Chapter 2
Failure Pattern and Corresponding Mechanism Analysis of LRE

2.1 Introduction

Liquid propellant rocket (LPR) has been studied, produced, stored, and used in China for over 50 years, the performance and fault analysis of the engine, core component of LPR, is involved throughout the process of study, production, storage, usage, and even retirement. The reason is mainly shown in the following aspects. First, the mission of space flight and the rocket weapon needs the LRE holding high reliability. It is known that each launch of the space vehicle costs more than hundred millions dollars. However, about 60 % fault of the carrier rocket is caused by the LRE failure. Second, fault analysis is the development basis of the design, production, and improvement of new products. By finding the weak point of the product and inheriting the mature technology, lot of cost can be saved and the development period can be shortened in the development of the new product. Third, the fault analysis can provide an important guarantee for the storage of rocket weapon. Since, the rocket is a long-term storage and one-time use object in poor environment, little failure information can be collected. Therefore, the fault analysis must be carried out to meet the increasingly demand of the storage, usage and launching decision, usage, to provide a basis for launching decision-making and optimize storage environment to the rockets, extending service life and provide the basis for weapon system, for weapon system maintenance, repair, management to provide a basis, and method guidance.

In this chapter, the mechanism of the LRE fault is studied based on statistical analysis of the rocket engine components and system failure modes. The standard models and performance characteristics of the common faults are established to facilitate the burden of fault analysis, detection, and diagnosis.

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2.2 Structure of LRE

LPR is composed of the propellant charging system, engine system, and propellant transportation system [44–46]. The engine system, choosing the double component gas generator cycle, is mainly comprised of the thrust chamber, turbine pump, gas generator, valve, cavitation pipe, heat exchanger, etc. In the thrust chamber, the propellant is burnt to produce high temperature and high pressure gas and transformed to the nozzle to produce the thrust. The turbo pump including gas turbine and centrifugal pump supercharges the fuel and oxidant. The gas generator using the fuel and oxidant as same as the thrust chamber is used to produce the working gas to turbine with the lower oxygen coefficient than the thrust chamber. In the supply lines of fuel and oxidant pumps, the pump valves are installed in order to separate the propellant tank from engine and the engine can be stored safely when the tank is filled with propellant. In the supply line of the propellant, the main valve and throttle valve are installed. Furthermore, to ensure the stability of the system, cavitation venturi tube, one-way valve, and the auxiliary valve are installed in the supply line behind the pump. The starting material of the turbine is provided by the explosive actuator. There are two heat exchangers. The first one, pressurizing oxidizer tank by the vaporization of the oxidant is located in the turbine exhaust pipe, the other one is placed in the supply line between the fuel pump and the thrust chamber partition and is used to pressurize the fuel tank by part of cool fuel-rich gas.

The propellant transportation system is comprised of propellant tank, relief valve, safety valve, sensors, pipe lines, and other components and is mainly used for charging, discharging, and storing the required propellant by the demand.

Propellant charging system, used to charge the rocket tank, releases propellant and stores the propellant with long time and is comprised of the hydraulic system which is comprised of gas path system, liquid road system, circuit system, and measurement control system.

2.3 Failure Pattern Analysis of the LRE

Development of liquid rocket fault monitoring and diagnosis system is beginning with the deep understanding of various failure modes. However, the failure mode which is varied with the type of engine brings great difficulty and inconvenience to the study. Foreign country (especially the United States and the Soviet Union) does the amount of research on failure mode, such as the United States announced “the list of SSME Failure mode, effect analysis and key project” in 1987 after analyzing the failure record during the past 70 years on the SSME. Finally, the fourteen critical faults with SSME were determined which covered five failure mode with occurrence frequency.

In the 80s later, the Soviet Union analyzed the fault of various liquid rocket to propose that faults were divided into three categories according to the time of failure: The first failure which occurs is shorter (about 0.05 s) than the completion of the work; The second occurs for 0.04–0.05 s mainly in the oxidant pump and can be tested and diagnosed by the algorithm based on the parameters such as pressure, temperature, etc.; The third occurs about tens seconds which is mainly in the bad sealing condition of combustion agent and gas tank, which can be tested and diagnosed by the algorithm based on parameter information. But, practice shows that it cannot completely prevent the appearance of the failure especially for the first failure during the liquid rocket works especially during flight, such as turbine and gas channel wear, turbine blade after working for a long time. Therefore, it is necessary to study the regional and failure mode of the fault.

In our propulsion technology field, the analyses of failure mode and effect are widely used in the engine fault analysis, which are based on test the statistical data, from the management of production and quality, test procedure control, design improvement, etc. These analyses and studies are very beneficial for the engine fault detection and diagnosis. Due to the previous failure analysis focused on quality management and design improvement, few qualitative and quantitative analysis to the variation of the engine parameters under failure is done. Even to the monitor of the main parameters of test or flying (such as oxidant injection pressure, turbine pump speed, and engine thrust, etc.), people usually use deviation zone test with strong empirical deviation inspection which often causes large false alarm and leakage alarm to error shutdown and drain off. Therefore, it is imperative to strengthen and improve the study of engine failure mode.

For the rocket engine in the storage and service condition, the main contents of fault analysis are composed of the investigations on the working condition of the failure occurrence, the manufacturing and service history before the failure, mechanical analysis of the failure engine, analysis and evaluation of the failure materials, analysis of abnormal situations, failure mechanism statistics and decision suggestion, etc. It notes that the mechanics analysis is a generalized conception, which contains the stress and strength analysis of the engine when the fault occurs. The stress is composed of all factors that may cause the failure and the strength is the ability to prevent any failures.

According to statistical analysis of the previous run-in, storage, usage, and other conditions, the failures occurred in the start-up procedure of the rocket engine are mostly caused by starting device including starter and starter valves, etc. In the stable working stage, the obstruction, leakage, and turbine system failure, etc., may occur. In the shutdown process, the failure may appear at the main valve and shutoff valve. From the failure phenomenon, the liquid path failure is mainly divided into three categories: the obstruction, the leakage, and the efficiency drop of pumps. According to the location of the fault, there are the thrust chamber fault, turbine fault, pump fault, gas generator fault, pipeline, and pressure vessel fault, etc. All faults may cause the performance degradation, parameter inconsistent and component damages. Comparatively, there are three types of gas path faults, such as the blocking, the leakage, and function failure. All these faults may occur at the high pressure vessel, the automatic device, the valve and the pipeline fault, etc. For the circuits, measurement and control system, failures are mainly composed of the short circuit, open circuit, sensor failure, or drift and actuator failure, etc.

2.4 Failure Mechanism Analysis of the LRE

2.4.1 Thrust Chamber and Gas Generator

By converting the chemical energy of liquid propellant to the jet kinetic energy and generating the thrust, the thrust chamber is composed of the liquid propellant injector, the combustion chamber, and the nozzle. Liquid propellants are injected in the combustion chamber with specified flow rate and mixing ratio at first. Then by atomization, evaporation, mixing, and combustion process, high temperature and pressure gas is produced and accelerated in the nozzle to be supersonic flow. The thrust is the anti-force of the supersonic flow performed on the thrust chamber.

Generally, the turbine power is supplied by the gas generator in the pump LRE. Similar to the structure of the thrust chamber, the gas generator works in the condition with lower mix ratio than the thrust chamber and provides power for the turbine by the gas. The power cycle of the engine will be influenced and expanded to the whole engine system if the gas turbine failure occurs.

The common failures of thrust chamber and gas generator include the injector clogging and ablation, combustion chamber tearing and cracking, unstable combustion, and nozzle ablation, etc., and all of these failures may occur in the process of study, production, and usage.

1. Injector clogging

Injector is a special device in which propellant component is introduced into the combustion chamber and atomization, which is easy to nozzle blockage because of the small diameter of the nozzle and the special structure form when the processing debris, foreign body, and floccule in propellant flow through the nozzle. Nozzle blockage will change the mixing ratio of the combustion chamber which can cause very high local temperature, the combustion chamber can still work when the degree is not enough to change the main system propellant flow that the venture-tube still works and the overall mix of the combustion chamber is not changed.

When the degree has caused the change of the main system propellant flow, the overall mixing ratio and flow rate of the combustion chamber have been changed which can cause the drop of the engine specific impulse, pressure drop of combustion chamber, and engine thrust reduction.

2. Injector ablation

Ablation of the injector nozzle will occur when unreasonable cooling design, decreased cool effect due to blockage of cooling nozzle, backflow of high temperature gas in combustion chamber, and high frequency unstable combustion in the combustion chamber happens. Ablation of the nozzle will cause the nozzle flow characteristics, decrease atomization effect, reduce and fluctuation of combustion temperature, pressure and thrust drop.

3. Ablation of thrust chamber throat

The insufficient cooling flow, blockage of cooling channel, the uniform mixture ratio of the propellant and asymmetric local mixing lead to combustion lag, which is easy to cause ablation of thrust chamber throat. Ablation of throat will decrease the rate of engine nozzle to area and increase throat to radius ratio, which can lead the increase of the flow rate of the nozzle, the pressure drop of the combustion chamber, the engine's specific impulse, and thrust loss.

4. High frequency instability combustion of thrust chamber

The phenomenon is called unstable combustion when the working parameters of the combustion chamber are disturbed and the vibration of large amplitude of the pressure takes place. When unstable combustion occurs, strong vibration of the engine, mechanical damage of thrust chamber and other parts, and injector face, nozzle, ablation of combustion chamber interior, and melt will cause engine failure. It is called high frequency instability combustion when the vibration frequency is more than 1000 Hz, which is the most easy to occur, the most difficult to suppress and must be solved, and occurs with the character of high volatility, high pressure fluctuations, sometimes up to 50–100 % of stable pressure, and vibration acceleration of tens to one hundred g, even to the flame appears strong flash and "sharp whistle".

The length of combustion chamber can be set to L_k, and the radius is R_k with closed two ends, in which it is filled with stationary and uniform gas and the natural frequency is:

$$f = \frac{a}{2}\sqrt{\left(\frac{q}{L_k}\right)^2 + \left(\frac{\alpha_{m,n}}{R_k}\right)^2} \tag{2.1}$$

Formula:

a Sound velocity of gas at steady state

q, m, n The integer, respectively, for the longitudinal, radial, and tangential vibration mode of the resonance frequency

$\alpha_{m,n}$ Coefficient.

During the working process of the combustion chamber, the flow fluctuation of the transportation system, start or stop of the engine, the instability and inconsistency of nozzle, and other parts of the mechanical vibration transfer will cause the disturbance of gas parameters (pressure, temperature); when the frequency of the parametric disturbance is consistent with the vibration frequency of the combustion chamber, all gas is regularly shocked with the inherent acoustic frequency in the combustion chamber, if the source of the disturbance is maintained or continuously excited, the high frequency instability combustion can be maintained and increased.

High frequency instability combustion has been effectively suppressed through several decades of research and experience from continuous summary [7], the effective measure to prevent the high frequency unstable combustion is to prevent the existence of the initial disturbance source for the rocket in the service.

5. Low frequency unstable combustion of gas generator

It is called low frequency unstable combustion, when the frequency of the unstable combustion chamber is lower than 300 Hz. Low frequency unstable combustion is the interaction between the pressure in the combustion chamber and propellant flow of conveying system, usually occurred in the engine start, stop or turn, which is prone to occur under the condition of low thrust or lower nozzle pressure drop relatively. Low frequency unstable combustion rarely occurs in modern engines with high pressure in the combustion chamber, but occurs in gas generator with low mixed and bad combustion organization or small thrust chamber. When low frequency unstable combustion occurs, it will lead to the transmission line and the other connecting components which are damaged, kinds of automatic devices cannot work properly, and it is possible to stimulate high frequency instability.

6. Abnormal cooling process of cooling jacket

Thrust chamber and gas generator are working in the high temperature, pressure, and speed environment, and with huge heat transfer, so it is necessary to effectively cool to thrust chamber and gas generator to guarantee the normal work.

It usually chooses combined cooling method, but regenerative cooling is the most basic and effective way which utilizes one propellant component (or two propellant components) as the cooling fluid, flows in certain velocity through the cooling channel between the inner and the outer walls of thrust chamber (or gas generator) before it enters the combustion chamber to take away the heat that transfers through gas to the inner wall. The cooling passage between the inner and outer wall is called cooling jacket, which is made in special processing and with narrow channel gap, and is easy to block or fluid channeling caused by sealing off after high temperature which will cause the reduced flow rate, the decreased cooling, and the abnormal cooling process. When it is in very serious conditions, it will result the ablation of injector face nozzle, thrust chamber inner wall and throat, the reduced thrust, and even to the failure of engine.

7. Mechanical damage

Mechanical damage is manifested in the cracks, tear, cracking, and fracture of the body or part. The reason is that the unreasonable structure design, the poor manufacturing process, the material defect, the big work load, and the other faults cause the violent vibration. The failure easily lead to leakage of propellant and even explosion, the accident will be disastrous. It mainly occurs in the engine development, rarely in the product after stereotypes.

2.4.2 Turbo Pump

1. Dynamic model of a turbo pump rotor system

Figure 2.1 shows Turbine pump system of liquid rocket.

Combustion agent pump, oxidant pump, turbine, inducer of two pump, and external force gear are placed on the same shaft which is supporting by two ball bearings. Seal is used for the isolation of each working medium. The whole system is firmly fixed on the engine. The shaft and the rotary table can be dispersed into the mass block and the rotor engine with no mass, so the dynamic model of the rotor system of the turbine pump can be established, as shown in Fig. 2.2.

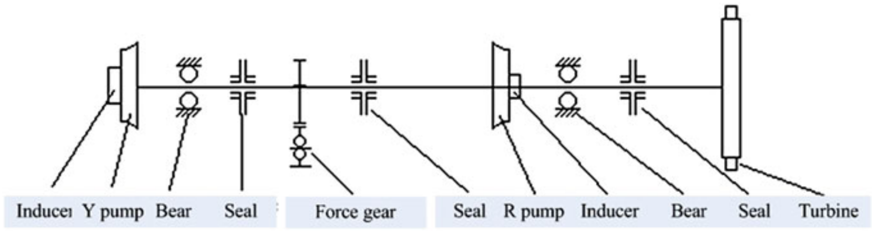


Fig. 2.1 Schematic diagram of turbo pump system

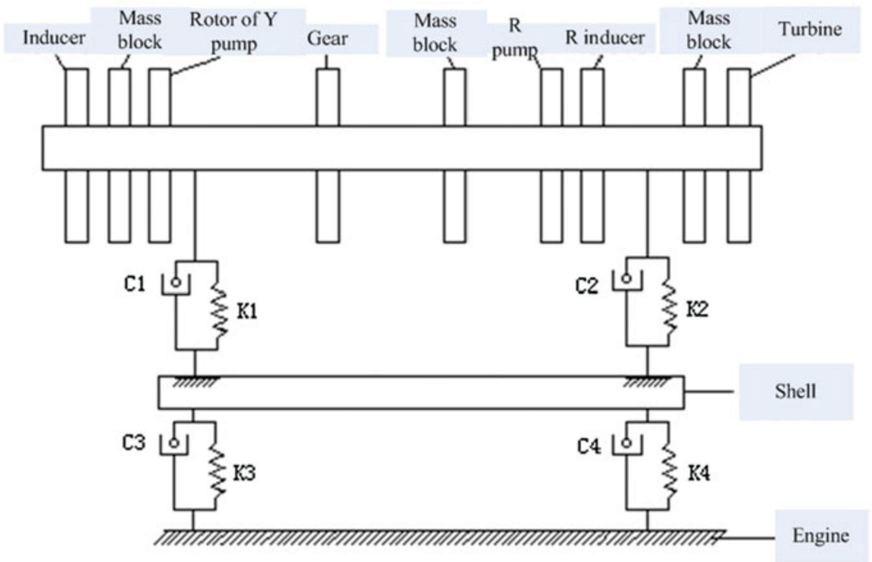


Fig. 2.2 Rotor system model of turbine pump

There are 4° of freedom per mass on the rotor (shift *x*,*y* and angle of rotation θx,θy), 6° of freedom on shell foundation (shift *x*,*y*,*z* and angle of rotation θx,θy,θz), and generally 2° of freedom on bearings, so the differential equation of the system is:

$$M\ddot{X} + \Omega J\dot{X} + C\dot{X} + KX = R \tag{2.2}$$

Formula: Mass matrix of the system:

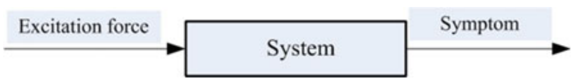
J Matrix associated with the moment of the system, the elements of which are the polar moment of inertia of the mass block
Ω Rotational angular velocity of the rotor
C System damping matrix
K Stiffness matrix of the system
R The external force array acting on the system.

The natural frequency and vibration mode of each order, unbalance response and stability of the system can be obtained by appropriate simplification of using various analysis methods.

For the turbine pump system, there is the gyro torque because the disks which are not in the middle of the two support, which is equal to elastic moment, in the positive precession, the deformation of the shaft is reduced and the elastic rigidity and critical speed of the shaft are improved, in the anti-precession, the deformation of the shaft is increased, the rigidity and critical speed of the shaft are reduced, in the case of small deformation and rotation speed, the gyro torque is small, and cannot be considered, here (2.2) is:

$$M\ddot{X} + C\dot{X} + KX = R \tag{2.3}$$

By formula (2.2), the stability, natural frequency, and vibration mode of the system will change when the system exists disturbance force or the variation of force *R* array, mass matrix *M*, damping matrix *C*, stiffness matrix *K*, etc. Some kind of symptom will appear when the parameter of the system changes or stimulated by the outside from the above formula, on the contrary, the system's change (fault) can be deduced according to the signs that is the basis of fault diagnosis of which is based on the symptoms. The relationship between the excitation force (external, internal), the symptom, and the system dynamic characteristic is shown as follows:



When the system is affected by some kind of stimulation (external or internal) which can cause the response, we can find out the incentive source and detect the fault by the response and analysis of the incentive. Response will change as the system change, which is in the form of self-excited vibration that is mainly the fractional frequency or fractional frequency hysteresis vibration, and with nonlinearity. During the analysis of fault mechanism for each fault, the first thing is to analyze the incentive and system and establish a simplified system model to find out the relationship between signs and failure.

2. Mechanism and characteristics of common failures of turbine pump system

The turbine pump is prone to failure, because it works with short start-up and shut down, the quick varied conditions, the turbine works in high temperature, high pressure, high speed, and pump also works with high pressure, high speed, flammable, explosive, highly toxic, strong corrosion in the propellant, which is shown in vibration mode, so that fault monitoring and diagnosis for the turbine pump is based on vibration parameters. It is necessary to the turbine pump vibration monitoring of whether the ground test or the flight. In order to monitor and analyze the fault, the mechanism and characteristics of the common failure of turbine pump should be analyzed and summarized. The mechanism and characteristics of common failures of turbine pump system are as follows:

1. Rotor unbalance

Rotor unbalance is divided into two kinds: rotor mass eccentricity and defect of rotor components. Mass eccentricity is caused by the manufacturing error, the assembly error, and the uneven quality of the rotor. Defect of rotor components refers that the parts such as (impeller, blade) damage locally, shed, and fragments fly off in operation to cause the imbalance, especially for turbine blades, induced blade wheel. In the turbo pump system, if the quality of the mass is imbalance in not considering the influence of the gyro moment, the external force excitation is caused by the mass eccentricity, formula (2.2) will be:

$$M\ddot{X} + C\dot{X} + KX = me\omega^2 \cos \omega t \tag{2.4}$$

Formula:

M Eccentric mass
e Eccentricity
ω Rotor angular frequency.

The vibration of the system will be forced vibration caused by mass eccentricity, the frequency of which is the same as rotor angular frequency, the M will change when the m mass parts defect and the vibration mode, natural frequency of the system will change, which is not big. The features of the rotor unbalance are shown that: regular time domain wave form and the frequency domain vibration energy are concentrated in the fundamental frequency with stable phase; the peak value and phase inversion occurs at the critical value, orbit of shaft center is elliptical, synchronous forward precession. If the forced vibration frequency of the mass eccentricity is equal or close to the natural frequency of one component in the system, resonance occurs. Because the eccentricity of rotor is inevitable, resonance also occurs in the normal state with small amplitude. But, the component defect in the turbine pump system occurs with sudden nature, it is the basis for division between the component defect and eccentricity. The following parts are often damaged in the turbine pump system:

(1) Blade fracture in rotor

Blade crack, machining marks, and material defects are the fatigue source of rotor blade. When the rotor is rotating at high speed, the blade is subjected to alternating load to result in fatigue damage as to emerge broken marks. Due to the small gap of the turbine cavity, blade fracture is very easy to block rotor and lead rotor blade defect which makes the turbine fail to work, which will lead the failure of engine instantaneous.

(2) Crack of pump-induced wheel

The fault such as the deep machining marks, stress concentration, and poor anti-fatigue performance exists, which make the inducer to produce fatigue fracture in the repeated alternating loads.

(3) Abscission of Turbine blade shroud

Abscission of Turbine blade shroud is caused by the friction that thermal deformation of turbine covers and the little gap between the turbine cover and the turbine guard, which will cause aggravated vibration of turbo pump and the unbalance of turbine rotor at work.

2. Rotor bow

The bending of the rotor in turbo pump system is caused by the unreasonable design of the shaft structure, the large manufacturing error, the uneven quality of the material and the long storage of the material. For the rotor installed in the rocket and turbo pump in rocket, the main cause is that the long-term improper storage leads the plastic deformation of rotor which results in the shaft bending. Bending emerges the same rotational excitation force as the mass eccentricity, so the performance of the rotor bending fault and the mass unbalance caused by mass eccentricity has the same feature. However, the vibration of axial happens when the rotor bends, and the vibration frequency is consistent with the rotation speed, sometimes accompanied with two frequency multiplication.

3. Rotor rubbing

Rotor rubbing happens when the shaft contacts with the fixed part, which is caused by the influence of the imbalance and the constant reduction of the gap between the static and the movement during work. Rotor rubbing is divided into two cases, one is radial collision caused by the contact between the outer rotor (the outer edge of the impeller) and static friction, the other is axial rubbing which is caused by the contact between the rotor in the axial and stator component. For turbine pump, it is common that the radial rubbing between the outer edge of impeller and stator component, the radial rubbing between rotary shaft and the sealing parts, rubbing between shaft and seal rubbing, which cause fracture failure and propellant channeling cavity sometimes failure or explosion.

When rubbing between the rotor and stator component happens, constantly changing stress is produced in the rotating shaft and accompanied with very complicated vibration phenomenon serious to failure. The simplified model of collision and friction is shown in Fig. 2.3, the gap between the outer edge of the impeller and stator component is set as δ, so the positive rubbing F_N and tangential rubbing F_T can be expressed as follow:

$$F_N = \begin{cases} 0 & (e < \delta) \\ (e - \delta)K_c & (e \geq \delta) \end{cases}$$

$$F_T = fF_N$$

Formula:

f	Friction coefficient between the rotor and stator component
K_c	Integer, respectively, for the longitudinal, radial, and tangential vibration mode of the resonance frequency
$e = (x^2 + y^2)^{1/2}$	Radial displacement of the rotor.

The stiffness of the rotor increases as the rotor and stator component contact instantly decreases when rotor is divorced from the contact after bounce of stator component and with lateral free vibration. Therefore, the rotor stiffness changes between the contact and noncontact, the frequency of which is the rotor vortex frequency which will produce a unique frequency of complex vibration response. The characteristics of rubbing are: cutting head cosine waveform, larger frequency vibration, vibration performance in full frequency, especially larger in the multiplier and divider vibration component, multiples of 1/2 components in typical spectrum, approximate trapezoid of axis orbit.

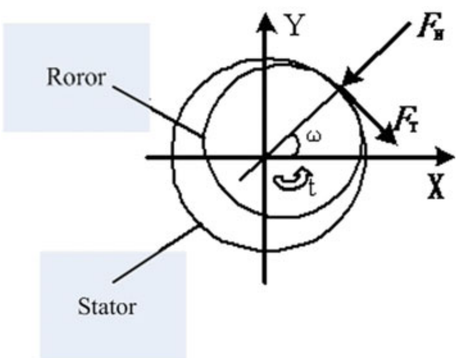


Fig. 2.3 The simplified model of collision and friction

4. Crack of Shaft

The turbine pump works in high temperature, pressure, corrosive environment, and with big load change gradient, temperature change gradient of the shaft, which is easy to crack even to fracture phenomenon and major accidents. The reason is that poor mechanical stress state is emerged in the high cycle fatigue, creep, and stress corrosion cracking, especially in the conditions of high temperature and strong corrosion also complex motion of the rotor ultimately leads to crack of shaft. The crack is in the opened, closed, sometimes opened, and sometimes closed states. The vibration is intensified when the crack is open, the deflection of the shaft is larger than the deflection of the crack, also the phase changes. The crack has no effect on the vibration of the rotor when the crack is in closed state.

When the stress in the crack area is self-weight or other radial load, the crack is periodically opened or closed that cause the complex vibration. The non-symmetry of rigidity caused by crack is not only the function of the depth of the crack, but also the function of the position of the shaft and the running time which is nonlinear vibration with two times, three times and high frequency harmonics of the rotating shaft, at the time the phase change, the crack propagation, the stiffness decreases and the amplitude of the vibration components increases. The harmonic resonance emerge when the working trajectory through 1/2, 1/3, 1/5, at the critical speed of the rotor during the boot process, the phase mutate at critical time, the axis trajectory is double ellipse or irregular.

5. Loosening of mechanical components

Due to the low installation quality in the turbo pump system, the $C3$, $K3$, $C4$, $K4$ in Fig. 2.2 change because of engine vibration that temperature causes inconsistent contraction of different materials, stress relaxation of fixed bolts for long-term storage and seals which result the loose of shell connection, bearing block, inducer and centrifugal wheel, and intensified vibration until to damage. When loosening occurs, periodic jump of the shell bearing block is caused under the action of unbalance force which leads to the change of system's stiffness and with impact response, and K, C will change in the model (2.2) which cause the change in vibration mode and natural frequency, when the loose gap increases, the vibration intensifies and the impact effect increases, which is easy to cause the resonance of the natural frequency of each order, as known nonlinear vibration. Characteristics are: the vibration frequency is precise 1/2 and 1/3, …, 1, 2, 3, … times of speed frequency which is expressed as fractional harmonic resonance, the other main characteristics are directional especially in the loose direction, different critical speeds in horizontal and vertical directions, vibration form can jump and the vibration will suddenly increase or decrease when the speed increases or decreases which is not continuous.

6. Fluid seal excitation

In turbo pump rotor system, various forms of sealing device are adopted in order to meet the need of isolation between the working medium, but fluid is sealed in the eccentricity of rotor relative to the fixed part which will cause sub synchronous precession that will result the destruction of the turbo pump rotor.

In the labyrinth seal, the sealing backlash is not uniform due to the error of manufacture, installation and operation, when rotor lean in sealed cavity if the rotor is in the vortex state due to the initial disturbance, the periodic variation of the seal gap between the rotor and the seal and the pressure in the seal chamber will also periodically change which will stimulate the rotor to aggravate the eddy and make the rotor failure.

On the other hand, kinetic energy of the fluid which flows into the sealed cavity cannot be completely lost. One flow along the axial direction and another rotate along the circumferential direction of the rotor. The uneven circumferential gap between rotor and the seal cavity, or the change of circumferential gap as time due to rotor precession motion, will cause inhomogeneous pressure distribution in the sealing cavity, and that the resultant force of the distributed pressure creates transverse component which is perpendicular to the displacement of the rotor which lead to the precession motion and instability of rotor.

The characteristics of fluid seal excited vibration are that: the vortex frequency is less than 0.6–0.9 times of the rotational speed, an ellipse axis orbit, positive precession and vibration frequency is sub-harmonic that is less than 0.5 times of speed frequency, which is always with one time, two times and higher harmonics, the instability of the vibration and phase, the disorder of the axis orbit, and the divergence.

For high speed gas turbine, when the rotor bends or turbine eccentricity which causes the uneven gap between tip and turbine casing in the circumferential, there is the sum of the axial forces except couple which acts on the blade, but also transverse power that is perpendicular to the displacement of the rotor which leads to the precession motion and instability of rotor, the vibration characteristics of which are similar to the fluid seal vibration.

7. Pump cavitation

During the working process of the pump, when static pressure of somewhere is below the cut-off saturation vapor pressure at that temperature that bubbles emerges and volume expanse, bubble condenses into liquid with volume shrinkage in the high pressure zone which leads the increasing pressure to the huge hydraulic shock. It is known as the pump cavitation that cracks and erosion forms by the alternating pressure shocks on the impeller surface. When cavitation occurs, the formation, growth, and rupture process of bubble will reach tens of thousands of times per second, the local pressure can reach hundreds of MPa, which results in the decline of flow rate, outlet pressure, and efficiency, until the cutout and impeller damage. Vibration extends to the whole rotor system, self-excited oscillation emerges. Low frequency oscillation of pump outlet pressure, wide spectrum of mechanical vibration, and noise which is easy to cause the resonance of the rotor system, so pump cavitation occurs several times in the development and production process. In the using, it will also induce pump cavitation in such condition (low pump pressure). It should strictly control the cavitation in the practical operation.

Characteristics of cavitation are: vibration performance is shown as broad spectrum of mechanical vibration and with a sudden, mild noise and “baba” sound when starts, vibration intensified and accompanied with detonation when severe, low frequency oscillation of pump outlet pressure, capacity, efficiency, and lift decreased rapidly.

8. Bearing damage

The bearings used in the turbo pump are the ball bearing which bear the radial and axial load, work in the serious environment and usually appear as the mode of the fatigue spalling, damage, fracture, and so on. Stiffness, damping, and external exciting force of rotor system all changed when bearing fail which lead to the instability of rotor system, intensified vibration, and axial float, at last the friction between rotor and other parts are severe which lead propellant channeling cavity to explode. Therefore, it should detect the bearing damage before the rotor loses stability.

Characteristics of rolling bearing failure are: intensified vibration, wide vibration frequency which is from below the low frequency (1 kHz) to high frequency even to very high frequency (thousands of Hz), accompanied with noise and impact, vibration of blade passing frequency and its harmonics and fractional frequency emerges, and temperature rise.

The impact vibration will generate at the surface fatigue spalling of the bearing parts, one is called “passing vibration” that low frequency pulsation when rolling body sequentially rolls over the defects of working surface which is subjected to repeated impact, and the corresponding frequency is known as “passing frequency” which can be obtained through the bearing parameter, general below 1 kHz. It is difficult to diagnose because of the big random noise and fluid dynamic noise. The other is natural vibration, including the natural frequency of each part and the acceleration sensor, and with 1–60 kHz frequency band. When the transient impact occurs and the natural vibration is excite, so the bearing fault and fault element can be judged according to the impulse frequency.

9. Pulsation of fluid pressure

Pulsation of fluid pressure is the phenomenon that the fluid flows by some disturbance to cause the variation of pressure. The reason for which contains in the pump fed liquid rocket system is that limited blades of centrifugal pumps, combustion instability of gas generator, tank pulsation of pressure caused by longitudinal vibration, hydraulic impact of propellant transport network, combustion instability of combustion chamber, leak, etc. Now, the technology has been quite mature to suppress combustion instability of the middle and low frequency in liquid rocket system, but pressure pulsation of the pipeline also happens when fault occurs such as plug of leakage, throttle, and liquid container. The resonance happens which is disastrous when the pressure pulsation is the same as the natural frequency of the piping system and the component, and the pulsation of pressure also affects the combustion process of incendiary agent to lead the unstable working process.

The frequency of the pressure pulsation is lower generally under the 1 kHz. The excitation force is the pressure pulsation excitation in the formula (2.2).

The characteristic frequency of the rotor response to the pressure fluctuation is the pressure pulsation frequency. When the pressure pulsation frequency and the natural frequency of the rotor coincide, which will lead instability of rotor system and vibration intensification, and the vibration direction is along axial direction which emerges the vibration of the blade passing frequency.

10. Structure resonance

The turbine pump rotor system is coupled with the engine. The high and low frequency unstable combustion during the engine work cause the severe vibration which is transmitted to the turbine pump system through the connecting device, and the pipeline vibration of the propellant conveying system will also be transmitted to the turbine pump system by coupling, the *K*, *C,* and *R* in the type (2.2) will alter which cause the vibration mode of the turbine pump rotor system. When the frequency of external excitation force is the same as natural frequency of the rotor system, the structural resonance of the rotor system will lead catastrophic accidents.

11. Gear damage

The gears in the turbo pump generally work in high speed, high power, and corrosive medium, and are close to the high temperature turbine and two pumps with great temperature difference. Damage is mainly due to the high speed of gear pitch circle, the large centrifugal force, the large meshing surface contact stress, severe fatigue or spalling caused by meshing surface lubrication and poor cooling. The large change of load causes large load impact on the gear transmission during the start-up of the engine, which is prone to bending fatigue and broken teeth. To the turbine pump, the main failure of the gear box part is the "pitting" caused by the free peeling of the gears and the "broken teeth" caused by the bending fatigue and impact.

Gear box is with quality and elasticity, and the meshing gear pair is a vibration system. When the gear rotates, the transmission force periodically changes with impact which causes the vibration of gear. Under the condition of no fault, gear transmission also vibrates which is known as conventional meshing vibration with approximate sine meshing waveform of vibration, frequency based on meshing frequency and harmonic component.

When the gear failure, change of vibration amplitude caused by fluctuation of tooth surface load that emerges complex frequency modulation and amplitude modulation vibration signal. For "pitting" and "broken teeth faults", the feature of the spectrum characteristics is mainly the rotation frequency, which is shown in Fig. 2.4.

Vibration excitation force which is mainly based on *fc* will intensify the vibration of the turbo pump system; it will cause the rotor system instability especially when the natural frequency of the rotor system is coincident.

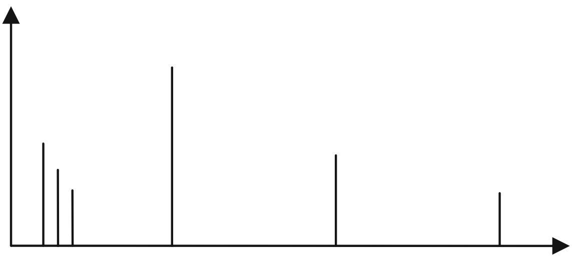


Fig. 2.4 Typical spectrum of gear fault

2.4.3 Seal Components

Seals are widely used in the engine as a key component of the pneumatic and hydraulic system. The space and rocket accident which are caused by the failure of the seal are disastrous. The main failure mode is leakage, wear, and physical damage.

(1) Sealing mechanism of seal

The sealing performance of static seals are relied on the assembly of pre-deformation and pressure transferred to medium, realized by the contact pressure and adhesion that seal adhere to the metal surface, as shown in Fig. 2.5.

The sealing force P:

$$p = p_0 + kp_j + f(t, T) \tag{2.5}$$

Formula:

P_0 The contact pressure generated by the pre-deformation is caused by the fastening bolts

P_j The pressure of working medium

$f(t, T)$ The adhesion force between the seal and the metal surface is a function of time t and temperature T

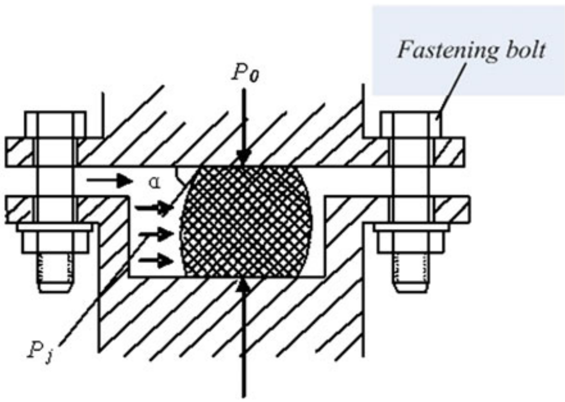


Fig. 2.5 The sealing theory

k The pressure transfer coefficient, which is related to the sealing material, $k = \mu/(1-\mu)$, is the Poisson coefficient of the sealing material.

Reliable sealing must meet:

$$P \geq P_j \cos \alpha \tag{2.6}$$

Formula:

α The angle between the tangent line of curvature of the contact surface and the sealing material

It just shows that:

1. When the pre-tightening force $P0$ reduce, the sealing force P reduce. The seal fail as the sealing force P reduce to a certain degree. The main cause of this failure is vibration and metal stress relaxation.
2. The vary of aging, corrosion, and temperature of the sealing material causes the change of k, μ, $f\ (t,\ T)$ and the decreases of sealing force, which lead to the failure of seal.
3. It may fail that the sealing force will not be guaranteed when the medium pressure P_j increases.

The seal material is mainly rubber, metal parts, and fluorine plastic part in the rocket engine, and fluorine plastic part is in the majority which is not easy to aging because of its special molecular structure. External shock to seal is small in the storage condition, only affected by assembly stress. Therefore, it cannot be considered long-term storage, the aging of fluoride and mechanical damage.

(2) Aging mechanism of rubber seal

The phenomenon is known as aging that high molecular compound is influenced by internal and external factors in using which causes the original mechanical properties and appearance shape change as time goes on. Aging is divided into two kinds, one is the main chain of the degradation that makes the molecules small, the performance of which becomes sticky, the other is to be oxidized, that peroxide is formed and rubber becomes brittle because of excessive cross-linking. The factors that affect the aging are: cross-linking deformation of the internal polymer and filler, environment (chemical and biological), and physical (light, heat, moisture, air and so on), which not only works alone but also in the form of coupling function. For rubber materials, the aging damage deformation is:

$$\varepsilon = Ktb \tag{2.7}$$

Formula:

ε Accumulation of aging damage deformation of rubber materials;

b Constant related to variety;
K Aging rate, $K = A\mathrm{e}^{-\frac{B}{T}}$, A, B is constant, T is temperature (K).

Thus it can be seen from the formula, temperature and time are the biggest impact on rubber aging. In dynamic environment such as dynamic sealing and vibration, heat produced by friction leads the rising temperature that accelerates the aging and reduces the rubber life.

The aging test of a certain type of engine seal showed that: the aging speed of the early stage is fast, but the aging of the rubber seal is not consistent to some certain.

(3) Principle of metal stress relaxation

Experiments have proved that: the leakage of seal is not caused by aging of the seal but the loosening of the fastener. Therefore, Variety of the relaxation and metal fasteners force problems should be mainly considered during the analysis of seals' performance.

Stress relaxation is the process that the stress reduces as time. The relationship between stress relaxation and time is:

$$\Delta\sigma/\sigma = K1\mathrm{Ln}(1 + rt) \tag{2.8}$$

Formula:
$\Delta\sigma$ Variation of stress
σ Stress
$K1$, r Relaxation constant
t Relaxation time.

It can be known: the fastener will automatically release in the storage and using, and the preload of the spring will automatically reduce. Therefore, measures should be taken to prevent some fasteners loose, that the fastener and the spring preload should be retighten before using. It should take measures to prevent vibration in the process of transport and using, because vibration will impose additional load on the force of the fastener and accelerate the stress relaxation.

It is similar with the failure mechanism and the analytic procedure of seal such as the leakage and function fault in other parts such as valve, regulator, filters, piping, pressure vessels, and power actuating device, except the defect structure.

2.5 Standard Failure Pattern of the LRE

The occurrence and development of fault are a process which supply time for the fault detection and diagnosis. In addition that faults are always shown in signs, there are early signs even to sudden failure which provide possibility and evidence for fault detection and diagnosis. Sign is represented in many aspects, sometimes

Table 2.1 Standard failure mode of thrust chamber

Failure mode		Fault characteristics and performance														
		Combustion chamber pressure		Injection drop		Combustion chamber vibration			Engine thrust		Cooling jacket outlet temperature		Venturi pressure		
		Drop	Fluctuation	Enlarge	Fluctuation	High frequency	Low frequency	Heavy intensity	Drop	Fluctuation	Drop	Deviation from normal values	Drop	Fluctuation	Rise
1	Injector plug	1		1					1			1		1	
2	Nozzle ablation	1	1		1					1					1
3	Throat ablation	1							1				1		
4	High frequency unstable combustion		1			1		1		1				1	
5	Abnormal cooling of cooling jacket											1			
6	Low frequency unstable combustion		1	1			1	1		1	1	1		1	

Note 1 indicates that the corresponding feature has occurred, 0 which means that the corresponding feature does not occur

Table 2.2 Standard mode of common failure of turbine pump system

Failure mode			Fault characteristics and performance																		
			0.00–0.39*fr*	0.40–0.49*fr*	0.50*fr*	0.51–0.99*fr*	1.0*fr*	2.0*fr*	3.0–5.0*fr*	0dd*fr*	>5.0*fr*	Meshing frequency	Roar	Component resonance frequency	Axial vibration	Gradual change	Muta-tion	Variation with load	Variation with speed	Main moni-toring site	Pump outlet pressure
I	1	Component mass eccentricity					0.90	0.05	0.05				1	1		1			1	1	
	2	Blade fracture					0.90	0.05	0.05				1	1			1		1	1	1
	3	Shaft bending					0.90	0.05	0.05				1	1	1	1		1	1	1	
II	4	Rotor radial rub	0.10	0.05	0.05	0.10	0.30	0.10	0.10	0.10	0.10		1	1		1		1	1	1	1
	5	Rotor axial rub	0.05	0.05	0.05	0.05	0.30	0.20	0.10	0.10	0.10		1	1	1	1		1	1	1	1
III	6	Shaft crack					0.40	0.20	0.20		0.20		1	1		1		1	1	1	
	7	Shaft rigidity is not equal						0.80	0.20				1	1		1		1	1		
	8	Bearing damage	0.10	0.10			0.40	0.20	0.20				1	1	1		1		1	1	
IV	9	Body connection loose	0.20	0.20			0.30	0.10	0.10	0.10			1	1			1		1		1
	10	Pressure fluctuation	0.20	0.20			0.10	0.10	0.30		0.10		1	1	1						1
	11	Structural resonance	0.20	0.20			0.50	0.10					1	1	1		1		1		1
V	12	Rotor component loosing	0.40	0.40			0.10		0.10				1	1				1	1	1	1
	13	Cavitation	0.50	0.30			0.05	0.05	0.05	0.05			1	1			1	1	1		1
	14	Loose bearing	0.70				0.20		0.05	0.05			1	1		1			1	1	
VI	15	Gear damage					0.20					0.80			1		1	1	1		

Note fr the working frequency of the rotor, the vibration spectrum of the space is 0; 1 represents that the corresponding feature is true, the space is 0, which means that the corresponding characteristic is false

Table 2.3 Standard failure mode of gas generator

	Failure mode	Fault characteristics and performance													
		Chamber pressure		Injection drop		Combustion chamber vibration			Turbine speed		Outlet temperature of turbine		Engine thrust		
		Drop	Fluctuation	Enlarge	Fluctuation	High frequency	Low frequency	Intensity	Drop	Fluctuation	Drop	Deviation from normal values	Drop	Fluctuation	Rise
1	Injector plug	1		1					1		1		1		
2	Nozzle ablation	1	1		1					1		1	1		
3	Propellant mixing uneven		1							1		1		1	
4	Low frequency unstable combustion		1	1			1	1		1				1	

Note 1 indicates that the corresponding feature has occurred, 0 which means that the corresponding feature does not occur

Table 2.4 Regulator standard fault mode

Failure mode		Fault characteristics and performance						
		Upstream pressure	Downstream pressure		Switch status indicator		Characteristic frequency	
		Normal deviation	Drop	Normal deviation	Normal	Abnormal	Medium flow	Leak
I II III IV V VI 1	Internal leakage		1	1	1		1	
2	Stagnation (switch failure)	1		1		1		1
3	Regulation failure	1		1	1		1	
4	External leakage		1	1	1		1	1

Note 1 indicates that the corresponding feature has occurred, 0 which means that the corresponding feature does not occur

Table 2.5 Valve standard fault mode

Failure mode		Fault characteristics and performance						
		Upstream pressure	Downstream pressure		Switch status indicator		Characteristic frequency	
		Normal deviation	Drop	Normal deviation	Normal	Abnormal	Medium flow	Leak
I II III IV V VI 1	Internal leakage	1	1	1	1		1	
2	Stagnation (switch failure)	1		1		1		1
3	External leakage	1	1	1	1		1	1

Note 1 indicates that the corresponding feature has occurred, 0 which means that the corresponding feature does not occur

explicit and sometimes implicit. It is not possible and necessary to detect all these signs in the monitoring and diagnosis. Some are known as the feature of fault which can character the faults. Features can be the fault performance of the research

Table 2.6 Standard failure mode of pipe line

Failure mode		Fault characteristics and performance							
		Upstream flow		Downstream flow		Upstream pressure		Downstream pressure	
		Increase	Drop	Increase	Drop	Increase	Drop	Increase	Drop
I II III IV V VI 1	Jam		1		1	1			1
2	Leak				1				1

Note 1 indicates that the corresponding feature has occurred, 0 which means that the corresponding feature does not occur

Table 2.7 Standard failure mode of pressure vessel

Failure mode		Fault characteristics and performance				
		Pressure		Maintain pressure		Characteristic frequency
		Deviation from normal values	Drop	Normal	Drop	
I II III IV V VI 1	Leak	1	1		1	1
2	Deformation					1
3	Safety valve failure	1		1		

Note 1 indicates that the corresponding feature has occurred, 0 which means that the corresponding feature does not occur

Table 2.8 Fault mode of filter standard

Failure mode		Fault characteristics and performance							
		Upstream flow		Downstream flow		Upstream pressure		Downstream pressure	
		Increase	Drop	Increase	Drop	Increase	Drop	Increase	Drop
I II III IV V VI 1	Jam		1		1	1			1
2	Leak				1				1
3	Filter element damage	1			1			1	

Note 1 indicates that the corresponding feature has occurred, 0 which means that the corresponding feature does not occur

object, but also can be the fault performance of research object in the whole system which should be more consideration in the establishment of the condition monitoring and diagnosis system. The features shown in failure modes are also many, and it is not only consuming machine time but also not necessarily good if these features are using directly for diagnosis. So it is necessary to make appropriate and necessary choice of the fault feature, but also make the dimension as less as possible. Therefore, it is necessary to establish the standard fault model of the engine which is not only beneficial to the online monitoring and diagnosis system, but also facilitate the development, production, and use. According to the above analysis, the standard failure modes of the engine components are established as shown in Tables 2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 2.7 and 2.8.

The above table is the initial value of fault standard mode, which should be developed and improved in the practical application and should be amended accordingly for specific equipment and system.

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