Frequency behavior of the large scale instability in assisted atomization of a liquid jet

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Abstract

In assisted atomization, a liquid jet stripped off by a fast gas stream produces fine drops at small distances downstream injection (Marmottant and Villermaux [1], Hong et al. [2], Varga et al. [3]). Yet, the incoming liquid stream is never fully atomized by stripping alone: the jet that remains at the end of the intact length experiences large scale lateral motion and breaks further downstream into droplets significantly larger than those due to stripping. The origin of these large-scale instabilities and the scaling of the flapping frequency with control parameters remain quite controversial. Indeed, the flapping frequency is found to linearly increase with the gas velocity (e.g. Arai and Hasimoto [4], Lozano et al. [5]), but there is no agreement on the influence of the injector geometry including the gas vorticity thickness at injection which is a key parameter of the shear instability involved in the stripping process (Marmottant et al. [1], Matas et al. [6], Fuster et al. [7], Matas [8]). To clarify this question, experiments have been undertaken that span a wide range of flow parameters (liquid velocities from 0.17 to 1.4 m/s, gas velocities from 10 to 140 m/s) and injector geometries (5 to 20 mm liquid diameters, 1.8 to 24 mm gas thicknesses). Flapping occurred for all conditions, and its frequency was found to be independent of the axial downstream position. Two quite different regimes have been identified. In the first regime, the flapping frequency increases with the gas velocity. Using stability analysis, we show that this regime is driven by the asymmetric shear instability so that the frequency scales as the gas velocity divided by the gas vorticity thickness at injection. In the second regime, the flapping frequency no longer varies with the gas velocity, a behavior not mentioned in the literature. In that case, the frequency scales as the liquid velocity over the liquid jet radius. The first regime is shown to occur when the wavelength associated with the shear instability is larger than the jet radius. Conversely, the second regime occurs when the expected shear-instability wavelength becomes too small compared with the jet radius: in the latter case, the system prefers to amplify a larger scale, comparable with the jet size. A quantitative criterion for this boundary is suggested based on experimental evidence and inspired from stability analysis results.

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Introduction

Assisted atomization is a process allowing the break-up a liquid jet into droplets with the help of a fast co-current gas stream. The stripping of the liquid surface produces fine droplets near the injector exit (Mar-mottant and Villermaux [1], Hong et al. [2], Varga et al. [3], Villermaux [18]). Yet, the incoming liquid stream is never fully atomized by stripping alone: the jet which remains at the end of the intact length experiences large scale lateral motion (the flapping) and breaks further downstream into droplets significantly larger than those due to stripping. The origin of these large-scale instabilities and the scaling of the flapping frequency with control parameters remain controversial. Besides, even though the flapping was observed in the coaxial round jet configuration, it has received much less attention than in the planar liquid sheet configuration.

For liquid sheets, the flapping frequency has been found to linearly increase with the gas velocity (e.g. Arai and Hashimoto [4], Lozano et al. [5]). Yet, there is no agreement on the influence of the injector geometry including the gas vorticity thickness at injection, which is known to be a key parameter of the shear instability involved in the stripping process (Mar-mottant et al. [1], Matas et al. [6], Fuster et al. [7], Matas [8]). To clarify this question, well-controlled experiments have been undertaken spanning a wide range of flow parameters and varied injector geometries.

Injection set-up

The injector is sketched on Figure 1. It is composed of two coaxial channels, an outer annular one for the gas and an inner cylindrical one for the liquid. The channel length (~1m) is long enough to ensure fully developed flow conditions for both phases.

The liquid channel is formed of two tubes. The bottom one can be changed in order to modify the exit diameter \(H_L\); the latter has been varied from 5 to 20 mm. We used tap water supplied with an overflowing tank to ensure stable boundary conditions. The liquid flow rate is measured with an Oval flowmeter LSF445 (range from 8 to 100 liters per hour, uncertainty of 1% of the measured value). The liquid velocities range from 0.17 to 1.4 m/s.

The gas channel is also built using two tubes: the top one is equipped with a damping chamber and the second one can be changed to modify the gas exit diameter \(D_G\) and hence the gas stream thickness \(H_G\). The latter spans the range 1.8 to 24 mm. The long tube allows the development of thick boundary layers. Clean air at room temperature delivered from a compressor feeds the gas stream. The reference air velocity is measured at the exit of the gas channel and at the center of the gas ring \((H_G/2)\) with a Pitot tube and a differential pressure sensor TSI DpCalc (uncertainty 1.5% of the read value). Gas velocities have been varied from 10 to 140 m/s.

![Figure 1. Injector design](image)

![Figure 2. Examples of velocity profiles obtained with hot-wire anemometry for the injector \(H_L=5\) mm, \(H_G=5\) mm.](image)
\[ \delta_g = \frac{\Delta U}{dU/dr}|_{\text{max}} \]

Let us underline that the lip of the splitter tube that separates the gas from the liquid has a thickness of 0.2 mm for all injectors. For all the experimental conditions considered here, this lip thickness remains smaller than 1.5 times the gas vorticity thickness.

**Flapping frequency measurements**

Shadowgraph pictures of the liquid jet are taken with a Vision Research Miro M310 high-speed camera equipped with a TAMRON 90 mm objective set at full aperture. The spatial resolution is about 0.2 mm per pixel. The exposure time was set to 90\( \mu \)s to gather frozen images. A typical example of collected images is shown in Figure 3: it illustrates the flapping motion characterized by lateral displacements larger than the liquid jet injection radius. The image processing of such pictures consists in background elimination and contrast enhancement. The liquid jet is extracted from the pictures with a connected algorithm available in the Image toolbox of Matlab. By extracting the edges of these connected areas, one can collect relevant information such as frequency spectra of interface position or of jet radius oscillation.

In order to measure the frequency of the flapping instability, raw shadowgraph images of the liquid jet are used and transformed to extract the center of the jet. Background elimination is performed, and a median filter is applied whose size is chosen so as to eliminate drops and ligament structures. Its size must therefore be adjusted according to the camera resolution and to the sizes of the structures to be eliminated. In the present experiments, the filter size ranges from 2 pixels to 40 pixels, in order to cut off objects with a size smaller than 1x1 pixels up to 20x20 pixels respectively. A horizontal gray level profile is then extracted for various downstream positions. On each profile, the jet center position \( x_c \) is computed from the intensity profiles \( I(x) \) as \( x_c = (\Sigma x I(x))/\Sigma I(x) \). For each flow condition, the data set consists in a time series of 5,000 pictures taken at a sampling frequency of 1 kHz to ensure the collection of independent samples. For each of these time-series, the computed liquid jet center is superimposed onto the original pictures on a movie, in order to check the correct functioning of the algorithm and also the good tuning of the filter length (in practice, the sensitivity to the filter size is systematically tested). A typical output of this data processing is shown in Figure 4.

The jet center determination is quite accurate in regions where the liquid jet is close to a cylinder-like shape. In other regions, in particular whenever bag formation occurs, the jet center is somewhat ill-defined, but the image processing provides smooth and continuous information, and the resulting spectra never exhibit spurious discontinuities because of jet shape. A typical example of the spatial evolution of the flapping frequency spectrum is given in Figure 5: clearly, the peak frequency remains the same whatever the downstream distance.

![Figure 3. Typical image of a flapping jet in the following conditions: \( H_L=5 \text{ mm}, H_G=5 \text{ mm}, U_L=0.28 \text{ m/s}, U_G=19.5 \text{ m/s} \).](image)
Figure 4 Raw image and detected jet center shown in red dashed line.

Figure 5. Flapping spectrum for multiple vertical positions downstream injection.

Figure 6. Evolution of the flapping frequency with the gas velocity for different injector geometries and various liquid velocities. Error bars represent the spectrum peak width at mid-high.

Results

Flapping frequency measurements are plotted in Figure 6 against gas velocity (measured at the center of the gas channel exit) for various geometries and mean liquid velocities. Clearly, two groups of data can be distinguished:

- A first group where the flapping frequency increases with gas velocity, named G1.
- A second group where the flapping frequency is almost independent of gas velocity, named G2.

The regime G1 where the flapping frequency monotonously increases with the gas velocity is commonly observed in sheet atomization (see among others Lozano & al [5], Araï & Hashimoto [4]). However, the fact that we observe two distinct behaviors, including one for which flapping frequency is independent of gas velocity, is new and has never been described in the literature neither for jets nor for sheets. For example, Lozano & al [5] varied the liquid sheet thickness by a factor as large as 10, but do not observe regime G2.
Regarding the sensitivity of the flapping frequency to the liquid velocity, we distinguish G1 and G2 behaviors, in Figure 7 and Figure 8 respectively. Globally the flapping frequency increases with the liquid velocity irrespective of the regime. Yet, the increase of flapping frequency with liquid velocity is not as regular for the G2 regime compared to the G1 regime. Note that a flapping frequency increasing with liquid velocity is also observed by Lozano & al. [5] in sheet atomization for low liquid velocities (say less than 1–1.5 m/s) while at higher liquid velocities, the evolution of the frequency with the liquid velocity is no longer monotonic.

**Figure 7** Flapping frequency as a function of liquid velocity for G1 behavior.

<table>
<thead>
<tr>
<th>U&lt;sub&gt;L&lt;/sub&gt; (m/s)</th>
<th>F&lt;sub&gt;flapping&lt;/sub&gt; (Hz)</th>
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<tbody>
<tr>
<td>0</td>
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<tr>
<td>0.2</td>
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<tr>
<td>0.4</td>
<td>150</td>
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<td>0.6</td>
<td>200</td>
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<tr>
<td>0.8</td>
<td>250</td>
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<td>1</td>
<td>300</td>
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**Figure 8** Flapping frequency as a function of liquid velocity for G2 behavior.

<table>
<thead>
<tr>
<th>U&lt;sub&gt;L&lt;/sub&gt; (m/s)</th>
<th>F&lt;sub&gt;flapping&lt;/sub&gt; (Hz)</th>
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<tr>
<td>0</td>
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<td>0.5</td>
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Diverse, mostly empirical, proposals have been made in the literature regarding the scaling of the flapping frequency for liquid sheets. Different Strouhal numbers built on various length scales (namely H<sub>L</sub>, H<sub>G</sub>, δ<sub>C</sub> or some combination of these) have been considered by authors. We have tested the propositions from Araï & Hashimoto [4], Lozano [5], Couderc 2007 [9] and Odier 2014 [10], but they were all unable to collapse our data. In particular, none of the above propositions provides a satisfactory dependence of the frequency on the liquid thickness. In addition, previous attempts to connect flapping to a shear instability have been unsuccessful (e.g. Lozano & al. [11]). Yet, these shear instabilities are quite complex processes and it is worth reexamining the situation taking advantage of recent advances in our understanding of their behaviour (Matas et al. [6], Fuster et al. [7], Matas [8]). In an attempt to clarify the parameters controlling the flapping frequency, let us consider first the G1 regime.

**Flapping frequency analysis for G1 regime**

For this regime, the increase of the flapping frequency with air velocity U<sub>G</sub> could be an imprint of the shear instability for which similar trends are observed. In order to test if there is (or not) a strong connection between flapping and shear instability, we performed wave frequency measurements close to the injector exit and we compared them with the flapping frequency. Let us first explain how these measurements were achieved. Wave frequency is measured using image segmentation with Matlab software and with the help of image toolbox. Raw pictures obtained with shadowgraphy and high-speed imaging of the jet are background-removed, thresholded with the Otsu’s method, and segmented using bwlabel function. The area connected to the injector exit is then assumed to be the continuous liquid jet, and we extract the borders of this connected area. Two signals are therefore built:
- the jet radius, given by the distance between opposite borders at a given downstream location,
- the absolute position of one border.

These signals were gathered at regular positions between the injector exit and a downstream distance of about 3H<sub>L</sub>. Spectra of these temporal signals are obtained with Fast Fourier Transform. The Shannon criterion is always fulfilled, and the frequency resolution is about 0.24 Hz.

**Figure 9.** Time evolution of an oblique shear instability wave.
Figure 11 (top and middle) shows the spectra of these two signals, while the bottom curve is the spectrum of the jet center that provides the flapping frequency as explained in previous sections. The spectrum of the jet radius (top curve) is a measure of the frequency of symmetrical waves: its peak differs from the flapping frequency. The spectrum of the jet edge (middle curve) exhibits two peaks, one corresponding to symmetrical waves (top curve) and the other one to the flapping frequency (bottom curve). Indeed, the interface position is affected both by large-scale motions of the jet as well as by interfacial waves on top of it. These features are the same whatever the downstream position up to 3 $H_L$. A very interesting feature is that the flapping frequency is not present in the jet radius spectrum (top graph): this implies that flapping waves are not symmetrical. This conclusion is also supported by Figure 9 that gives an example of an asymmetric wave and of its evolution in time: oblique waves continuously evolve to ultimately form large-scale structures characteristic of the flapping.

In Figure 10, we plot the frequency of shear instability symmetrical waves, which we named KH (for Kelvin-Helmholtz) in the sequel, along with the flapping frequency.

Figure 10 Flapping and symmetrical wave frequency (KH) as a function of air velocity. Experimental conditions: $H_L=5$ mm, $H_G=5$ mm, $U_L=0.28$ m/s.

Figure 10 shows that symmetrical waves (KH) have a slightly larger frequency than flapping waves. In order to explain this behavior, we have carried out a linear stability analysis.

Figure 11 shows that symmetrical waves (KH) have a slightly larger frequency than flapping waves. In order to explain this behavior, we have carried out a linear stability analysis.

Figure 11 Radius, interface and flapping frequencies of the liquid jet. The different curves on a given plot correspond to various measuring positions downstream injection. Experimental conditions: $H_L=5$ mm, $H_G=5$ mm, $U_L=0.28$ m/s, $U_G=19.5$ m/s.
This stability analysis is based on studying amplification of normal perturbations of the following shape:

\[
\eta' = \eta_0 e^{-kz + \omega t + n\theta}
\]  

(1)

where \(\eta'\) is the interface position perturbation and \(\eta_0\) is the unperturbed interface position. In a cylindrical frame, \(z\) is the vertical distance from injection, \(k\) is the associated wavelength, which is complex in the spatial analysis we have chosen to carry out. The pulsation \(\omega\) is real in a spatial analysis and complex in a temporal analysis. When both are complex, a spatio-temporal analysis is made. The pulsation \(\omega\) is real in a spatial analysis and complex in a temporal analysis. When both are complex, a spatio-temporal analysis is made. The polar angle \(\theta\) is multiplied by \(n\): if \(n = 0\), the perturbation shape is axisymmetric, when \(n = 1\) or \(n = -1\), the perturbation is a helix (without any plane of symmetry), and the superimposition of both \(n = \pm 1\) modes yields a perturbation with a symmetry plane. The shape of modes \(n=0\) and of \(n = \pm 1\) is shown on Figure 12 and Figure 13. Pressure and velocity perturbations are expanded in normal modes similar to that of the interface.

**Figure 12.** Example of symmetric (varicose) mode \(n = 0\).

A viscous spatio-temporal stability analysis would be very complex to carry out in a cylindrical frame when \(n \neq 0\), due to the difficulty to decouple pressure and velocity perturbations, and due also to the high order of the system to solve. For a planar mixing layer, and by analyzing the energy budget, Matas [8] has been able to show that the instability mechanism is mainly supplied by kinetic energy of the perturbation is mainly fed by inviscid terms, namely gas Reynolds stresses contribution, at high gas velocities. The precise domain of validity of that conclusion is more complex than a simple condition on the gas velocity, and it will not be discussed in detail here.

**Figure 13.** Example of combination of \(n = \pm 1\) modes (sinuous).

For such conditions, an explicit expression for the frequency was obtained for the mode \(n=0\) (Matas et al. [6]). The same methodology has been used here to investigate the mode \(n=0\) in the case of a liquid jet: we searched for each flow condition what kind of mechanism drives the shear instability. For all data corresponding to an air velocity larger than \(~30 \text{ m/s}\), we found that the shear instability is fed by inviscid contributions (Reynolds stress contribution). For these “inviscid” conditions, we can therefore perform an inviscid simplified spatial analysis (i.e. without including viscosity), in order to examine the stability of non-axisymmetric modes. Figure 14 shows the results of such an inviscid stability analysis for the modes \(n=0\) and \(n=\pm 1\), for the following experimental conditions: \(H_L = 5 \text{ mm}\), \(H_G = 5 \text{ mm}\), \(U_L = 0.28 \text{ m/s}\) and \(U_G = 45 \text{ m/s}\). The dispersion relations with \(n = 1\) or with \(n = -1\) are the same, due to the symmetry of the problem.

**Figure 14.** Dispersion relation for the following
experimental condition: $H_2=5\text{mm}$, $H_2=5\text{mm}$, $U_L = 0.28 \text{ m/s}$ and $U_G = 45 \text{ m/s}$, $\delta_G=0.052 \text{ mm}$. $k_i$ is the imaginary part of the wave number $k$.

In Figure 14, we plot two dispersion relations, for the same injection conditions, but with $n = 0$ (filled circles) and $n = 1$ (empty squares). For a convective instability as is the case here, the most amplified frequency is the one which has the greater absolute value of $k_i$, which is the imaginary part of the wave-number, $k$ (this is the “most dangerous” mode). Due to notation convention, $k_i$ is negative when perturbations are spatially amplified. Then, the greater absolute value of $k_i$ gives the prediction of the most amplified frequency. From Figure 14, it happens that the asymmetric mode $n=1$ is more amplified than the symmetrical mode $n=0$, its negative $k_i$ being smaller. Beside, the frequency of the $n=1$ mode is smaller than the frequency of the $n=0$ mode (KH): this is in agreement with our experimental results if one associates the flapping frequency with $n=1$ mode. These considerations indicate (or at least are consistent with) the idea that the flapping corresponds to the large-scale amplification of $n=\pm1$ asymmetric modes of shear instability waves. We are therefore in a position to compare our data with the analytical prediction of the frequency derived in the planar case under an inviscid assumption (Matas et al. [6]). This scaling is the following:

$$f_{flapping} \approx \frac{\rho_0}{\rho L} \left(1 + 5\sqrt{2} M^{-1/2} / 2\right)$$

(4)

where $M = \frac{\rho \rho_G U_G^2}{\rho L U_L^2}$ is the dynamic pressure ratio.

Figure 15. Test of the inviscid scaling eq.(4) (solid line) on the group G1 of the flapping frequency data set.

Figure 15 shows the Strouhal number built on the vorticity thickness and on the air velocity as a function of $M^{-1/2}$. Clearly the prediction given by Eq.(4) is parallel to a significant number of experimental data. This sub-set of G1 group corresponds to conditions for which the Reynolds stresses are indeed predominant in the shear instability energy budget. The scaling eq.(4) exhibits the correct trend although it slightly under-predicts the frequency. The remain-

ing sub-set of data, at a larger frequency, most probably corresponds to a shear instability mechanism driven by an absolute interaction between viscosity and surface tension, as described by Otto & al [17]. This conclusion has been ascertained for the mode $n=0$ by analyzing the energy budget in a viscous spatio-temporal approach. Strictly speaking, the analysis would have to be done anew for $n=1$. Besides, a scaling of the kind of the one proposed in eq.(4) remains to be determined for asymmetric modes.

**Frequency analysis for regime G2**

Let us now discuss the data corresponding to the regime G2. Figure 16 shows the flapping and KH frequencies as a function of air velocity for a reduced data set pertaining to the regime G2. Clearly, the flapping frequency remains close to the KH frequency below an air velocity of about 50 m/s, but beyond the two series diverge. In particular, the KH frequency is still increasing with gas velocity while the flapping frequency remains constant. Hence, in regime G2, there is no connection between flapping and asymmetric shear instability waves.

![Figure 16](image-url)
The stability theory results were exploited to estimate the liquid acceleration due to gravity and also to non-linear gas induced drag on the waves. Instead, we exploited stability theory results to estimate $\lambda_{KH}$. The shear instability wavelength was computed using the frequency of the symmetrical waves (KH) in the inviscid case, combined with the phase velocity as given by Dimotakis [14]. This estimation is fully consistent for the sub-set of G1 data corresponding to an inviscid mechanism. We applied the same procedure for all others data, namely the subset of G1 regime corresponding to viscous-surface tension instability mechanism and the G2 regime. In a sense, this procedure compares the jet radius with the shear instability wavelength that would occur under an inviscid mechanism. The results are plotted Figure 18. Interestingly, the proposed $H_L/\lambda_{KH}$ criteria allows to clearly discriminate between the two regimes. Clearly, the jet radius alone is not sufficient to determine the regime since data for large liquid jets are found in the two regimes. Globally, the regime G2 is characterized by smaller wavelengths compared with the regime G1, leading thus to higher $H_L/\lambda_{KH}$. A crude frontier between the two regimes is given by $H_L/\lambda_{KH} \approx 0.6$, but more data are required to fully determine that transition criterion that may also depend on extra parameters. The first regime occurs when the wavelength associated with the shear instability is larger than the jet radius. Conversely, the second regime occurs when the expected shear-instability wavelength becomes too small compared with the jet radius: the system prefers then to amplify a larger scale, comparable with the jet size. In that regime, the flapping arises from an opportunistic amplification of noisy perturbations and its response is no longer connected with the shear instability.

**Frontier between the two regimes**

It is worthwhile to discuss now the frontier between the two regimes. As the flapping instability mechanism is related with the gas recirculation and lift-off around asymmetric waves, the spacing between axial waves happens to be a key parameter when examining the action of the gas on the jet. In addition, and according to inviscid stability analysis, the amplification of symmetrical and of asymmetrical mode happens to be controlled by the ratio of the jet radius to the axial wavelength: when that parameter is small, asymmetrical modes could be more amplified than symmetrical ones. We thus considered the ratio $H_L/\lambda_{KH}$ and computed it for all our data. Yet, and contrary to frequency, the wavelength is not easy to measure. Indeed, it strongly varies in space because of the liquid acceleration due to gravity and also to non-linear gas induced drag on the waves. Instead, we exploited stability theory results to estimate $\lambda_{KH}$. The shear instability wavelength was computed using $f_{\text{flapping}} H_L/\lambda_{KH} = 0.8$.

Yet, the dispersion in Figure 17 is somewhat significant, indicating that some hidden parameters remain to be identified and accounted for.

Figure 17. Strouhal number based on liquid velocity and liquid thickness as a function of the liquid Reynolds number for all the data corresponding to the regime G2.

Figure 17 shows an encouraging collapse of the data of Figure 16 around a nearly constant Strouhal number about 0.8, leading therefore to the following expression for the flapping frequency in the second regime:

$$f_{\text{flapping}} H_L/\lambda_{KH} = 0.8$$

Conclusion

By analyzing the flapping frequency over a large range of flow conditions and injector geometries, the existence of two regimes has been demonstrated: a first one where the frequency increases with the gas velocity and a second one where the frequency is independent of the gas velocity. The first regime
is shown to be connected with the asymmetric modes of the shear instability, leading thus to a flapping frequency controlled by the shear rate $U_C/δ_c$. This result clearly confirms that the gas vorticity thickness at injector exit does influence the frequency. A more precise scaling for the frequency has been established (see eq.(4)) when the instability mechanism is inviscid. When viscosity and surface tension are involved, the determination of a precise scaling remains to be done. In the second regime, the shear instability wavelength is too small compared with the jet radius. Hence, the system amplifies incoming perturbations with a resulting frequency of the order of $U_C/δ_C$ that is no longer connected with the shear instability. The transition between the two regimes is as first order controlled by the parameter $H_C/λ_{KH}$. Our current understanding of flapping mechanism in coaxial axisymmetric assisted atomizers is summarized in the sketch of Figure 19.

Concerning perspectives, it would be interesting to determine if the above picture is also relevant for liquid sheet atomization, and in particular, if the second regime can be observed on liquid sheets in the limit of small shear instability wavelengths.

**Figure 19.** Recap scheme of the flapping origin and of the flapping frequency scaling in coaxial atomization.

**Acknowledgements**

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n°265848 and was conducted within the FIRST project. The laboratory LEGI is part of the LabEx Tec 21 (Investissements d’Avenir - grant agreement n° ANR-11-LABX-0030).

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