Experimental investigation of surge instability in the centrifugal compressor volute

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ABSTRACT

Surge, as one of the most important operational instabilities of centrifugal compressors, especially at low mass flow rates, can cause severe pressure fluctuations, reverse flow, and mechanical damage. In this study, surge instability in a turbocharger-based centrifugal compressor was investigated experimentally and at high rotational speeds. First, the compressor characteristic curve was extracted at several rotational speeds. Then, rapid data acquisition was performed at a rate of 1000 samples per second and in an interval of 3 seconds, at speeds of 57000, 80000, and 90000 rpm, and the static pressure was recorded at three points in the volute region. Statistical and frequency domain analysis using fast Fourier transform were used to identify instability indicators. The results showed that at speeds of 57000 and 80000 rpm, the changes in standard deviation with decreasing mass flow rate were limited, and it was not possible to detect a definite surge entry based on this alone; in contrast, at a speed of 90000 rpm, a noticeable increase in the amplitude of pressure fluctuations was observed. Also, in the unstable state, a dominant frequency component around 47 Hz was clearly excited and was strengthened by decreasing the mass parameter. Comparison of measurement points showed that the intensity of fluctuations was maximum at the end of the volute, before its outlet, and the amplitude of pressure fluctuations increased by about 2.6 times.

KEYWORDS

Centrifugal compressor, surge instability, high rotational speed, volute, fast Fourier transform.

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1. Introduction

The performance of a radial compressor becomes unstable under some operating conditions under the influence of various factors. One of the most important of these instabilities, which mainly occurs at low mass flow rates, is the surge phenomenon [1]. So far, several studies have been conducted on the surge phenomenon in centrifugal compressors. Lim et al. designed and built a laboratory device specifically to study surge instability in centrifugal compressors and conducted numerous experiments in the surge region. The results of these experiments led to the identification of two dominant frequencies of 21 and 7 Hz associated with surge oscillations and showed that this instability can be classified into two categories: mild surge and deep surge based on the intensity of pressure oscillations [2].

Despite the extensive research conducted, in most of the past studies, the main focus has been on the impeller region of the centrifugal compressor, while the unsteady flow behavior in the volute chamber can also play an important role in the occurrence and development of the surge phenomenon. Therefore, the focus of the present study is on identifying the characteristics of instability in the compressor volute using experimental methods.

2. Case Description

The experimental tests of this research were conducted in the Gas Turbine Laboratory of Sharif University of Technology. This laboratory provides the possibility of conducting hot tests and examining the performance of gas turbines and turbomachinery components (including compressors and turbines) in steady and unsteady conditions. The details of the testbed and its real image are presented in Figure 1. The rotational speed of this compressor at the design point is 92000 rpm, the average inlet air temperature is 28 °C, and the inlet pressure is 0.86 bar. The actual image of the compressor, including the impeller, vaneless diffuser, and volute, as well as the locations of the static pressure sensor mounting points (numbers 1, 2, and 3), are indicated in Figure 2.

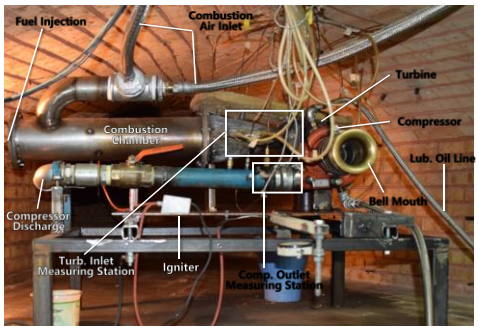

Figure 1. Gas turbine testbed.

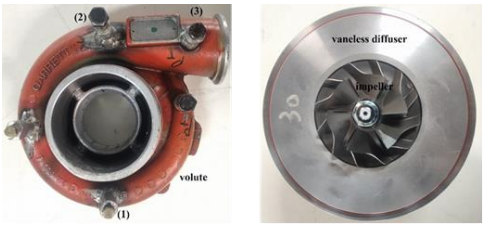

Figure 2. Compressor image along with the installation position of the static pressure sensors.

3. Methodology

In each series of experiments, the rotational speed is set at a constant value, and the compressor mass flow rate is gradually reduced from the maximum value until the system enters the instability region. Along this path, data are recorded at several intermediate operating points. In this study, statistical parameters such as average and standard deviation are mainly used. Variance is usually represented by σ^2 and is defined according to equation 1.

$$\sigma^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \overline{X})^2 \quad (1)$$

$$\overline{X} = \frac{1}{n}\sum_{i=1}^{n}x_i \quad (2)$$

4. Results and Discussion

The experimental studies of this research were carried out in the first step with the aim of extracting the compressor characteristic curve. For this purpose, it is necessary to obtain the compressor performance characteristics at several operating points for each rotational speed. Given that the experimental results at 90000 RPM significantly indicate entry into the surge region, at this point, for further investigation, other points of the flow range within the turbocharger are also examined. Point 2 is inside the compressor housing and at the impeller outlet. Table 1 summarizes the data acquisition results at this point.

Table 1. Geometrical parameters of the compressor.

Mass Parameter $[(kg*\sqrt{K})/(s*bar)]$	Static Pressure [Pa]	Standard Deviation [Pa]
6.85	136036	523
2.61	166475	704
2.14	168200	808
1.98	170372	1289
1.28	165920	1345

Figure 3 shows the variations of the dimensionless static pressure over time for different values of the mass parameter from the highest to the lowest value. As can

be seen from this figure, with decreasing mass flow rate, the amplitude of the fluctuations increases, especially in low flow rate regions. Also, the frequency spectrum of the dimensionless static pressure signal is presented in Figure 4. According to this figure, as the mass flow rate decreases and the surge region is approached, the dominant frequency component at around 47 Hz is noticeably excited and exhibits a significant increase in amplitude.

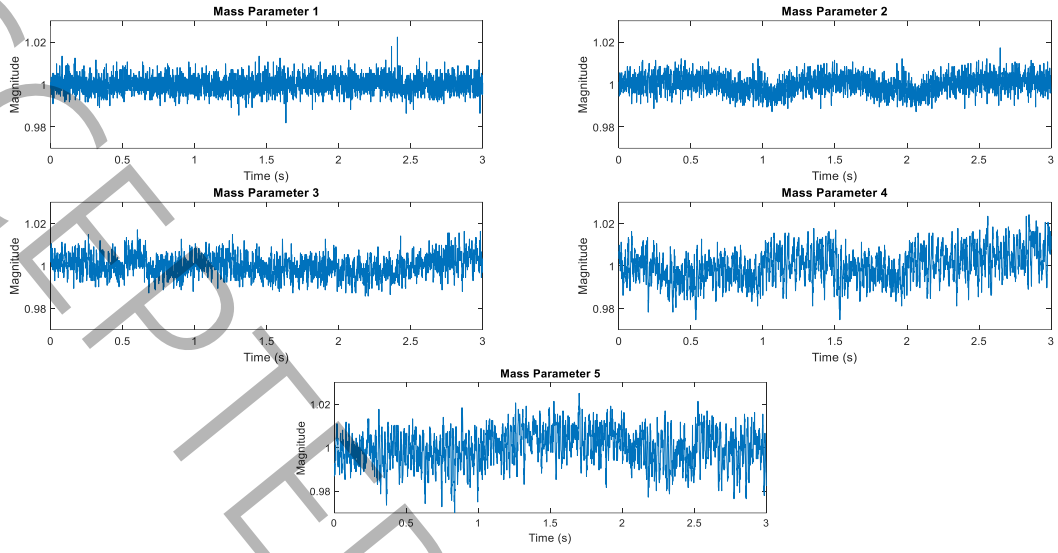

Figure 3. Point 2 pressure fluctuation amplitude over time at five different flow rates at 90000 RPM.

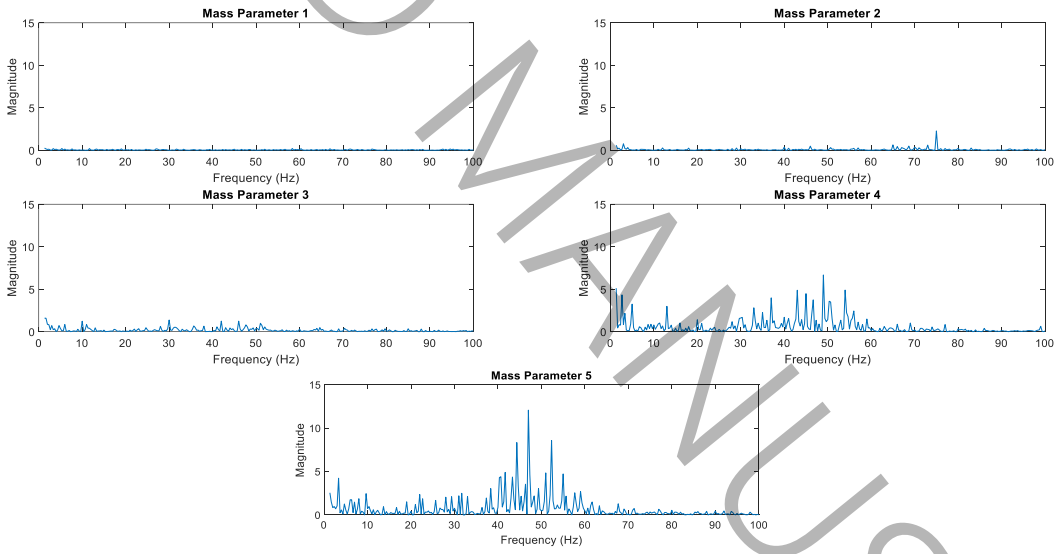

Figure 4. Point 2 pressure fluctuation amplitude over frequency at five different flow rates at 90000 RPM.

5. Conclusion

In this study, the phenomenon of surge instability in a centrifugal compressor, especially at high rotational speeds, was investigated experimentally. Examination of the data obtained at a rotational speed of 90000 RPM and in the transition from the stable region to the surge region reveals two important results: first, upon entering the surge region, the amplitude of pressure fluctuations increases noticeably, and at some operating points, an increase of about two times compared to the steady state is observed. Second, in the unstable state, a dominant frequency component around 47 Hz is clearly excited and becomes more intense with a decrease in the mass flow rate (or mass parameter), such that this component can be considered as one of the important indicators of the occurrence of instability in these conditions.

6. References

[1] M.P. Boyce, Centrifugal Compressors: A Basic Guide, PennWell, 2003.
[2] K.T. Lim, S.Y. Yoon, C.P. Goyne, Z. Lin, P.E. Allaire, Design and Characterization of a Centrifugal Compressor Surge Test Rig, International Journal of Rotating Machinery, 2011(1) (2011) 738275.