Band-pass filtering algorithms for adaptive control of compressor pre-stall modes in aircraft gas-turbine engine

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Abstract. The methods for increasing gas-turbine aircraft engines’ (GTE) adaptive properties to interference based on empowerment of automatic control systems (ACS) are analyzed. The flow pulsation in suction and a discharge line of the compressor, which may cause the stall, are considered as the interference. The algorithmic solution to the problem of GTE pre-stall modes’ control adapted to stability boundary is proposed. The aim of the study is to develop the band-pass filtering algorithms to provide the detection functions of the compressor pre-stall modes for ACS GTE. The characteristic feature of pre-stall effect is the increase of pressure pulsation amplitude over the impeller at the multiples of the rotor’ frequencies. The used method is based on a band-pass filter combining low-pass and high-pass digital filters. The impulse response of the high-pass filter is determined through a known low-pass filter impulse response by spectral inversion. The resulting transfer function of the second order band-pass filter (BPF) corresponds to a stable system. The two circuit implementations of BPF are synthesized. Designed band-pass filtering algorithms were tested in MATLAB environment. Comparative analysis of amplitude-frequency response of proposed implementation allows choosing the BPF scheme providing the best quality of filtration. The BPF reaction to the periodic sinusoidal signal, simulating the experimentally obtained pressure pulsation function in the pre-stall mode, was considered. The results of model experiment demonstrated the effectiveness of applying band-pass filtering algorithms as part of ACS to identify the pre-stall mode of the compressor for detection of pressure fluctuations’ peaks, characterizing the compressor’s approach to the stability boundary.

1. Introduction
Aircraft gas-turbine engines (GTE) of the new generation have substantially innovative features:
− the increase of loads on the compressor and turbine stages for a reduction of engine weight and the number of components, in particular - the number of compressor and turbine stages;
− the reduction of levels of noise and harmful substances’ emission;
− the use of artificial intelligence technology in automatic control systems to adapt the engine components to real operating conditions and faults, i.e. an increase of reliability.

The implementation of these properties on the one hand gives the engine a new quality, but on the other hand it puts new scientific and technical problems.

Thus, for example, joint implementation of increased loads at compressor stages and reduced emission of harmful substances in the combustion chamber significantly reduces the range of steady operation of the GTE depending on fuel consumption for both static and especially dynamic regimes.
in acceleration and throttling. In fact, the upper bond of stable operation is determined by the flow disruption (stall) and auto-oscillations in the compressor, and the lower bond - by the flame blowoff in the low-emission combustion chamber. At the same time, the stall boundaries both in the case of the compressor and in the case of the combustion chamber in the engine’s parametric coordinates depend essentially on many factors, first of all, on the background of the process (system’s state), i.e. they are variables, respectively, they can not be apriory determined by software.

So, the fault-tolerant operation of aircraft gas-turbine engines is one of the main problems of adaptive digital automatic control systems (ACS). The effectiveness of ACS significantly depends on the chosen methodology for identification of the critical regimes when the engine approximates the stability boundary.

One of the signs of the instability of the gas systems with the compressor, such as GTE, is the presence of flow pulsations in the suction or discharge pipeline [1]. The reason for such fluctuations may be the approach to the stall mode, characterized by large dynamic loads, which can lead to the destruction of the compressor.

Thus, the problem of algorithmic control of the pre-stall modes of the gas turbine engines’ operation, adapted to the boundaries of its stability, is topical. In this case, the upper limit of stable operation is determined by the flow disruption and self-oscillations in the compressor, and the lower limit - by the failure of combustion in the low-emission combustion chamber.

In this study, the possibility of identifying of the compressor pre-stall phenomena by the use of bandpass filters is considered.

The paper dwells on the design of a bandpass filtering algorithms to provide the detection functions of the compressor pre-stall mode for ACS GTE.

2. Materials and methods

The problem of identifying the pre-stall phenomena is not new, but its solution has been limited to investigating the sign of a stall in the subsonic or transonic stages of the compressor [2-5]. Rare publications of pre-stall features in multi-stage compressors are found [6].

At present, the most characteristic feature of pre-stall phenomena is the increase of pressure pulsation amplitude over the impeller at frequency \( f_0 = 0.6 \cdot n \cdot z \), where \( n \) is the rotor speed of the compressor (“rotary” frequency), and \( z \) is the number of blades in the impeller (it is obvious that \( f = n \cdot z \) is the “blade” frequency).

Physically, this fundamental frequency characterizes the onset of the beginning of pre-stall phenomena. Frequency \( f_0 \) is determined by the kinematics of the flow in the radial clearance of the impeller and depends on the load on the profile of the compressor blade (the difference in pressure between the trough and the back). When a stall mode is approaching, the pressure difference and, consequently, the velocity component of the transverse flow are increased. When the vector sum of the velocity in the longitudinal and transverse directions becomes such that the trajectory of the vortex sheet in the radial gap intersects with the leading edge of the neighboring blade in the wheel, then the local angle of attack increases and the flow disruption is generated, which is fixed as a surge of the pressure pulsation amplitude. The phenomena are a sign of a stall beginning (breakdown of the flow).

There is a rather simple procedure [2, 3] for determining the trajectory of a vortex sheet, under the condition of a known pressure distribution along the profile of the end section of the compressor blade (for example, from a two-dimensional flow computation). Since compressors have similar parameters for load, speed, etc., this criterion, namely the appearance of a peak of pressure pulsations at frequency \( f_0 \) is a rather common sign of a stall beginning for subsonic and in some cases for transonic compressors. In the case of supersonic flow in the impeller, in most cases determining the stability limit of the compressor as a whole, this feature becomes irrelevant. Taking into account the current trend of development of supersonic stages, it becomes relevant to find a sign of a stall beginning for supersonic stages operating in a multi-stage compressor system.

An eight-stage compressor with a pressure increase degree of 16 and a supersonic first stage was chosen as the object of the experimental study. The compressor was provided with pressure pulsation
sensors mounted on the inlet casing, above the first impeller and at the outlet. The compressor stability margin was controlled by throttling the output section. As a result, the pressure pulsation signals, corresponding to the four throttle positions and the operating modes of the compressor from normal to stalling, were obtained.

Figure 1 shows the experimental oscillogram of the pulsation of pressure over the impeller of the first stage of the compressor approaching the stability boundary in the time and frequency domains. This oscillogram was obtained by the registration of the full-scale (motor) tests results in a pre-stall mode.

![Figure 1. The experimental oscillogram of the pulsation of pressure over the impeller of the first stage of the compressor approaching the stability boundary (pre-stall mode) in the time and frequency domains.](image)

Thus, the problem is reduced to identifying of the pressure ripple peaks at the indicated frequencies, characterizing the approaching to the stability boundary. The solution of this problem will allow expanding the capabilities of the ACS GTE.

One of the ways to solve the problem is to apply bandpass filtering algorithms. The used bandpass filtering method is based on integration of the digital low-pass filters (LPF) and high-pass (HPF) recursive filters with infinite impulse response (IIR).

Reasoning from theoretical premises, the impulse response (or the filter core) is the main characteristic of the filter. And the impulse response of the HPF, equal to $k_1(t)$, can be determined through the known impulse response of the LPF, equal to $k_2(t)$, by the method of spectral inversion [7].

The obtained signal of pressure pulsations $\Delta P(t)$ can be interpreted as an superposition of high-frequency $\Delta P_1(t)$ and low-frequency $\Delta P_2(t)$ components:

$$\Delta P(t) = \Delta P_1(t) + \Delta P_2(t).$$ (1)
To detect the low-frequency constituent, the convolution operation is applied:

\[
\Delta P_2(t) = \Delta P(t) \ast k_2(t).
\]

(2)

Taking into account basic convolution property \( x(t) = x(t) \ast \delta(t) \), where \( \delta(t) \) - Dirac delta function, from (1) and (2) for the high-frequency component of the signal the following will be obtained:

\[
\Delta P_1(t) = \Delta P(t) - \Delta P_2(t) = \Delta P(t) \ast \delta(t) - \Delta P(t) \ast k_2(t) = \Delta P(t) \ast \left( \delta(t) - k_2(t(t)) \right) = \Delta P(t) \ast k_1(t).
\]

(3)

Thus, from (3) it follows that the impulse response of the HPF is:

\[
k_1(t) = \delta(t) - k_2(t).
\]

(4)

Pulse response of bandpass filter \( k(t) \) is determined by the convolution:

\[
k(t) = k_2(t) \ast k_1(t).
\]

(5)

According to the known formula which relates the impulse response and the transfer function of the bandpass filter \( W(p) = L[k(t)] \), the transfer function of the HPF having the same cutoff frequency as the considerd LPF is determined from (4) and (6):

\[
W_1(p) = L[k_1(t)] = L[\delta(t) - k_2(t)] = 1 - W_2(p).
\]

(6)

In accordance with (5), the transfer function of the bandpass filter (BPF) can be found by the convolution theorem:

\[
W(p) = W_2(p) \cdot W_1(p) \doteq k_2(t) \ast k_1(t) = \int_{-\infty}^{+\infty} k_2(\tau) \ast k_1(t-\tau) d\tau.
\]

(7)

In this case, the HPF and LPF have cutoff frequencies \( f_1 \) and \( f_2 \), respectively.

Thus, according to the selected LPF transfer function, a bandpass filter (BPF) can be built for the given frequency bandwidth \([f_1; f_2] \) (Hz) using formulas (6) and (7).

It is known that the simplest LPF has a transient response:

\[
h(t) = 1 - e^{-\frac{t}{T}}.
\]

(8)

So, according to the known formula which relates the transient and impulse response \( k_2(t) = h'(t) \), the impulse response of the designed low-pass filter can be found as:

\[
k_2(t) = h'(t) = \frac{1}{T_2} e^{-\frac{t}{T_2}}.
\]

(9)

where \( f_2 = \frac{1}{T_2} \) (Hz) is the LPF cutoff frequency and the upper bound of the BPF transmission band.

The transfer function of designed LPF may be obtained from (10) as:

\[
W_2(p) = L[k_2(t)] = \frac{1}{T_2p+1}.
\]

(10)

Obtained transfer function \( W_2(p) \) corresponds to the first-order aperiodic element [8].

The transfer function of designed HPF with cutoff frequency \( f_1 = \frac{1}{T_1} \) (Hz) is obtained from (6):

\[
W_1(p) = 1 - W_2 \bigg|_{when \ f_1 = 1 - \frac{1}{T_1p+1} = \frac{T_1p}{T_1p+1}}.
\]

(11)

Frequency \( f_1 \) corresponds to lower bound of the BPF transmission band.

Obtained transfer function \( W_1(p) \) corresponds to the real first-order differential element [8].

According to (7), (10) and (11), it is possible to get the resultant BPF transfer function:
\[ W(p) = W_2(p) \cdot W_1(p) = \frac{1}{T_1p + 1} \cdot \frac{T_1p}{T_1p + 1} \quad (12) \]

\[ W(p) = \frac{T_1p}{T_1T_2p^2 + (T_1 + T_2)p + 1} \quad (13) \]

The obtained second-order band-pass filter’s transfer function corresponds to a stable system. This can be proved by using the Lyapunov stability criterion. According to this criterion, it is necessary and sufficient for a linear system stability that the real parts of the roots of the characteristic equation \( T_1T_2p^2 + (T_1 + T_2)p + 1 = 0 \) were negative, that is, they lay to the left of the imaginary axis of the plane of the roots. The roots of the characteristic equation describe the free motion of the BPF or dynamic modes. In this case, \( p_1 = -\frac{1}{T_1} = -f_1, p_2 = -\frac{1}{T_2} = -f_2 \). As \( f_{1,2} \) are frequencies, which are always expressed by positive and real numbers, the roots of the characteristic equation are always negative and real numbers.

There are many implementations of the BPF with the obtained transfer function. In this study, two structural schemes of recursive filters with infinite impulse response (IIR) were synthesized and presented in Figure 2 (a, b).

The first scheme of the BPF (Figure 2, a) is obtained from formula (12), as a series connection of high and low frequency filters.

The second scheme of the BPF (Figure 2, b) is realized as a real second-order differentiating element, corresponding to the resultant transfer function from formula (13).

**Figure 2.** Structural diagrams of bandpass filter (BPF) implementations.
3. Results and Discussion

An experimental corroboration of the developed band-pass filtering algorithms’ efficiency was made with MATLAB tools. Structural diagrams of Simulink-models of two band-pass filter implementations are shown in Figure 3 (a, b).

![Simulink-models of two band-pass filter implementations](image)

**Figure 3.** Simulink-models of two band-pass filter (BPF) implementations.

The best amplitude-frequency response $A(\omega) = |W(p)|$ of both implementations of bandpass filter (AFR BPF) tuned to bandwidth $[f_1 = 1490 \text{ Hz}; f_2 = 1510 \text{ Hz}]$ (or for angular frequency $[\omega_1 = 0.94 \times 10^4 \text{ rad/s}; \omega_2 = 0.95 \times 10^4 \text{ rad/s}]$) is shown in Figure 4. This AFR corresponds to the second implementation of BPF.

The form of both filters’ implementation, when examined to finer precision, proves to be not rectangular. Apparently, this is associated with the imperfection of the filters’ implementation, which introduces deviations in the filter transmission band and an imperfect signal suppression in the filter rejection band.
Figure 4. The best amplitude-frequency response (corresponds to the second implementation of the band-pass filter)

As the experiment showed, the first BPF implementation has the worst quality of the amplitude-frequency response - the maximum transmission factor in the transmission band is 0.35, while for the second implementation of the filter, this factor is 0.5. Reasoning from theoretical premises, for ideal filters, the transmission factor in the passband should be close to 1. This is explained by the specific features of the transmitting properties of series connection of dynamic elements and systems with multiple feedbacks, realizing the deviation control strategy. So, the second BPF implementation was chosen for further research.

Figure 5. MATLAB simulation of the bandpass filter’s operation in the time-domain pre-stall mode (the upper graph is the input signal of the BPF; the lower graph is the output signal of the BPF).
When the compressor with the first supersonic stage operates in the pre-stall mode with further throttling, the circumferential flow heterogeneity generated at the “rotary” frequency splits into three zones (1st rotor, 4th rotor and 7th rotor frequency with subharmonics). These zones are allocated in the frequency domain by the presence of local maxima. Since the number of blades in the supersonic wheel of the first stage of the compressor is 21, the inhomogeneity zone, located evenly around the circumference, grasps three blades (or interblade channels). So, the presence of a significant level of pressure pulsations in the impeller at a frequency of $f = \frac{21\pi}{3}$ can be the sign of this compressor’s approximation to a breakdown of the flow (stall).

The spectra of the input (the upper graph) and output (the lower graph) BPF signals are shown in Figure 6. The main peak of pulsations in the pre-stall mode falls on frequency $f = 500\text{ Hz}$, which is central in the selected transmission band of the filter.

![Figure 6. Spectra of the input and output signals of the BPF (the upper graph is the input signal of the BPF; the lower graph is the output signal of the BPF).](image-url)
The frequencies, corresponding to the maximum amplitude of the harmonic components of the input signal (peaks of pressure pulsations), are: rotary frequency \( f_r = 200 \text{ Hz} \) and frequency \( f = \frac{nz}{3} = 1500 \text{ Hz} \), where \( nz \) is the “blade” frequency (\( \approx 4500 \text{ Hz} \) in the current study). Thus, the significant level of pulsation of pressure in the impeller at \( f = 1500 \text{ Hz} \) is observed. This allows one to identify the pre-stall mode.

As a result of operation of the considered bandpass filtering algorithm, an output signal is obtained which maximum amplitude corresponds to a harmonic with \( f = 1500 \text{ Hz} \). The amplitudes of the other dominant harmonics (including the harmonic, corresponding to “rotary” frequency) are approximately 2.4 times smaller. This makes it possible to design a fairly simple logic for detecting the pre-stall mode. This requires the introducing of a threshold value of the pulsations’ amplitude increase at a frequency of \( f = \frac{nz}{3} \), for example, doubling.

4. Conclusion
As the experimental studies have shown, the use of bandpass filtering algorithms in the automatic control system for identification of the compressor’s pre-stall modes is quite effective for the distinguishing of pressure ripple peaks under the blade.

Having conducted studies of different structures of band-pass filters, it is possible to conclude that the use of the recursive filter with an infinite impulse response (IIR) may have a simpler implementation than filters with a finite impulse response (FIR).

To improve the quality of the BPF, it is possible to use window sinc-filters (for example, Hamming or Blackman), which increase the amplitude of the signal in the transmission band and the signal attenuation outside it [9].

In general, the proposed expansion of the ACS GTE functions will provide an opportunity to increase the engine reliability and safety of flights.

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