Oscillation Dynamics in Short-Lived Facular Regions During Their Lifetime

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Abstract
We performed a multi-wave study of the oscillation dynamics in short-lived facular regions during their lifetime. We studied oscillations in five regions, three of which belonged to the beginning of the current solar-activity cycle and two of them existed at the end of the previous cycle. We found that in the facular regions of the current cycle, low-frequency (1 – 2 mHz) oscillations dominated in the early stages of the facular formation, while in the regions of the previous cycle, five-minute oscillations dominated at this stage. At the maximal development phase of all the facular regions, the locations of the observed low frequencies are closely related to those of the coronal loops. These results support the idea that the sources of the low-frequency oscillations in the loops lie at the loops’ foot points.

Keywords Solar – Faculae · Solar – Oscillations

1. Introduction
Solar faculae are small bright spots seen in white-light images, which correspond to bright magnetic points in the photosphere. A region of faculae is usually cospatial with a plage: a bright region in the chromospheric images. Facular regions are well identified in small active regions or new/old active regions without sunspots. Due to their prevalence and relatively large area, a facular region can play an important role in the processes of energy exchange and transformation. In addition, along with active regions containing sunspots, facular regions may be sources of solar flares. Of all manifestations of solar activity, solar flares, and coronal mass ejections have the most pronounced effects on the Earth, near-Earth space and the configuration of the magnetosphere. Oscillations in facular regions have been

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studied for over half a century (Orrall, 1965; Howard, 1967). Most of the research on this topic has been based on velocity-signal oscillations. It was noted that, in general, oscillations in facular regions are weakened in comparison with the surrounding quiet Sun. Five-minute oscillations stand out among the observed oscillations both in the photosphere and in the chromosphere (Centeno, Collados, and Trujillo Bueno, 2006; Vecchio et al., 2007). It was also found that the observed oscillations are non-uniformly distributed over the area of the facular regions: three- and five-minute oscillations prevail within the chromospheric cells, and oscillations of lower frequencies (1.2 – 2.0 mHz) prevail over the network (Kobanov and Pulyaev, 2011). Mainly three-minute waves propagate upwards in the central parts of facular regions in the chromosphere, and five-minute waves propagate at the periphery (de Wijn, McIntosh, and De Pontieu, 2009). Oscillations with long periods, up to 4.5 hours, were also studied in facular regions (Strekalova et al., 2016; Kolotkov et al., 2017).

A small, developing facular region soon after appearing on the surface may be similar to a sunspot, because, like a sunspot, it is a case of emergence of a compact region of an enhanced magnetic field on the surface. The magnetic-field configuration in these regions, however, is more chaotic than in sunspots (Martínez Pillet, Lites, and Skumanich, 1997), which complicates their study. This is especially pronounced in the chromosphere, where the magnetic pressure becomes comparable to the plasma pressure and the environment becomes much less homogeneous. Chelpanov, Kobanov, and Kolobov (2015) found that 3–6 mHz oscillations dominate in the chromosphere over the magnetic-field concentration nodes, while the dominant frequencies over the peripheral regions are lower: 1.5–3 mHz. The characteristics of the magnetic-field oscillations in the magnetic hills of the facular regions – local maxima of the magnetic-field strength – were studied (Muglach, Hofmann, and Staude, 2005; Kobanov and Pulyaev, 2007; Chelpanov, Kobanov, and Kolobov, 2015, 2016; Ji et al., 2021).

Solov’ev et al. (2019) studied the oscillations in the magnetic nodes of facular regions and revealed a wide range of frequencies in them, which are influenced by changing physical parameters in the nodes.

In the works listed above, the characteristics of oscillations were investigated in the fully formed facular regions in the phase of their maximum development. A facular region, however, is a dynamic object and studying oscillation characteristics during its evolution is of considerable interest. As short-lived facular regions we define regions whose full life cycle can be observed in the visible hemisphere of the Sun under 14 days. In order to distinguish them from other short-lived objects such as, e.g., coronal bright points (CBPs), we chose the lower life-time limit to be three days, given the life time of 95% of CBPs does not exceed 20 hours (Alipour and Safari, 2015). Despite a considerable number of facular regions, few of them meet this criterion. Earlier, Chelpanov and Kobanov (2020) observed the region that was registered as the first active region of the current 25th solar cycle. This work describes the dynamics of the oscillation spectra at different stages of the active region’s development. Two questions arose based on these results: First, will the results obtained be typical of the other facular regions in this cycle? Secondly, are there differences in the oscillation dynamics of the active regions of the ending previous cycle and at the beginning of the new one? Of the five facular regions that are used in the analysis, three regions belong to the current cycle and two regions belong to the end of the previous cycle.

The aim of this work is to try to answer these questions and to expand our knowledge of the oscillatory processes in the short-lived facular regions.
2. Data and Analysis

For this article, we used the Solar Dynamics Observatory (SDO) data for five facular regions that appeared and developed at the visible side of the Sun. In the analysis, we used the Atmospheric Imaging Assembly (AIA) 1600 Å, 304 Å, and 171 Å channels, which represent the chromosphere, transition region, and lower corona, respectively, and Helioseismic and Magnetic Imager (HMI) line-of-sight magnetic-field data. The instruments provide full-disk observations in the emission intensity and magnetic field. The cadence of the AIA data is 12 seconds (24 seconds for the 1600 Å channel) and the cadence of the HMI data is 45 seconds. The spatial sampling is 0.6 and 0.5 arcsec per pixel for AIA and HMI, respectively. To prepare and de-rotate the SDO data, we used the algorithms provided by the SunPy core package (The SunPy Community et al., 2020). To construct the distributions of the oscillation frequencies over the active regions’ areas, we used the Fast Fourier Transform algorithm: For each spatial point, we calculated the oscillation spectra, then, based on these spectra, we found the central frequency of the one-mHz-wide window that yielded the highest integrated oscillation power.

The five facular regions that we analyze appeared on the surface of the Sun on 13 February 2019, 09 December 2019, 6 July 2019, 25 September 2020, and 23 October 2020. They evolved into fully formed medium-sized regions and mostly decayed while still on the visible side of the Sun. The oscillation dynamics of the facular region that appeared on 6 July 2019 were considered by Chelpanov and Kobanov (2020).

Spectral observations of the facular region that appeared on 6 July 2019 were performed with the use of the ground-based Horizontal Solar Telescope of the Sayan Solar Observatory. Observations were carried out on 7, 8, 10, and 11 July while the region moved across the visible side of the Sun. We used spectrograms of two chromospheric lines: Hα 6563 Å and He I 10830 Å. The temporal rate of the series is 1.5 seconds, and the spectral sampling is around 16 mÅ. We estimate the real spatial resolution to be 1.0 – 1.5 arcsec due to the atmospheric limitations. Based on the spectrograms, we calculated the intensity and line-of-sight velocity signals.

We divided the lifetime of the facular regions into four phases: i) emergence – the appearance of increased magnetic field at the photospheric level and bright structures in the chromospheric channels; ii) growth – increase in the size and brightness of a region; iii) maximal phase – size and brightness are at their peak, and the coronal loop system in the 171 Å channel is fully developed; iv) decay – decrease in brightness and a fading coronal loop system. Based on the fast Fourier transform spectra, we calculated the frequencies that dominated within the facular region borders at each phase of the region lifetime. The region borders were determined based on the 1600 Å channel images. Table 1 shows the obtained frequency ranges divided into 0.5 mHz intervals. For the Facular Region 2 these intervals are 1 – 2 mHz.

3. Results

The analysis of the spatial distribution of oscillations in facular regions is more complicated than in sunspots because of a more complex field topology: a facular region may contain several locations of magnetic-field concentration, often of different polarities. In general, the shapes of facular regions are more chaotic and less symmetrical than those of sunspots. Figure 1 shows the morphological features of the studied regions in their maximal phase in the chromosphere, the transition region’, and the lower corona (the Hα line, the 304 Å and
Figure 1  Images of the five analyzed facular regions in their maximal phases in the Big Bear Solar Observatory Hα data and in the 304 Å and 171 Å AIA channels. The Hα data are missing for the dates of Facular Region 1.

| No. | Active Region          | Development phase | Dominant frequencies [mHz] |
|-----|------------------------|-------------------|---------------------------|
|     |                        |                   | 1600 Å | 304 Å | 171 Å |
| 1   | 13 Feb – 15 Feb 2019   | I                 | 3.0–3.5 | 3.0–3.5 | 3.0–3.5 |
|     |                        | II                | 2.0–2.5 | 3.0–3.5 | 1.5–2.0 |
|     |                        | III               | 2.5–3.0 | 3.0–3.5 | 2.0–2.5 |
|     |                        | IV                | 3.0–3.5 | 2.0–2.5 | 3.5–4.0 |
| 2   | 09 Dec – 12 Dec 2019   | I                 | 3.0–4.0 | 2.0–4.0 | 2.0–4.0 |
|     |                        | II                | 3.0–4.0 | 2.0–3.0 | 2.0–3.0 |
|     |                        | III               | 3.0–4.0 | 2.0–3.0 | 1.5–3.0 |
|     |                        | IV                | 3.0–4.0 | 2.0–3.5 | 2.0–3.5 |
| 3   | 6 Jul – 14 Jul 2019    | I                 | 1.5–2.0 | 1.0–1.5 | 1.5–2.0 |
|     |                        | II                | 2.0–2.5 | 3.0–3.5 | 1.5–2.0 |
|     |                        | III               | 2.0–2.5 | 2.0–2.5 | 1.5–2.0 |
|     |                        | IV                | 2.5–3.0 | 2.5–3.0 | 3.0–3.5 |
| 4   | 25 Sep – 02 Oct 2020   | I                 | 1.0–1.5 | 1.5–2.0 | 1.5–2.0 |
|     |                        | II                | 2.0–2.5 | 2.5–3.0 | 1.5–2.0 |
|     |                        | III               | 2.0–2.5 | 2.0–2.5 | 1.0–1.5 |
|     |                        | IV                | 3.0–3.5 | 3.0–3.5 | 3.0–3.5 |
| 5   | 23 Oct – 31 Oct 2020   | I                 | 1.5–2.0 | 1.5–2.0 | 2.0–2.5 |
|     |                        | II                | 2.0–2.5 | 1.5–2.0 | 1.5–2.0 |
|     |                        | III               | 1.5–2.0 | 2.0–2.5 | 1.0–1.5 |
|     |                        | IV                | 3.0–3.5 | 3.0–3.5 | 2.5–3.0 |

The information on the strength and inclination of the magnetic field in the faculae is diverse and somewhat contradictory.

The three facular regions of the new solar-activity cycle show similar oscillation dynamics. In the emergence and growth stages, low frequencies prevail in the 1600 Å and 304 Å signals. In the 171 Å channel signals, low frequencies dominate in the first three stages, especially in the maximal phase. In the decay phase, periods close to five minutes dominate in all observed AIA channels.

Table 1 shows that the oscillation spectra in the facular regions of the previous activity cycle differ from those of the current cycle. In the emergence phase, 3.0 – 3.5 mHz oscil-
Figure 2  Spatial distribution of dominant oscillation frequencies and coronal loops in the 171 Å channel during four development phases in Facular Region 2 in Table 1.

Oscillations dominate in the observed AIA channels in the regions of Cycle 24, while for the regions of the current cycle, the dominant range is 1.5 – 2.0 mHz in this phase. In the Facular Region 1, five-minute oscillations (3.0 – 3.5 mHz) dominate in the 304 Å signals up to the decay phase, when the frequency drops to 2.0 – 2.5 mHz. This is probably connected with the submergence of the coronal loop system in this active region during this phase. In the decay phase of the facular regions of Cycle 24, nearly all channels show oscillations with periods close to five minutes, as well as in the regions of the current cycle.

More detailed information on the spatial frequency distribution in the facular regions of Cycle 24 during the evolution can be found in Figures 2 and 3. In Figure 3 with the three spectral channels used in Table 1, we show the spatial distributions of the dominant frequencies in the photospheric LOS velocity and HMI magnetic-field signals. The spatial frequency distribution of the photospheric LOS velocity signals provides little information. Mostly five-minute oscillations prevail at the photospheric level in all the evolution phases of this facular region in the LOS-velocity signals. In the magnetic-field signals, low frequencies dominate in the growth and maximal phases in the two facular regions of Cycle 24 (Figures 2, 3). Note that for the first facular region of the current cycle (Chelpanov and Kobanov, 2020), the densest low-frequency concentration in the magnetic-field oscillation distribution was observed during the emergence phase.

Unfortunately, spectral observations in the chromospheric Hα and He I 10830 Å lines were only made for AR 12744 (Facular Region 3) in the interval 7 to 11 July 2019. Nevertheless, it is useful to examine the spectral dynamics of the chromospheric oscillations in this region. Figure 4 shows examples of raw intensity and velocity signals, and intensity oscillation spectra in the two chromospheric lines. The intensity signals contain more noise compared to the velocity signals, so below we focus on the LOS velocity-oscillation spectra.
The contour shows the boundaries of the region in its fully developed phase as seen in the 1600 Å channel.

In the chromosphere, during the time from the emergence of the region to the development into a fully formed facular region, the spectral composition of the velocity and line-width oscillations changes significantly. From the spectral observations of the velocity in the region that appeared on 6 July 2019, it can be seen that low frequencies dominate in the facular chromosphere in the first phase, and starting from the growth phase, frequencies in the range of 3 – 4 mHz become dominant, i.e. five-minute oscillations (Figure 5). The high-frequency peaks that appeared in the spectra of the maximal phase, especially in the He I 10830 Å line, may be explained by the reduction in the relative weight of low frequencies in the chromosphere at this phase, as well as by the complicated He I line-formation mechanism, which involves UV radiation from the upper layers of the atmosphere. We should note that the presence of low frequencies in the intensity and half-width signals is typical of the maximal phase (Figure 5).

4. Discussion

Usually, developed facular regions show the presence of strong five-minute oscillations in the photosphere and chromosphere, but the stages of appearance and growth show a concentration of low frequencies of 1 – 2 mHz (Figure 3) in the magnetic-field signals. They may occupy a significant part of the area of the emerging active region (Chelpanov and Kobanov, 2020). Low-frequency areas are also found in the transition region (Kobanov and Pulyaev, 2011; Kobanov, Kolobov, and Chelpanov, 2015). Such a spatial distribution of dominant oscillation frequencies in small facular regions fundamentally differs from that observed in fully formed sunspots. In sunspots, the frequencies in the center, on the contrary, are high,
and they decrease with distance from the center. Low frequencies of 1 – 2 mHz are observed only at the very edges of the spot, or even beyond them (Kobanov and Makarchik, 2004; Maurya et al., 2013; Kobanov, Kolobov, and Chelpanov, 2015).

In the earliest stage, the active facular region does not manifest itself prominently in the corona, and in the distribution of the dominant frequencies it stands out weakly against the surrounding background. Later, at the stage when an active region evolves into a more developed structure, a system of coronal loops is formed above it. At this time, the elongated shapes of coronal loops appear in low frequencies (1 – 2 mHz) in the distribution of dominant frequencies of the active region in the 171 Å coronal line (Figures 2, 3).

The distributions of the magnetic-field oscillation signals show that, in the earliest phase of the region formation, patches of low frequencies appear at the location of the facular region. Such patches can be also seen in the 1600 Å emission, although in a less pronounced form. Later, in the magnetic-field signals, these frequencies occupy most of the facular area.

In the AIA channels’ spectra, we note some differences in the oscillation-spectra dynamics between the facular regions of the current cycle and those of the end of the previous cycle. At present, we cannot explain these differences. Such a research would require a larger set of observational material. Probably the causes can be found in the magnetic-field topology characteristics connected to the phases of the solar-activity cycles. One should bear in mind that the active-region loop system comprises loops of different heights (Mandrini et al., 1996; Kwon et al., 2012), which influences the characteristics of the dominant frequencies.

Figure 4 Examples of intensity and LOS velocity signals and intensity-oscillation spectra in the ground-based observations for the maximal phase of Facular Region 3.
distribution in different spectral channels. We should note that the facular regions at the end of the previous cycle existed for a much shorter time than the regions of the current cycle. The maximal LOS magnetic-field strength in one of them, however, was over 1 kG, which is higher than in some other regions in the table. Note also that the three facular regions of the current cycle in Table 1 are located in the southern hemisphere, while the two regions of Cycle 24 are located in the northern hemisphere. The north–south asymmetry of the solar activity (van Driel-Gesztelyi and Green, 2015; Madjarska, 2019) may play a role in the evolution characteristics of these regions.

We assume that the low frequencies observed in the chromospheric distributions and the low frequencies observed in the loops in the corona are interconnected and represent the same process. The frequency distributions show that the low frequencies correspond to the location of the loops in the layers of the atmosphere. In the initial stages of the facular region formation, the magnetic tubes rising to the surface penetrate only the lower layers. At the same time, the lower layers of the facular region are filled with low frequencies. In subsequent stages, the magnetic structures rise to coronal heights and form coronal loops, where the distribution of low frequencies outline the pattern of these loops.

Figure 6 shows a schematic representation of the magnetic loop at the time of the facular region emergence and in the developed stage. In the lower layers, only vertical footpoints of the loops are observed, where they occupy smaller areas. In this case, the pattern of low frequencies in the distribution of oscillations in the lower layers breaks up into separate small domains. In the last phase of the facular region’s evolution before its decay, the picture of the coronal loops dissipates. Lower, in the transition region, low frequencies become sometimes more present (for example, see Figure 3). This may indicate that the loops sink lower from the corona in the process of their disappearing.

Such a picture of the relation between low frequencies and magnetic coronal loops supports the presence of some kind of wave-guiding mechanism for the oscillations propagating...
Figure 6 The position of a coronal loop in a facular region relative to two layers and the location of low frequencies in them. On the left, the loop only reaches the lower atmosphere levels of the photosphere and chromosphere. On the right, the loop’s upper part is in the coronal heights. The panels in the middle represent what the distributions of the low frequencies look like in the chromosphere and the lower corona. The red areas show the observed low-frequency regions.

from the foot points. Earlier, Chelpanov and Kobanov (2020) showed that low frequencies in coronal loops indeed propagate as variations in brightness separately from their transverse oscillations as a whole.

5. Conclusions

In this work we have studied the dynamics of the spatial distribution of oscillation frequencies in five facular regions, two of which belong to the end of Cycle 24 and the three others belong to the beginning of Cycle 25. The conclusions are as follows:

i) We established that the dynamics of the oscillation spectra is similar in different facular regions of the current cycle, while the regions of Cycle 24 show a number of differences.

ii) During the facular-region life cycle, the spatial distribution of the dominant frequencies shows significant changes in the intensity and LOS magnetic-field signals. For the LOS-velocity oscillations at the photospheric level, these changes are insignificant. In the maximum phase, the spatial distribution of low frequencies in the 171 Å line corresponds to the locations of the coronal loop apexes. In the decay phase, five-minute oscillations dominate in the intensity signals of all AIA channels. These characteristics are observed in all the studied faculae.

iii) For the facular regions of the current cycle, it was found that immediately before the first signs of brightening of the observed regions in the EUV lines, the signals of the magnetic field and the 1600 Å line intensity show concentrations of low-frequency oscillations (1 – 2 mHz) in the central parts of the future facular region, while in the facular regions of the previous cycle, five-minute oscillations dominated in this phase. Besides, in one of the facular regions of Cycle 24, low frequencies (2.0 – 2.5 mHz) in the 304 Å channel become more apparent only in the decay phase. This was probably caused by the submerging coronal loop system.

We assume that in the facular regions of the current cycle, the observed spatial concentration of low-frequency oscillations in the signals of the magnetic field, the 1600 Å channel intensity or the LOS velocity in the Hα and He I 10830 Å chromospheric lines may be considered as one of the early predictors for active-region formation. Due to limited statistics, the conclusions on differences in solar-cycle behavior should be considered preliminary. Definitive results require a larger data set.

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**Data Availability** The spectral ground-based data used in this work are available from the corresponding author upon request. The SDO data are available to download through the Joint Science Operations Center (JSOC) Data Explore service (jsoc.stanford.edu/ajax/lookdata.html).

**Declarations**

**Disclosure of Potential Conflicts of Interest** The authors declare that they have no conflicts of interest.

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