Experimental analysis of a rotor system with two-phase flow squeeze film dampers under low supply pressure

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Summary: Squeeze film damper (SDF) in rotor system can provide a proper damping to suppress the vibration traversing critical speeds. In SFD, the air ingestion from the outside environment and cavitation may lead to a foamy lubricant that weakens oil film damping and dynamic performance of rotor system. This paper investigates the nonlinear dynamics of a rotor system supported on two-phase flow squeeze film dampers using physical experiment. A rotor test rig with double disks mounted on ball bearing and SFD is constructed. Air and oil supplied systems are built to simulate the air ingestion which can range from pure oil to all air. The results show that two-phase flow produces a significant influence to the system's stability and dynamical response. The damping properties are weakened by entrained gas, such as the damping on high frequency components of rolling ball bearing. Super-harmonic resonance and rubbing between parts can be resulted as the critical speed is passed. Low frequency components resulted by the two-phase flow was also observed.

Introduction

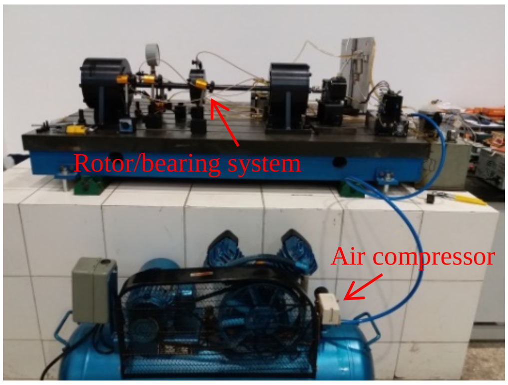
Two-phase flow is a pervasive fluid state inside SFDs, which can influence the dynamical coefficients of oil film and rotor dynamics through modifying the lubricant density and viscosity, as a function of the volume fraction of air content entrained in the lubricant.

Many scholars recently concentrate on the study of two-phase flow in SFD. San Andrés and Diaz [1-4] carried out several physical tests on a SFD with two-phase flow. They pointed out that the dynamical characteristic of a two phase flow SFD can be device-dependent and proposed a homogeneous model. Inayat-Hussain and Mureithi[5] concluded that a rotor with cavitated squeeze film dampers may lose its stability via period-doubling and saddle-node bifurcations, as variations of the gravity, unbalanced excitation and SFD geometric parameters. Meanwhile, other scholars investigate the two phase flow effects on dynamics of rotor supported on squeeze film dampers. Zeidan and Vance[6] analyze the cavitation and air entrainment effects on the response of SFD supported rigid rotor. They found that Both the cavitation and air entrainment can lead to a nonlinear jump phenomenon. Vapor cavitation can result a nonlinear hardening spring characteristic, while air entrainment a nonlinear softening effect. Moreover, the reduction of damping due to two phase flow can cause an increase or a jump-up of vibration amplitude. Inayat-Hussain and Mureithi[7] conclude that rotor with cavitated squeeze film dampers may lose stability via period-doubling and saddle-node bifurcations at certain gravity, unbalanced excitation and SFD geometric parameters. San Andrés and Santiago[8] test the dynamic response of rotor supported on flexure pivot tilting pad bearing and integral squeeze film damper with bubbly mixture. When crossing a critical speed, the amplitude does not show any difference as the gas volume fraction in the mixture changes from 0 to 1. While the bearing is lubricated with oil, it shows that the oil flowing out of the bearing is sucked into the SFD oil chamber. Hence, the damping capacity is preserved. Younan and Allaire[9] propose a model of squeeze film damper considering air content entrained in the lubricant by modifying the lubricant density and viscosity as a function of the mass ratio of air to oil, and analyze the nonlinear rotor dynamical response under the effect of air entrainment.

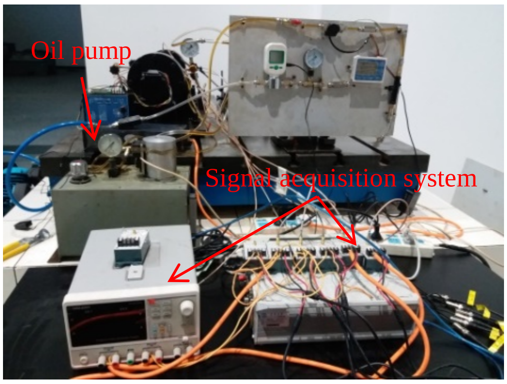
All the achievements referred above indicate that a bubbly mixture not only leads to the reduction of SFD oil film damping, but also produces a significant influence on the rotor dynamics with SFDs. The nonlinear dynamical response of a two-phase flow SFD rotor is investigated in this paper experimentally by using a test rig with low oil supply pressure.

Test rig

A rotor test rig is constructed shown in Fig.1 which contains rotor/ball bearing system, oil and gas supplied system and signal acquisition system. The rotor is built by a shaft (672mm long and 24mm in diameter) and two disks (30mm width each and can be in any configuration along the shaft). The left end of the shaft is supported on a rolling bearing with a squeeze film damper. The oil film of SFD is generated between squirrel cage and understructure. The right end is supported by only a rolling bearing and its squirrel cage, and connected to a 400W DC motor through a flexible coupling. The motor can speed up to 4000rpm. Two eddy current sensors are used to record the disk displacement along vertical and horizontal directions respectively. Other two eddy current sensors placed at the support section are also used to pick up the vertical and horizontal vibrations of the squirrel cage.



(a) Rotor part with SFD



(b) flow supply and signal acquisition parts

Figure 1 the two-phase flow test rig

Fig.2 displays the squeeze film damper lubrication system. A feed pump continuously draws pure oil into the oil line and an air pump drives dry air into the air line. Two needle valves are installed in the oil and air lines respectively to mix air and oil in any gas volume fraction (0 to 1). A jet device placed at the upstream of the SFD generates an air in oil mixture. The mixture flows into the SFD oil clearance and then is discharged into a bubble eliminator. After the air is removed from the mixture, the pure oil returns to the oil reservoir.
An oil flow meter installed in the oil line measures the oil flow (Q_l). Similarly an air flow meter is fixed in the air line to measure the air flow (Q_{g1}). A pressure meter is laid close to the air meter to gauge the pressure(P_{g1}). Note that pure air is considered as compressible, and air flow varies with pressure. That is to say Q_{g1} is the flow under P_{g1}, which does not equal to the air flow into the SFD chamber, as the pressure drops when air travels from the air meter through the jet device to SFD inlet. The other pressure meter is installed at the SFD inlet to measure the SFD inlet pressure(P_{inlet}), driving air in oil mixture into SFD oil film clearance. According to the ideal gas law [10], the air flow at SFD inlet can be estimated as:

$$P_{g1}Q_{g1} = P_{inlet}Q_{airinlet} \tag{1}$$

Gas volume fraction is calculated using

$$GVF = \frac{Q_{airinlet}}{Q_l + Q_{airinlet}} \tag{2}$$

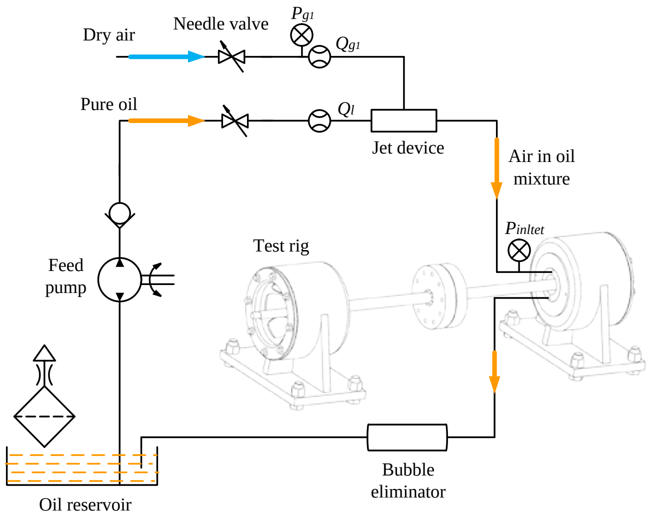


Figure 2 Squeeze film damper lubrication systems

Experimental results

Primary resonance

The amplitude of vertical vibration is displayed in Fig.3 in terms of the rotating frequency for selected GVFs. In this case, the disk is balanced and the rotor is under slight imbalanced excitation.

The primary resonance means the vibration amplitude of rotor increases remarkably as the excitation frequency approached the 1st nature frequency (43.46Hz) of the shaft lateral deflection, and then decreases or even jumps down to a lower branch after the amplitude peak is passed. The experiment shows that the vibration amplitude always arrive to a peak at 43.46Hz and jumps down to a low branch at 45.9Hz for all GDF value. That is to say the rotor response is unstable between the frequencies ranging of 43.46 to 45.9Hz. The higher the GVF at inlet is, the larger the vibration amplitude rises. The phenomenon proves that the damping of the SFD oil film decreases as the GVF increases.

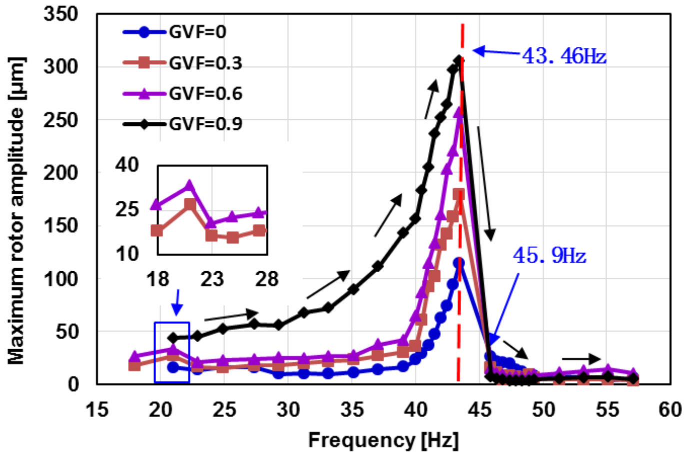


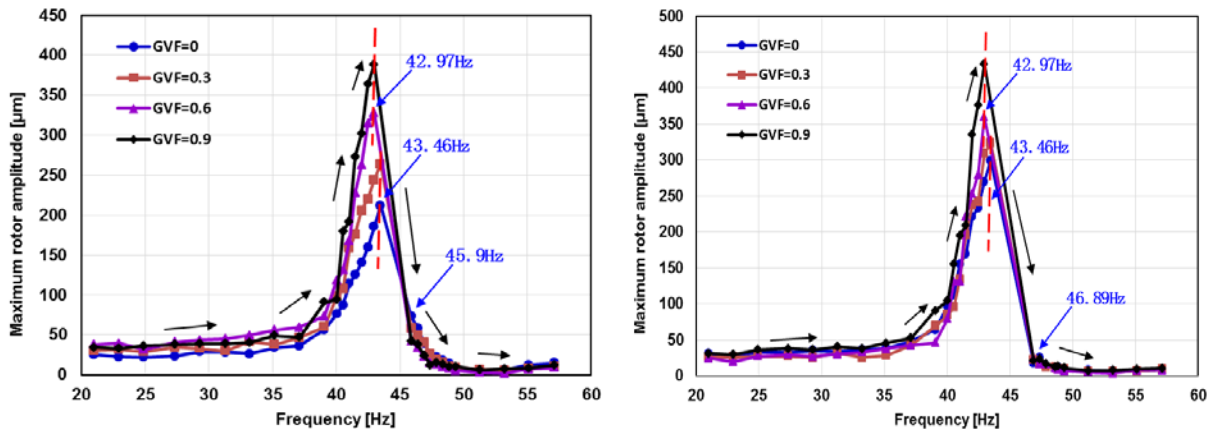
Figure 3 Amplitude-frequency curves under different GVF

The unstable region of primary resonance

Two bolts with 1.42g and 1.81g weights respectively, as shown in Fig4, can be installed in the disk to introduce imbalanced excitation to rotor system. The amplitude of vertical vibration versus pitching frequency for selected GVFs is shown in Fig.5.

Figure 4 Bolts used to add imbalance

In the experiments, the amplitude of rotor motion increases as the excitation frequency approaching the 1st order nature frequency 43.46Hz, and declines dramatically to a very low value at 45.9Hz(1.42g imbalance) and 46.89Hz(1.81g imbalance) respectively.



(a) 1.42g weight (b) 1.81g weight

Figure 5 Amplitude-frequency curves under different GVFs at inlet

As displayed in Fig.6, the resonant amplitude increases linearly with the GVF at inlet for slight and small imbalance cases, and nonlinearly for large imbalance excitation. Because the resonant amplitude peak shifts left slightly as the GVF at inlet increases, the unstable region of primary resonant response is widen both with the imbalance excitation is increased or SFD is supplied with more air.

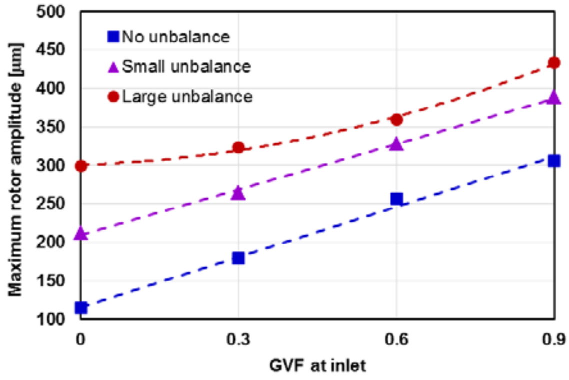
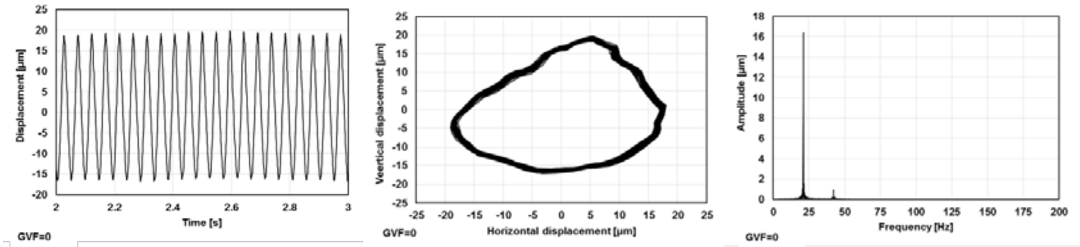


Fig.6 Maximum amplitude of rotor at different GVFs and imbalance

Super-harmonic resonance and low frequency vibration

The dynamical response of rotor at 21Hz is shown in Fig. 7, when SFD is lubricated with pure oil. The steady time history, the ring-like orbit and the A/F spectrum with only one main peak at 21Hz exhibit that the motion is periodic. The rough curve of the disk center orbit may be resulted from the high-frequency pitching vibration of the disk.

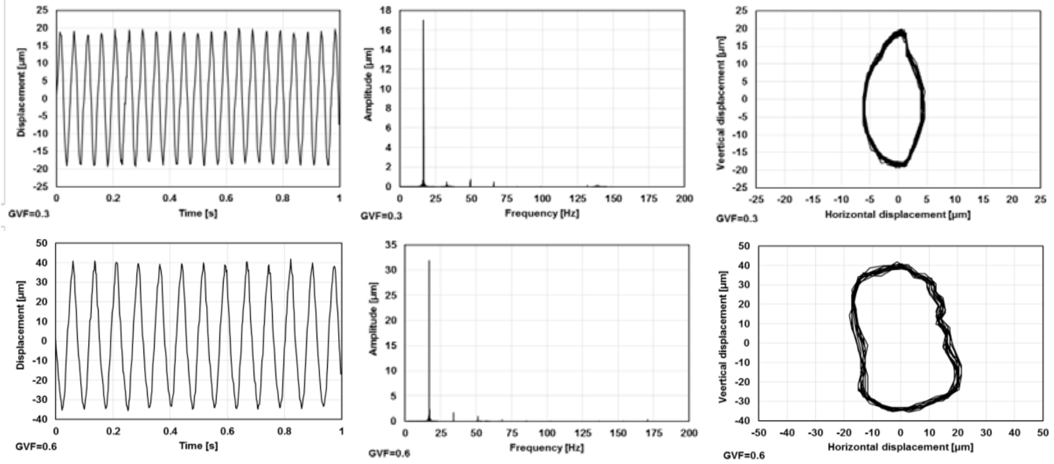


(a) Time history (b) Motion orbit (c) A/F spectrum

Figure 7 Dynamical response of rotor for pure oil at 21Hz

Inayat-Hussain and Mureithi[11] pointed out that the cavitated squeeze film dampers may cause the rotor lose its stability. In our experiment investigation, the 2nd super-harmonic resonance is found when air/oil mixture is supplied for the SFD.

Fig.8 displays the dynamical response of rotor at rotating frequency 18.13Hz when the SFD is lubricated by air/oil mixture with GVF=0.3 and 0.6 at inlet respectively. Similar to the result in Fig 7, the steady time history, the ring-like orbit and the A/F spectrum with only one main peak at 18.13Hz exhibit that the motion is also periodic. As the rotating frequency increases to 21Hz, two frequency peaks, the rotating frequency and its double, appear in the A/F spectrum simultaneously, as shown in Fig.9. Both the time histories and twined-orbits of motion also indicate that the response is of period-two.



(a)Time history (b) Frequency spectrum (c) Motion orbit

Figure 8 Rotor response at 18.13Hz, GVF=0.3 and 0.6

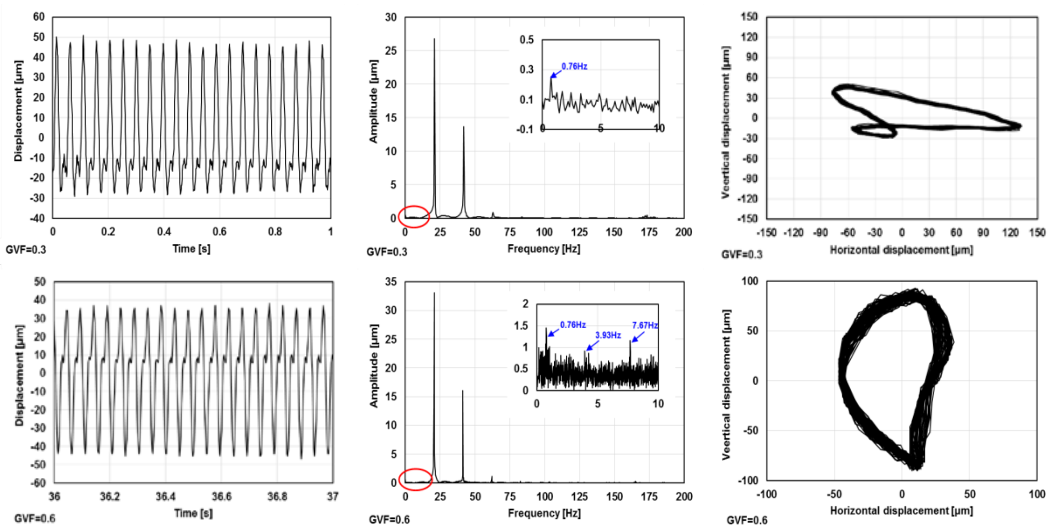
Since the higher frequency nearly equals to the natural frequency of lateral deflection of shaft (43.46Hz), such a bifurcation is resulted from the 2nd super-harmonic resonance. This phenomenon corresponds with the results shown in Fig.3, that the amplitude of motion for GVF=0.3 jumps up at 21Hz and that for GVF=0.6 also does at 20.75Hz. The two motions both fall back at 22.95Hz.

For example, there is only one peak at 0.76Hz in A/F spectrum for GVF=0.3. As GVF=0.6, 3 peaks at 0.76Hz, 3.93Hz and 7.67Hz respectively can be found. The low frequency motion is related to the residence time (τ) of single liquid phase in the SFD clearance:

$$\tau = V_c / Q_L \tag{3}$$

where V_c=πDcl is the volume of SFD clearance, and Q_L is the liquid volumetric flow rate.

In the experiments, the oil flow rate is set to 0.068L/min constantly. Therefore, the resident time is 1.38s and corresponding frequency is 1/1.38=0.73Hz. Therefore, 0.76Hz is the frequency of liquid flowing into SFD clearance, 3.93Hz and 7.67Hz are the high frequency components.



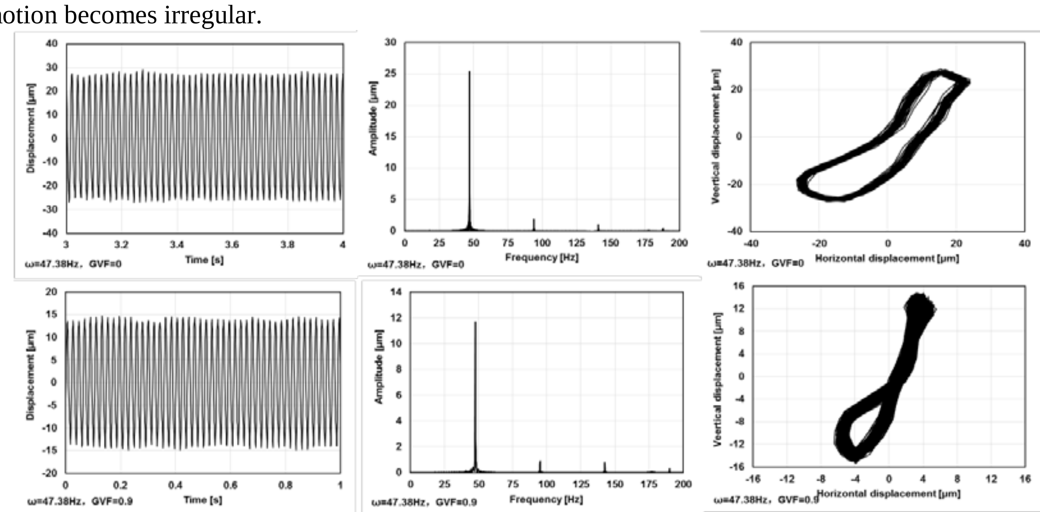
(a) Time history (b) Frequency spectrum (c) Motion orbit

Figure 9 Rotor response at 21Hz, GVF=0.3 and 0.6

Transient response

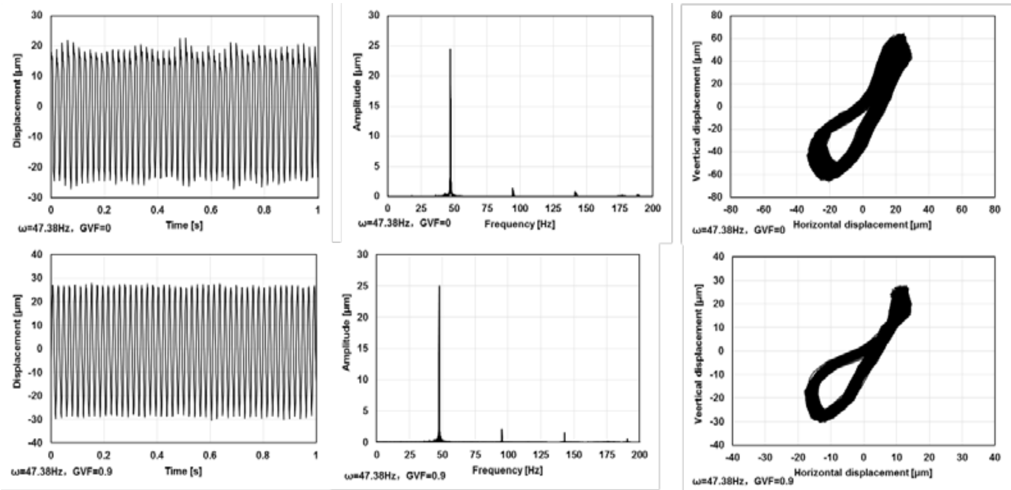
Fig.10 and Fig.11 show the transient response of rotor at 47.38Hz with small and large imbalance respectively, when the SFD is supplied with pure oil and air in oil mixture.

For all the cases, there is one main peak in each A/F spectrum in the response, all the time histories exhibit almost periodic. As the GVF at inlet increases to 0.9, more air is supplied to SFD, the oil film damping decreases, and the orbit of motion becomes irregular.



(a) Time history (b) Frequency spectrum (c) Motion orbit

Figure 10 Rotor response at small imbalance at ω=47.38Hz, GVF=0 and 0.9



(a)Time history (b) Frequency spectrum (c) Motion orbit

Figure 11 Rotor response with large imbalance at *ω*=47.38Hz, GVF=0 and 0.9

Conclusions

In this paper, the dynamics of a rotor system with two phase-flow lubricated squeeze film damper is investigated through practical experiments. Conclusions are got as follows:

1. Air entrainment weakens SFD oil film damping and has great influence on the dynamics of rotor system.
2. The vibration amplitude of rotor increases dramatically when traversing the critical speed, and then jumps down to a lower branch after the amplitude peak is passed, due to the nonlinearity of SFD oil film coefficients.
3. The lateral resonant amplitude increases linearly with GVF when the rotor imbalance is small, and the pitching resonant amplitude decreases as the GVF at inlet increases.
4. Super-harmonic resonance occurs as air is supplied to SFD. It occurs at rotating frequency 21Hz, which is a component 2 times the rotating frequency appears in the spectrum of response, as shown in Fig.9.
5. There are low frequency components in the response. The low frequency motion is related to the residence time of the single liquid phase in the SFD clearance.

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