



INVESTIGATION OF START-UP IMPACT CHARACTERISTICS OF LIQUID ROCKET ENGINES

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Abstract

The wavelet analysis is applied to process start-up impact signals of liquid rocket engines in this paper. With good localization in time and frequency domains, the wavelet analysis can focus on any desired parts of the object signals and is very suitable for analyzing strong time-dependant or non-stable signals. By analyzing the time-energy charts, the frequency-energy charts and the time-frequency-energy charts at the same time, fine difference in time sequence and frequency of different impact signals is checked. The possible factors affecting the impact level is analyzed then. The study may be helpful for fault diagnostics of the start up of LRE.

1. INTRODUCTION

The most faults or failures of LRE are occurred during the start up phase. The faults may cause the failure, or in the worst case, the engine or launch vehicle even may be destroyed. Therefore, the research on the start up process becomes an important part of the whole system researches. The signal processing and analysis become the important measure of the start up research. The start up is a high density energy release process. In this phase, the operation processes of each LRE units are unsteady, the burning units are suffered serious pressure and temperature shocks. The pump shells and supply system pipes are suffered strong shock loads. All of these cause the strong time-dependent, transient and unsteady features of the start up dynamic signals and the high dimension, nonlinear properties of the LRE mathematical model. All of these decrease the practicability and reliability of the detecting and diagnose methods.

The wavelet analysis is a time-frequency tool, developed in the past ten years. It overcomes the drawbacks of the Fourier analysis which is absent any time domain resolution. With both time and frequency domain localization properties, the wavelet can analyze signals of any given frequency band and time interval with any desired scale. Therefore, it can focus any details of the signal. It is especially suitable for the analysis of the time variant and unsteady signals; therefore it is called "the microscope of signal analysis". The wavelet analysis has been

widely applied in science and technical area, such as signal processing, operation mode identification, biology-medical, fluid turbulent flow, machine fault diagnose and etc.

In this paper, the transient signals of LRE hot tests are analyzed by wavelet analysis. The method makes great improvement in the signals of start up phase of LRE. It is also of great practice value for status monitoring, performance identify, fault detection and diagnose.

2. THE LRE START UP SHOCK ANALYSIS

The LRE start up process is a high density energy releasing process. In this phase, all the engine parameters, such as the flow rate, temperature, pressure and rotating speed have to be transited from original status into main stage status; its reflection is the high energy shock signals in engine structure vibration signals. The shock-vibration induced structure failures are the normal failure modes of engineering structures. Therefore, the analysis on the induced reasons of shock and vibration, the feature of the signals, the components of the signals, and search for the way to eliminate and/or decrease the shock-vibrations and base on the feature of the signals to increase the shock-vibration resisting capability of the structure become two major contents of shock-vibration research. But the accurate signals analysis is the base of all the researches.

The system of LRE is very complicate. Following factors affect the start up features: the action time series, the characteristics of each units and the dynamic characteristic of regulator. The effects of these factors will be direct reflected in each transient signals. Therefore, the signal analysis becomes an important measure for the research of the start up phase. The start up property of a LRE is not stable, some times the shock energy of two starts of the same engine under same operation conditions may be differ about 10 times. There also the difference of the maximum energy peak time positions. The abnormal and normal time domain shock signals of the start up phase are showed in Fig. 1.



Fig. 1 High start up shock signal and optimal start up signal

The applicability and reliability of Fourier transform based traditional signal analysis method are decreased when it is dealing with strong time dependent variation and strong transient shock signals. But the better localization properties of the wavelet analysis both in time and frequency domain permit signals in any given frequency band or in any given time section can be analyzed with any scaling factor, and any detail of the signals can be focused.

Therefore, the method is especially suitable for the minor time series or frequency component difference distinguish of different start up signals.

3. WAVELET TRANSFORM AND ITS CHARACTERISTIC

3.1 Continuous Wavelet Transform

Definition 1 Wavelet is the series functions after compressing and shift treatments of $\psi(t)$; it is named analysis wavelets or continuous wavelets.

$$\psi_{s,x}(t) = |s|^{-\frac{1}{2}} \psi(\frac{t-x}{s}) \quad s, \tau \in R, s \neq 0$$
 (1)

In which, $\hat{\psi}(w)$ is the FT of $\psi(t)$.

Definition 2 If $\psi(t)$ is the basic wavelet, the $\{\psi_{s,x}(t)\}$ is the continuous wavelet given by (1). For $f(t) \in L^2(R)$, $W_f(s,x)$ is the continuous wavelet of f(t) and can be defined as

$$W_{f}(s,x) = |s|^{\frac{1}{2}} \int_{\mathbb{R}} f(t)\psi(\frac{t-x}{s})dt$$
 (2)

The continuous inverse wavelet transform is

$$f(t) = \frac{1}{C_{\psi}} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \frac{1}{s^2} W_f(s, x) \psi(\frac{t-x}{s}) ds dx$$
(3)

In practical application, the continuous wavelet and its transform is usually in discrete form. Here, the discretion is focused on the continuous scale s and continuous shift x, not focused on the time variation t.

3.2 Continuous Wavelet (CW) Analysis and STFT

The wavelet analysis is a localization analysis with changeable time and frequency windows, the longer time interval can be used to obtain more accurate low frequency information, the shorter time interval can be used to obtain high frequency information. This is in accordance with the signal features that the low frequency part changing slowly and the high frequency part changing quickly. The STFT is another time-frequency domain analysis tool. Fig. 2 explains the feature of these two methods by the STFT and CWT processing results of a re-frequency modulated signal.



Fig. 2 the analysis of STFT and CWT

It can be seen that STFT analysis the whole signal with same resolution, the time-frequency trends of the signals can be better reflected. The CWT can realize the real time high frequency and low frequency analysis with different resolution: at low frequency range, the frequency resolution can be higher; at high frequency range, the time resolution can be higher. The auto focus function of the CWT makes the reality of above feature.

4. THE SHOCK SIGNAL ANALYSIS OF 6 DIFFERENT START UP PROCESSES

To identify the reasons, signal features and frequency components of these shock signals, and to find the ways and measures for eliminating or decreasing the shock amplitude, the classical shock signals of 6 different starts up processes of the gas generator are analyzed in this paper. The features of the shock signals in the time-energy spectrum, time-frequency-energy spectrum analysed.

4.1 Abnormal Shock Signals

It can be seen from fig. 3 that the shock energy happened around 1.6 seconds of the 1st start up process, the maximum energy is about 6×10^4 , peak positioned around 90 Hz.



(2) Time-frequency-energy spectrum

Fig. 3 the Shock Signal of 1st Start Up

Fig. 4 indicates that the shock energy is happened around 1.2 second, the amplitude is about 6×10^4 , and peak locates around 90 Hz.



Fig. 4 the Shock Signal of 2nd Start Up

4.2 Normal Shock Signals

Fig. 5 shows that the time range of peak shock energy is larger, the peak is not very steep, the largest energy amplitude is about 7×10^3 , the largest peaks distribute around the 25Hz frequency components of the 1.4 to 1.7 second interval. There are also peaks of 75 Hz components of 0.8 to 1.0 second interval, but the energy amplitude of these peaks are only about tenth of the abnormal shock peaks.



Fig. 5 the Signal of 3rd Start Up

It can be seen from Fig. 6 that the time range of the peak shock energy distribute is larger, the peaks are relative flat, not very steep. The largest peaks are happened around 1.0 to 1.1 seconds and distributed around 90 Hz. Their energy amplitudes are only about tenth of abnormal shock signals.



Fig. 6 The Shock signal of 4th Start Up

It can be seen from Fig. 7 that the time range of the peak shock energy distribution is large, the peaks are relative flat and not very steep .The largest peak energy is about 7×10^3 class. The peaks are happened around 90 Hz of 1.0 seconds period and 70Hz of 0.8 to0.9 second period. The amplitude of 25Hz peak is only the tenth of the abnormal peaks.



It can be seen from Fig. 8 that the shock energy peaks of 6^{th} start up distribute on a more broad range, and locate at earlier phase. Their maximum energy amplitudes are about 8×10^3 class, the peaks distribute around 0.75 second are 70Hz. There are also peaks around 25Hz.



4.3 Analyses

According to above analysis, the energy amplitudes of abnormal shock signals are of 6×10^4 class, the maximum energy peaks locate at different time, but the energy are centred, the peaks concentrated in the 90 Hz frequency range; the maximum energy amplitudes of normal shock signals are about 8×10^3 , the shock energy are happened in a broader time range, their distribution is more steady, and peak number is increased but distributed in a more discrete way.

The 90Hz range is the natural frequencies of injector upper stream liquid loop, the 90Hz disturbances will be induced in the liquid loop when the turbo pump rotating speed passes through this frequency range, the speaks of same frequency are produced by gas generator. Since the increasing process of the turbo pump rotating speed has to pass through this frequency range, therefore, nearly almost every signal contains the peaks of 90Hz range. Because the rotating speed quickly passes through this frequency range, therefore, no resonance is happened. The process of the system transiting from internal stage into main stage brings each parts of the system with severe disturbances. If the transition process is more steady, more natural

frequencies of the system will have the same opportunity to be reflected in each measured signals. If the transition process is unsteady, and the most fast transition period is coincidence with the 90Hz rotating speed duration, the long time and high amplitude 90Hz severe coupling resonance will happened in injector upstream liquid loop, the system will suffer more severe shock. Therefore, whether the stage transition is steady is the key factor which determines the start up shock amplitude.

5. CONCLUSION

The signal analysis of some start up shocks indicate that the fastest engine start up rotating speed transition, the relative relations between 90Hz rotating speed and 90Hz natural frequency of gas generator upstream liquid loop are the key factors which determines the start up shock amplitude. The key factors for controlling above relation are the flow rate regulator. Therefore, the research on the dynamic characteristics and the system operation stability in a detail and deeply manner is the important way to improve the start up quality. On the other hand, the differences of time and domain characteristics for the normal and the abnormal start up processes can be seen from the start up signals. Therefore, there are lot of detail analysis and research has to do for the perfect design and control on the start up process.

In this paper, the wavelet analysis is used to analyze the LRE start up shock signals. Because of the better localization performance of the analysis both in time and frequency domain, it can perform any scale analysis on the components of any given frequency band or time section, therefore, any details of the signal can be focused. It is especially suitable for the minor differences of the time series and frequency components of different start up signals. With the time-energy spectrum, the frequency-energy spectrum, the time-frequency-energy spectrum, the multi view focused analysis of the start up shock signals can find the minor time series and frequency component differences of different signals. The potential of wavelet theory and its application on the LRE signal analysis should be further exploit.

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