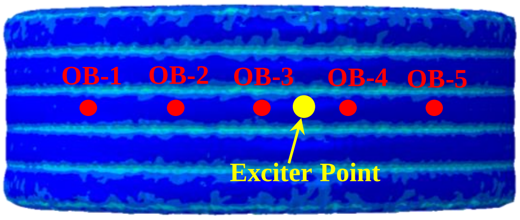

Figure 3: Locations of laser displacement sensors

After the laser displacement sensors are positioned, a person manually strikes the inflatable membrane structure from the inside to excite the structure. At the same time, all laser displacement sensors record the vibration displacement data of observation points, which is the time-displacement data. This time-displacement data will be used as the raw data for modal identification. The excitation point is located near the center of the structure, as indicated by the blue dots in Figure 3. Such an excitation position can effectively stimulate the structure while ensuring that no lateral displacement occurs.

2.2.2. Modal identification method

The modal identification method is a technique used to obtain structural modal information, such as mode shapes and frequencies, by processing time-displacement data. The FFT method in the frequency domain and the SSI method in the time domain are widely applied in modal identification of engineering structures. The FFT method can accurately identify structural frequencies but cannot obtain mode shapes. Although the SSI method can identify frequencies and mode shapes, it generates many redundant results. Combining the characteristics of the FFT and SSI methods, their joint application effectively identifies the frequencies and mode shapes of structures, which has been validated in rectangular membranes and air cushions[9,10]. Therefore, this paper will utilize the combination FFT and SSI method to process displacement data to obtain structural frequencies and mode shapes. Figure 4 depicts the flowchart of the modal identification method. As shown in Figure 4, f_a and f_b represent the structural frequencies calculated by the FFT and SSI methods, respectively, and ϕ_b represents the structural mode shape identified by the SSI method. Considering $f_a = f_b$ and ϕ_b being the reasonable mode shape, f_b and ϕ_b are the true results. Otherwise, they are false results.

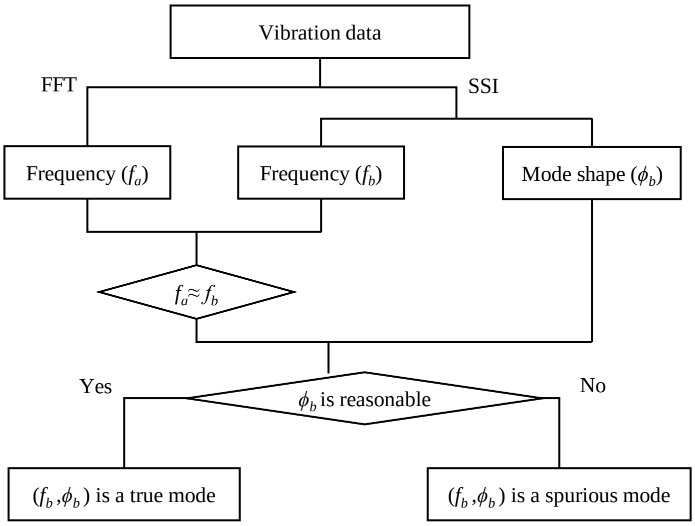

Figure 4: Modal identification method

2.3. Experimental procedures

As mentioned in the previous section, a modal identification experimental system for inflatable membrane structures has been designed and integrated. The inflatable membrane structure is inflated to a preset internal inflation pressure state by an intelligent inflation pump to complete the preliminary formation of the structure. After the preliminary formation of the structure, the laser displacement sensor array is arranged according to the arrangement of observation point positions and measurement range requirements. After completing the above preparations, the structure is manually struck at the excitation point. At the same time, the laser displacement sensors record the vibration information of the observation points. After collecting the data, the modal identification method is used to process the time-displacement data obtained by the laser displacement sensors to obtain the frequencies of the structure.

3. Results and discussions

3.1. Structure spans in different internal inflation pressures

The prefabricated structural framework is inflated using an intelligent inflation pump to obtain the inflatable membrane structure. This paper explores the vibration characteristics of the inflatable membrane structure under different internal inflation pressures. Table 3 lists the changes in the span of the structure under different internal inflation pressures. Table 3 indicates that the increase in internal inflation pressure causes the structural span to decrease gradually, but the magnitude of the change is small. The friction between the inflatable membrane structure and the ground leads to the above phenomenon, which is also one of the advantages of the inflatable membrane structure. When the internal inflation pressure of the structure reaches the preset value, small changes in the internal inflation pressure of the structure have little impact on the span of the structure.

Table 3: Structure spans in different internal inflation pressures

Internal inflation pressure (KPa)	Structure span (m)	Internal inflation pressure (KPa)	Structure span (m)
1.5	7.372	3.0	7.356
2.0	7.375	3.5	7.344
2.5	7.364	4.0	7.346

3.2. Frequencies and mode shapes in different internal inflation pressures

Figure 5 shows the structural mode shapes under different internal inflation pressures. Figure 5 demonstrates that the first two mode shapes of the structure are anti-symmetric and symmetric, respectively, similar to the mode shapes of an arched structure. Table 3 also indicates that the span of the inflatable membrane structure remains stable after inflation, indicating that the friction between the structure and the ground effectively constrains the displacement of the structure. Such practical constraint transforms the inflatable membrane structure into a structure similar to an arch, hence its mode shapes resemble those of an arched structure.

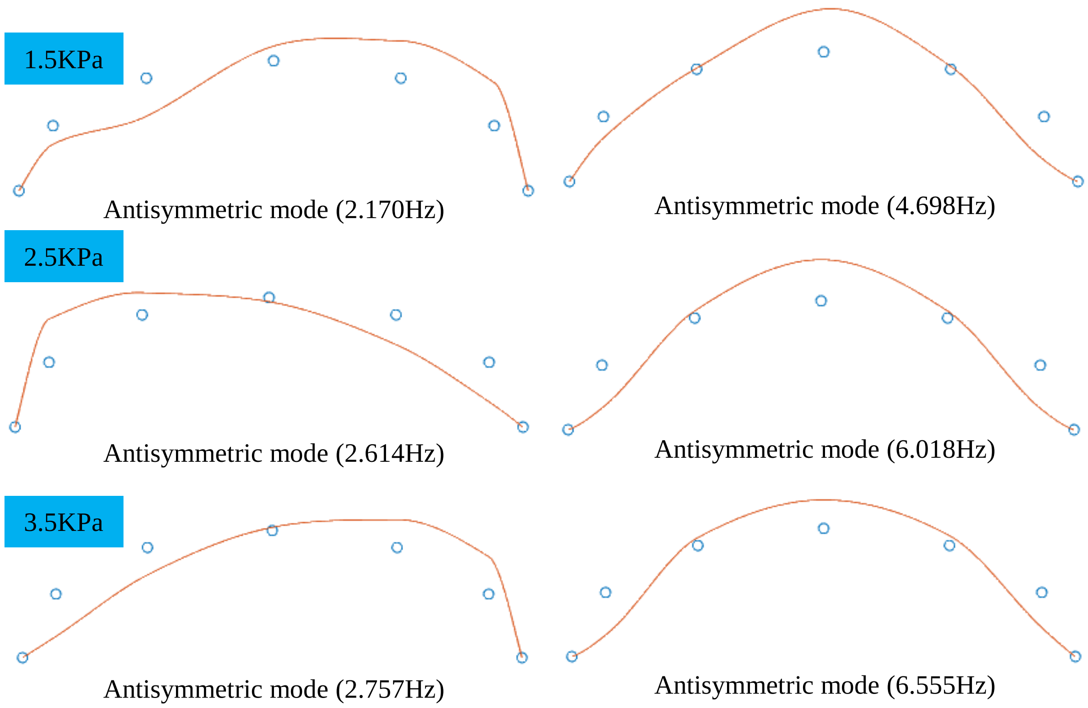

Figure 5: Mode shapes in different internal inflation pressures

Figure 6 depicts the changes in structure frequencies under different internal inflation pressures. Figure 6 shows that as the internal inflation pressure increases, the frequencies of the first two modes gradually increase. As a flexible structure, the structural stiffness of the inflatable membrane structure is mainly provided by internal inflation pressure. The increase in internal inflation pressure can effectively enhance the stiffness of the inflatable membrane structure, thereby increasing the structural vibration frequencies. The frequency tends to stabilize with increasing inflation pressure for the first mode's anti-symmetric vibration. Meanwhile, the second mode's symmetric vibration frequency shows a similar trend. These results suggest that when the internal inflation pressure reaches a certain level, the effect of increasing internal inflation pressure on enhancing structural stiffness diminishes.

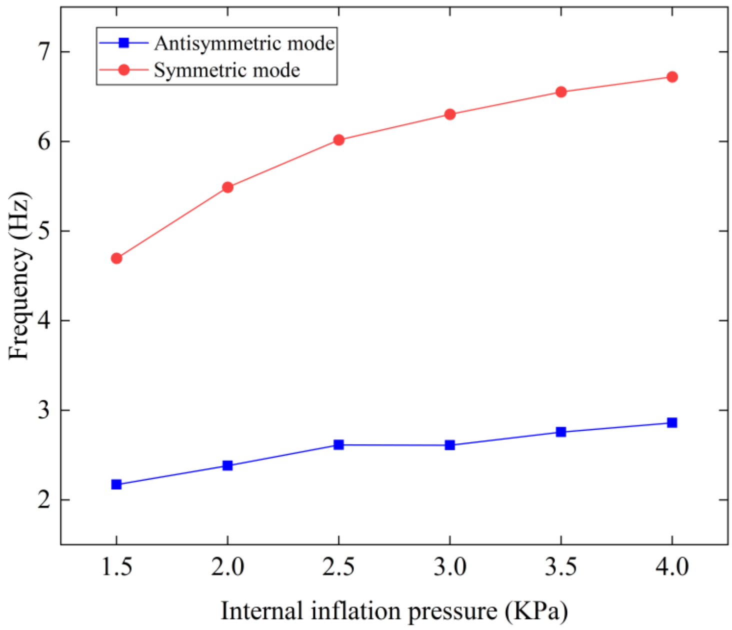

Figure 6: Frequencies in different internal inflation pressures

4. Conclusions

As a new type of inflatable structures, the pull-tab multi-chamber arched inflatable membrane structure is faster to install than traditional inflatable structures. This structure completes the fabrication of the structural framework through factory prefabrication, and during application, it only needs to be inflated on-site to the set internal inflation pressure. This new architectural structure greatly shortens the installation construction period and is easy to transport due to its high packing ratio. In this study, a modal test system is designed and fabricated to investigate the structure's dynamic characteristics under different internal inflation pressures. The modal identification subsystem is used to identify the vibration frequencies and mode shapes. Based on the experimental results, the following conclusions can be drawn:

（1） The span of the inflatable membrane structure gradually decreases with the internal inflation pressure increase, but the change's magnitude is tiny. The slight change in span indicates that the bottom of the structure is effectively constrained, which means that the friction between the inflatable membrane structure and the ground effectively restrains the deformation of the structure.

（2） The first two mode shapes of the inflatable membrane structure are antisymmetric and symmetric modes, consistent with the characteristics of an arched structure. The vibration frequency of the inflatable membrane structure gradually increases with the increase in internal inflation pressure. However, the frequency tends to stabilize when the internal inflation pressure reaches a certain level. This indicates that when the internal inflation pressure of the structure is low, increasing the internal pressure can effectively increase the structural stiffness. However, this improvement effect gradually diminishes when the internal inflation pressure reaches a certain value.

The test results indicate that the internal inflation pressure of the pull-tab multi-chamber arched inflatable membrane structure has a significant impact that cannot be ignored. In general, these reasonable observations and useful values are indispensable for investigating the vibration characteristics of pull-tab multi-chamber arched inflatable membrane structure.

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